ELECTROPHOTOGRAPHY

HISTORY

Humankind uses three principal methods for making permanent images on paper. The oldest is direct contact, which includes the printing press, the typewriter, and the pen and the ink jet. It relies on mechanical contact between liquid ink and paper. The next to be developed was photography, which uses light-induced chemical reactions to change the color of a substance. The most recent is electrophotography, which forms its images by the electrostatic force on charged particles.

Each of these three major methods of writing (mechanical, chemical, electrical) has numerous variations and adaptations, some with different names. When it was introduced commercially, the electrostatic method of writing was called xerography, from the Greek words for "dry writing." Early, the absence of liquids in the process was seen as one of the advantages of the method, and it was emphasized by the choice of name. Eventually the process was successfully commercialized by the Haloid Corporation (now called the Xerox Corporation) in the form of a copying machine. When other companies joined the race to manufacture copiers based on electrostatics, they preferred to use an older name for the process (electrophotography) because the existing copiers all depended on light to modulate the charge associated with the image. Later, additional methods for using electrostatic printing were developed that used liquids (instead of dry particles in air) and produced the charge image directly without the intervention of light. Although these methods, strictly speaking, do not, correspond to the derivations of the names, most people continue to use either electrophotography or xerography to refer to all printing methods based on electrostatic force. In this article, we use the term electrophotography.

Electrophotography was almost single-handedly created by a single person, Chester Carlson. As a patent attorney, he saw the need for an inexpensive and simple way to copy the many documents that crossed his desk every day and set out on a deliberate quest to invent an entirely new method of putting marks on paper. After many years of work, he produced the first image (Fig. 1) in 1938 and later enlisted Battelle Laboratories to work out the practical aspects of printing electrostatically. Although numerous companies had previously turned down his invention, the Haloid Corporation, a small maker of photographic paper in Rochester, NY, decided to make a copying machine for office use. The resulting commercial acceptance of Xerox copiers became one of the greatest success stories in manufacturing history. When the basic patents expired, a number of other companies joined the contest. This led to a competitive struggle that produced a number of substantial improvements from the research labs of Canon, Eastman Kodak, and others.

As often happens, this completely new technology produced many changes in society. Perhaps the most important was the capability of printing many high-quality copies of a document without the large capital costs associated with a printing press. Before electrophotography, it was said, "freedom of the press belongs to those who own one." Now, virtually everyone has access to some means of publishing. This is especially true with the advent of the laser printer, a modification of the basic electrophotographic copier in which light is controlled by a computer and which led to a new industry called "desktop publishing."

Although this technology has allowed anyone to publish, it has also allowed anyone to make an exact copy of any printed document without explicit permission from the original producer of the document. In 1960, anyone who wanted to study an encyclopedia article (like the one you are reading now) had to go to a library, wait until any other readers finished, and then take laborious handwritten notes on the content because the expensive volume could not be taken from the library. Today, you are most likely reading a electrophotographic copy of the article, rather than the original, and you are in permanent possession of it. Readers enjoy this release from drudgery, but publishers perceive it is as lost income. The battle over copyrights that began with the Xerox copier will continue for some time. It has become much more heated with the ad-

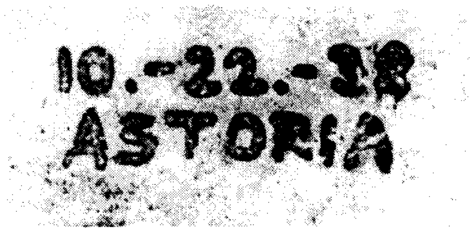

Figure 1. The first xerographic image made by Chester Carlson and Otto Kornei in 1938. (Courtesy Xerox Corporation.)

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vent of the color copier to an economic world based on bank notes and stock certificates.

Electrophotography is used mainly in two related machines, copiers and laser printers. The next section discusses the basic steps in the process, as applied to the original machine, the light-lens copier. Afterward, the aspects peculiar to the laser printer are covered, followed by the modifications needed to convert a monochrome printer into a full-color copier or printer.

BASIC STEPS IN THE ELECTROPHOTOGRAPHIC PROCESS

The electrophotographic copier incorporates a number of steps that must be carried out in proper sequence. These steps form the foundation of the process, whether used in a copier or a printer. The first step is *charging* an insulator, as illustrated in Fig. 2. This is the charge that attracts the oppositely charged toner powder, and initially it is uniformly distributed over the surface. The insulating sheet holds the charge until the image has been developed. Depending on the type of electrophotographic application, the insulator is called by various names, such as photoreceptor, electroreceptor, or substrate. In this article, the most commonly used term photoreceptor is used.

As long as the charge on the photoreceptor is uniform, any developed image is uniformly gray. The image information is put into the process in the next step, called *exposure.* The photoreceptor is photoconductive, so that any area exposed to light becomes conducting, removes the charge from the surface, and neutralizes it. In a conventional copier, the light originates in a lamp and is reflected onto the photoreceptor from the document to be copied. Optical lenses focus the light so that it forms a sharp image and discharges the photoreceptor wherever the light from the white parts of the document strikes it. The dark areas of the photoreceptor, corresponding to the type and pictures, remain charged.

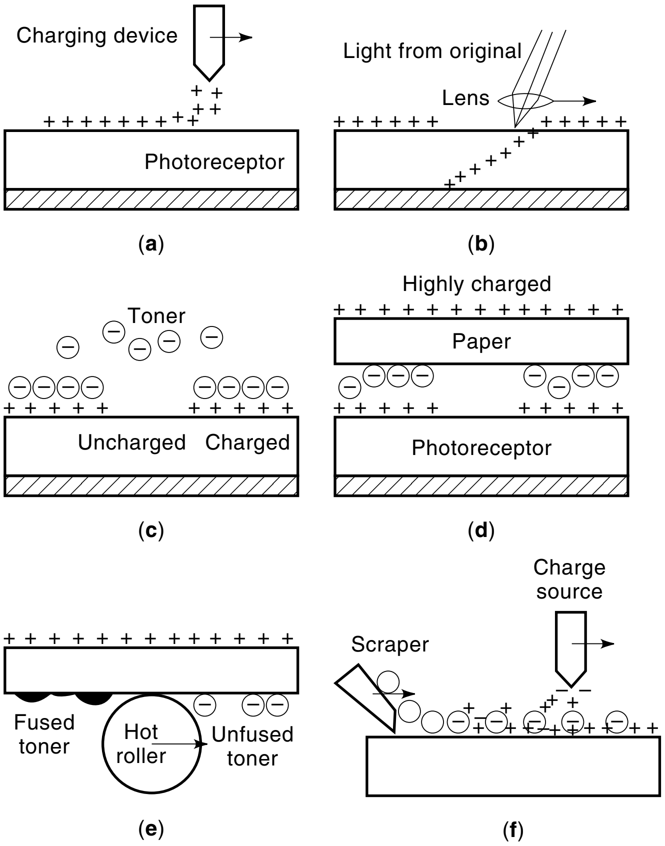


Figure 2. The basic steps of electrophotography, which are a part of every copier or laser printer. (a) Charging; (b) exposure; (c) development; (d) transfer; (e) fixing (or fusing); (f) cleaning.

Next the photoreceptor enters the *development* step, in which many small, charged, colored particles are brought into contact with the charged surface. These particles, called toner, have a charge opposite in sign to the photoreceptor charge, so that they stick to the photoreceptor in the areas that are still charged and form a visible image. The uncharged areas of the photoreceptor, which correspond to the white areas of the original document, do not attract the toner and remain clear.

Now the image is visible, but to become useful it must be transferred to paper. This is accomplished in the transfer step. The photoreceptor and the paper are brought into contact, and a large electric field is applied to pull the charged toner away from the photoreceptor toward the paper. Because of the adhesion between the toner and the photoreceptor, not all of the toner is transferred, and some remains behind on the photoreceptor.

At this point, the image consists of particles of dry powder on a sheet of paper. It can be easily brushed off or smudged. To prevent this, the toner must be firmly attached to the paper by a process called *fusing*. Most commonly, this consists of heating the toner to soften it and applying pressure so that it flows into the paper fibers. After cooling, the image is permanently fixed to the paper.

Finally, *cleaning* the photoreceptor is needed to prepare it for the next cycle. In addition to the untransferred toner, the surface often picks up paper lint and other debris that is removed by scraping or brushing. The charge pattern that formed the image of the document also remains on the photoreceptor and must be removed to prevent ghost images on the next copy.

These six steps make up the electrophotographic process that is carried out in virtually all copiers and laser printers available today. Together, they make up the basic *electrophotographic engine.* In the original electrophotographic copiers, these processes were carried out by hand on a flat sheet of photoconductive material. Today, however, all copiers use a continuous, automatic procedure that occurs in sequence along an endless belt or on a drum, as shown in Fig. 3. This illustration is typical of the layout in most copiers, which have the original input document above the drum at the top of the machine. As the drum rotates clockwise, the image of the document is focused on the charged photoreceptor, causing it to lose charge. Following that, the image is developed and then transferred to paper. On the left side of the drum, the photoreceptor is cleaned, discharged, and recharged in preparation for the next exposure. The fusing step usually occurs elsewhere in the machine because it usually involves special heating arrangements.

All of these steps (except fusing) involve electrostatic forces or charge flow. It is essential to know the nature and locations of all electrical charges at any point in the cycle to understand and design a good electrophotographic machine. There are

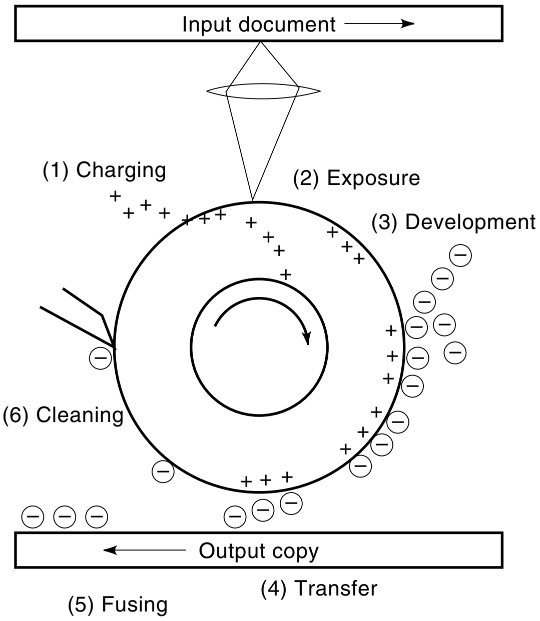


Figure 3. Cross section of an electrophotographic engine showing how the basic steps are carried out in sequence in a typical drum-based copier.

two carriers of charge in the machine, the photoreceptor and the toner. The charge on the photoreceptor comes from an external charging device and is deposited on the surface as shown in Fig. 2(a). In the exposure step, some of the charge remains on the surface, and some is conducted through the photoreceptor to ground. The remaining surface charge persists through the development and transfer steps until it is removed in the cleaning step.

The toner arrives at the development area with a charge opposite in sign to the charge on the photoreceptor. It sticks to the charged areas of the photoreceptor until it reaches the transfer region, where an opposite charge is placed on the back of the paper. This sets up a strong electric field that pulls the toner away from the photoreceptor and onto the paper. The toner (and the paper) often remain charged for some time afterward.

CHARGING

In electrophotography, the force between the charges on the photoreceptor and on the toner drives the writing mechanism. The amount of charge involved has to be maintained at a level that is both high enough to enable writing and uniform enough to prevent uneven images. In general, large amounts of charge are preferable for forming good images, but the charge level is limited in practice by the need to avoid electrical breakdown in the photoreceptor or in the surrounding air. In addition, many photoreceptors show increased electrical conductivity under high electric fields, so the field must be limited to prevent the charge from leaking away before it can be used.

The charge is initially applied to the free surface of the photoreceptor, as shown in Fig. 4. When the photoreceptor is far from other objects, the electric field produced by the charge is directed down toward the ground plane and passes through the bulk of the photoreceptor material. The magnitude of the electrical field in the material is given by

$$E = \frac{\sigma}{\epsilon} \tag{1}$$

where σ is the surface charge density in coulombs per square meter, and ϵ is the permittivity of the material in farads/m. Permittivity is related to the dielectric constant χ by

$$\epsilon = \kappa\epsilon_0 \tag{2}$$

where ϵ_0 is the permittivity of free space. Because the electric field is limited, it is clear that the charge on the photoreceptor is also limited in practice. The values of the electric field depend on the particular material, but a typical charge density is on the order of 1 mC/m^2.

The primary goal of the charging system is to deposit a layer of charge on the top of the photoreceptor and to ensure that the charge is uniformly distributed. Large charge densities can better attract the toner particles and provide a better image. If there are nonuniformities in charge, however, they leave their trace as streaks or mottle in the final image. Most of the charging units in current production involve ions produced by corona discharge from a very fine wire stretched across the process direction. The requirements for charge magnitude dictate the choice of corona devices. The particular type of device is often selected based on the uniformity of the charge under the given conditions.

The charging system must bring the surface of the photoreceptor to this charged state in the brief time it spends in the charger. Naturally, this becomes more difficult in high speed printers, where the photoreceptor moves rapidly. The total current demanded from the charge is related to the speed, U, and width, w, of the process, as given by

$$i = \sigma U w \tag{3}$$

For a typical copier producing 60 pages/min, the process speed is around 20 m/min or 0.33 m/s. A width of approximately 0.5 m requires a current output of 10 mA from the charge source for a typical charge density (1 mC/m^2).

The charge raises the voltage of the photoreceptor's surface to a value that depends on the h thickness of the insulating

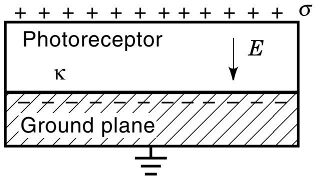


Figure 4. A charged photoreceptor is subjected to an electric field as a result of the charge on its surface.

layer. This voltage,

$$v = Eh = \frac{\sigma h}{\kappa \epsilon_0} \tag{4}$$

plays an important role in the charging process because it repels additional charges coming in and thus limits the speed of charging. For the example, the voltage at the top of the selenium photoreceptor is

$$v = \frac{(0.001)(50 \times 10^{-6})}{(6.3)(8.854 \times 10^{-12})} = 896\,\mathrm{V} \tag{5}$$

indicating that the charge source must work against this much adverse voltage while maintaining its output. The need for relatively high charging currents, coupled with the ability to operate in spite of adverse potentials on the order of hundreds of volts, generally leads to the selection of a gas discharge device, usually based on corona discharges.

Corotron

The earliest charging device (which is still in use) is the corotron. The key component is a very thin wire stretched across the process path, as shown in Fig. 5. The wire is connected to a high-voltage power supply on the order of several thousand volts. This produces an electrical field high enough to ionize the air in the vicinity of the wire. Because the wire is very thin, the field falls off rapidly with distance, so that ionization is confined to the immediate vicinity of the wire without developing a spark or an arc. This type of electrical discharge is called a corona.

The most important aspect of corona discharge is the permanent region of ionization (called the corona) around the wire, which contains numerous positive and negative ions. Although the creation of ions is limited to the vicinity of the wire, the ions themselves are free to travel throughout the surrounding air under the influence of the weaker fields far from the wire. If the wire is positive, as in the figure, then the negative ions are attracted toward the wire, whereas the positive ions are forced away toward the photoreceptor, the shield, and any other objects in the vicinity.

The shield around the corotron wire is a metal tube connected to ground. It serves to define the electrical fields in the region of the wire so that the discharge is not affected by other objects. At the bottom of the shield is a slit that runs across the entire width of the photoreceptor and allows ions to escape. These ions are deposited on the photoreceptor, giving it the desired initial charge.

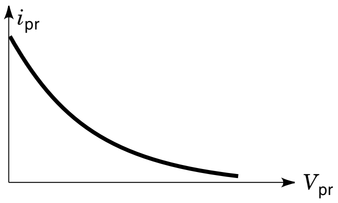


Figure 6. The output current from a corotron decreases as the charge is deposited on the photoreceptor.

The fraction of these ions that goes to the photoreceptor constitutes the output current of the corotron. As the ions deposit on the photoreceptor, they raise its potential, so that later ions are partially repelled from the photoreceptor and toward the shield. As a result, the output current decreases slowly as the photoreceptor charges, as shown in Fig. 6. The wire voltage is much higher than typical photoreceptor voltages (several hundred volts), so that some positive ions continue to flow to the photoreceptor as long as it is in the charging station. This can lead to nonuniform charge distribution along the process path if the motion of the drum is not steady. Speed variations show up in the final output copy as bands of lighter or darker images.

In addition to nonuniform charge output, the corotron has a further disadvantage when negative charging is required. Negative corona does not take the smooth, sheathlike appearance of a positive corona along the wire. Instead, it occurs as a series of emitting regions (“tufts”) scattered along the wire, separated by dark, nonemitting regions. As the photoreceptor passes under a wire in a negative corona, it acquires a charge that varies across the process direction, and higher values are under the tufts. This leads to dark or light streaks in the final image. For this reason, the corotron is normally used only for positive charging.

Scorotron

When negative charging is desired or if speed variations are expected, a modified form of the corotron is normally used. The important change is the addition of a grid or screen between the wire and the photoreceptor, as shown in Fig. 7. (Scorotron is a contraction for “screened corotron.”) The

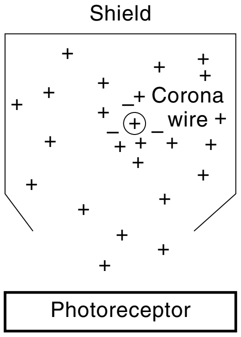


Figure 5. A corotron produces a stream of charge by using electric fields to select ions of one sign from a corona discharge.

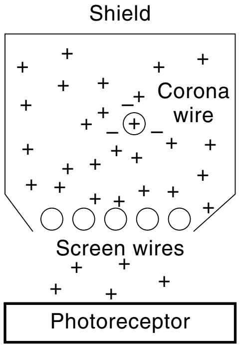


Figure 7. A scorotron establishes a fixed potential above the photoreceptor by using a screen at the output of a corotron. This sets an upper limit to the potential reached by the photoreceptor.

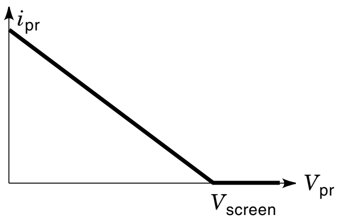


Figure 8. A scorotron exhibits an output current which drops to zero when the photoreceptor reaches the screen voltage.

screen separates the wire from the voltage buildup on the photoreceptor, as it charges. As an example, assume that the screen is held at 500 V by a power supply whereas the corona wire is held at 5000 V. The wire sees an environment in which the voltage of the nearby electrodes (the shield and the screen) remains constant. At the same time, positive ions from the wire penetrate the screen, and if the substrate below is at an even lower voltage (e.g., 100 V) they continue on to charge the surface. Clearly, the surface charging ceases when the photoreceptor voltage rises to the value of the screen voltage because the electric field that drives the ions from the screen to the photoreceptor vanishes at that point.

The output characteristic of an ideal scorotron (Fig. 8) shows this effect clearly. As long as the process speed is slow enough to allow the photoreceptor to charge to the screen voltage, the charge is very insensitive to variations in speed. With a negative corona, the screen has the added advantage of smoothing out the lengthwise variation of current along the wire, leading to a smoother and more uniform charge distribution on the photoreceptor.

EXPOSURE

Once the photoreceptor is fully charged, it is selectively exposed to light that varies in intensity according to the image. The optical path for light in a typical copier is shown in Fig. 9. The input document on the platen is illuminated by the light source, and its reflected light travels via mirrors through a lens that focuses the image on the surface of the photoreceptor. Light changes the photoreceptor from an insulator to a conductor and allows the charge at the exposed surface to bleed off. In the dark areas, of course, the photoreceptor remains insulating and holds the original charge. Thus there are two components of the exposure system, the light source and the photoconductor.

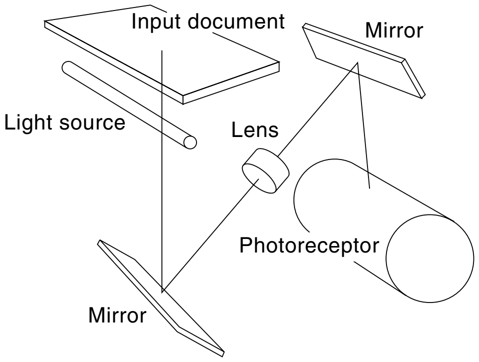


Figure 9. The light lens system in a typical copier focuses the image of the input document on the photoreceptor via lenses and mirrors.

Photoconductors

The photoconductor must be a good insulator in the dark to hold the original charge, and also a good conductor in the light to remove the charge before it reaches the development section. Because there are many insulators capable of holding a charge for several seconds, the choice of photoreceptor is usually based on its ability to remove charge after illumination.

The charge current that flows in solids is most often expressed as the product

$$J = nqu \tag{6}$$

where J is the current density (A/m^2), n is the number of carriers per unit volume, q is the charge of the carrier, and u is the carrier velocity. In many cases, the carrier velocity is proportional to the local electric field strength:

$$u = \mu E \tag{7}$$

where μ is the mobility of the carrier. A good conductor must have either a high mobility or a large number of available carriers.

To be useful in electrophotography, the photoconductor should have high mobilities but very few carriers in the dark. If any carriers are generated (either thermally or photoelectrically), they move across the photoreceptor quickly as a result of their high mobility and discharge the photoreceptor before it can be exposed to light.

There are a number of other requirements that may be placed on photoreceptors. If the machine is a copier with a light lens to create the optical image, then the photoreceptor should respond over the full visible range. This requirement is not so stringent for copying black and white documents, but essential if the original contains colored images, such as signatures in blue ink or advertising brochures. The lamp that supplies the illumination has its own spectrum that must be considered together with the photoreceptor. Often the lamp and photoreceptor can be chosen so that a low lamp output in one part of the spectrum is balanced by high photoreceptor sensitivity there. Matching the two in this fashion can give very good panchromatic response.

In fabricating the photoreceptor, the thickness of the layer must be carefully chosen. If the layer is too thick, the carriers may recombine before reaching the opposite side, and the charge is not fully neutralized. This leads to weaker electric fields in the development step that follows and thus to a poor final image. A thick photoconductor also allows fringing fields to attract carriers from other regions of the surface and thus to smear out the image. A thin photoreceptor is a particular advantage in high speed machines because the charge transport across the photoreceptor occurs faster if the distance is shorter.

On the other hand, a very thin photoreceptor leads to relatively weak fields in the air above the surface, and this makes it harder to attract and hold toner particles to the charged image. In practice, the photoreceptor is typically on the order of 10 μm to 50 μm thick.

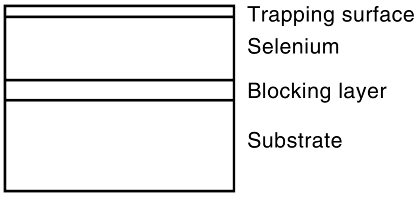


Figure 10. A bulk photoreceptor has a uniform interior, but the upper surface and lower blocking layer have different electrical characteristics which control the response to light.

Bulk Photoconductors. Once the electrical requirements for the photoreceptor have been satisfied, the physical properties of the photoreceptor must be optimized. For a bulk photoconductor, like selenium, the typical arrangement of the layer is shown in Fig. 10. This arrangement is useful if the photoconductor both generates carriers and allows them to move easily. In practice, amorphous selenium is the material most commonly used in bulk photoreceptors. It is a very good insulator in the dark and produces both positive and negative carriers (called holes and electrons) when illuminated. Both carriers have relatively high mobilities Holes are about twice as fast as electrons. Both carriers are subject to recombination as they move. A typical range is on the order of 10 μm. This implies that a photoreceptor much thicker than 10 μm cannot completely neutralize the charge, leaving a 'residual voltage' on the photoreceptor. In typical machines, the initial voltage is on the order of 500 V, and the residual voltage is below 100 V.

Residual voltage can be a problem in producing images because it means that even the discharged areas have some charge with the right polarity to attract toner. This leads to faint development in the areas of the paper that should be white. This defect, called background development, is usually corrected by applying an additional electric field that is of polarity opposite to the development field. If its magnitude is properly chosen, then the net electric field points in opposite directions above the charged and uncharged regions and repels the toner from the background areas.

In selenium, most of the incident light is absorbed in the topmost 0.1 μm of the layer, so that all of the charge generation occurs at the top surface. Like most surfaces, it is structurally different from the interior, and the carriers often find themselves in solid-state 'traps' that prevent them from leaving without the assistance of an electric field. In the ideal case, the carriers that have the same sign as the applied charge migrate down to the grounded substrate, and the charge that was deposited on the top is neutralized by photogenerated carriers generated inside the bulk selenium. If the applied charge and hence the internal field are too large, however, the surface is discharged even in the absence of light. Typically this begins to happen when the surface charge levels exceed approximately 1 mC/m^2. This phenomenon limits the amount of charge that can be applied in practice.

Usually, the photoconductor is not in direct contact with the conducting ground plane but is separated from it by a thin insulating layer, called the blocking layer. If this layer were not present, the high electric fields set up by the charge on the free surface of the photoconductor might cause injection of carriers directly from the ground plane into the photoconductor. Once inside, they take advantage of the high mobility in selenium to travel across the photoconductor and neutralize the charge on the upper surface. This effect can remove the charge before the imaging step and prevent the formation of a latent electrostatic image.

Layered Photoconductors. In many applications, it is less expensive and more convenient to work with plastics, which are usually more flexible and allow the use of belts instead of drums. Because most of the suitable plastics do not combine good carrier generation with good transport, an alternate structure was developed. Organic photoconductors are softer than selenium, so they were used originally in the lower speed machines where durability was not as important.

Organic polymers do not usually combine the attributes of good photogeneration and high mobility, although there are many plastics that possess one of these properties. If the photoconductor is composed of two layers of different materials, the advantages of each are combined. The structure of a typical layered photoreceptor belt is shown in Fig. 11. The entire structure is fabricated on a thick sheet of polyethylene terephthalate (Mylar) that supports the electrically active layers and gives the belt strength. The top of the Mylar is coated with a thin aluminum layer that is a ground plane. Directly above this layer is an organic material that is sensitive to light and generates charge carriers in response to exposure. It is very thin because the material rarely allows good transport, and only charges generated near its surface escape.

Above this is the transport layer, which is transparent (and thus not able to generate carriers by absorbing light). If carriers are introduced from outside, however, they can move very quickly because of the high mobility inside the layer. In the presence of a charge layer at the upper surface, the carriers enter this layer from the charge-generating layer below, move quickly across, and neutralize the charge. In most commercial transport materials, the positive carriers (holes) have the highest mobility, so the upper surface must be charged negatively.

Light Sources

Generally speaking, the type of light source selected for exposure depends on the use of the electrophotographic engine. In the original application (the copier), the goal is to reproduce an image that already exists as a hard copy on paper. In this circumstance, lenses focus an optical image of the original onto the photoreceptor. The lighter areas of the original reflect more light onto the photoreceptor and cause it to discharge rapidly. The image need not be presented in its entirety, and in drum based machines the lamp and lens usually move along the original document, focusing a different part of

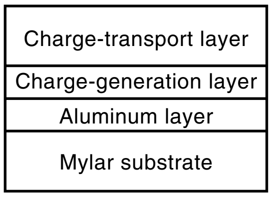


Figure 11. In a layered photoreceptor the region of charge generation is separated from the region of charge transport to allow a wider choice of materials.

the original at different locations on the drum. If the copier is based on a belt, rather than a drum, it is possible to illuminate the entire original document with a single brief flash of light. In either case, the light source is a lamp, and the image is optically focused on the photoreceptor.

DEVELOPMENT

In the development step, charged toner is attracted to the oppositely charged areas of the photoreceptor where it sticks to form the image. The two important components of the process are the composition of the toner itself and the nature of the forces that attract and hold it to the photoreceptor.

Toner

The toner used in electrophotography consists of small particles of black or colored material. Although there is often a distribution of particle size in a given toner, there are certain restrictions for good performance. The largest size should be less than the smallest image component. For example, in a 600 dot per inch (dpi) laser printer the particles should be much smaller than the individual dot size (approximately 42 μm), or the optical noise generated by the toner particles degrades the spatial resolution of the image. At the other extreme, the particle should not be so small that it is easily entrained in the surrounding air because then it settles over any available surface (including the white areas of the output image).

Another consideration in toner size is the height of the resulting toner layer. In the electrophotographic process, this layer is formed from a pile of loose toner particles that are later fused into a solid image. When the pile of toner particles is high, it is liable to be smeared before the fusing step, leading to poor image quality. It can also lead to curling of the paper by blocking the flow of moisture at the surface of the sheet during and after the fusing step. Excessive pile height is especially vexing for color images, which are typically formed from four superposed layers of toner. To preserve image quality, it is common to require that individual toner particles are no larger than 5μm to 10 μm in diameter.

Toner is usually charged triboelectrically by rubbing or tumbling it against a second material. Although the quantum mechanical details of this process are still not clear, the basic idea is that different molecules have different chemical affinities for electrons, based on whether their outer orbitals are filled. Chlorine, for example, has a single vacancy in its outer shell and abstracts electrons from other molecules that it contacts. Thus PVC, which contains chlorine, charges negatively, whereas other materials lose electrons and charge positively when they come in contact with it.

Practical triboelectric charging is a stochastic process. The charge always has a distribution and may even have the opposite sign on some particles. These particles, called “wrong-sign toner,” should be minimized because they deposit on areas that should be kept clear in the image. This leads to an overall graying of the white (“background”) parts of the image.

Most toners are composed primarily of a polymer, such as polystyrene, mixed with a pigment to give it color. Black toner normally uses carbon black, whereas colored toners use a variety of commercially available colorants. Smaller amounts of other additives are usually added to control the charging behavior, flow properties, and so forth. Some toners that rely on magnetic forces to assist in development also contain magnetic materials.

Development Forces

In the development step, the charged toner is transferred from a donor surface to a receptor surface under the influence of electrical and other forces. This process is shown schematically in Fig. 12, where a toner particle is moving from the donor above to the receptor below. The donor can take many forms, such as a larger bead, a drum, or a fluid suspension, but the basic condition for development remains the same. The net force pulling the particle toward the receptor must exceed the sum of the forces that hold it to the donor. This basic condition can be written as

$$F_e > F_i + F_a \tag{8}$$

The term F_e, the electrostatic development force depends on the net charge q, on the toner, and on the external field E that drives the development and is expressed as

$$F_e = qE \tag{9}$$

The remaining terms represent the forces holding the toner to the donor surface. These are the electrostatic image force F_i and the adhesion force F_a. The adhesive (or van der Waals) force appears between any two materials when they are in contact. It is generally considered to be the result of interactions between the electron orbitals of individual molecules and is independent of the net charge on the object.

The image force arises from the attraction between the toner charge and its image induced in the donor material. It is often written in the approximate form

$$F_i = k\frac{q^2}{16\pi\epsilon r^2} \tag{10}$$

which is based on an ideal model in which the dielectric constant is the same for all materials and the charge is concentrated at the center of a spherical particle of radius r. The factor k is included to account for departures from the ideal model. More complicated expressions are available for the image force, but the key result is that the force is proportional to the square of the charge.

The effect of toner charge on the development process is best appreciated by comparing the force of development with

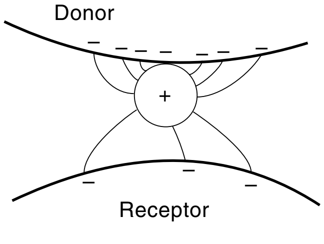


Figure 12. A toner particle between donor and receptor surfaces experiences forces pulling it in both directions.

the forces of attachment to the donor, as shown in Fig. 13. The development, or coulombic, force is linear with toner charge and increases from the origin. The attachment force is the sum of a constant adhesive force and a quadratic image force. So it begins at a finite value and increases rapidly with charge. It is clear from the figure that the detachment force exceeds the attachment force over a finite range of toner charge. Very lightly charged toner is not developed because the adhesive force is not overcome. Very highly charged toner is not developed because the image force is not overcome. Only toner with charge in an intermediate range is removed by the external development field. The rest of the toner remains attached to the donor.

In addition to its effect on the ability to move the toner across the development nip, the charge has a strong effect on the appearance of the developed image. Each charged toner particle neutralizes a definite amount of opposite charge on the photoreceptor and provides an amount of pigment that depends on its mass. If the particles are small and highly charged, then only a few are needed to neutralize the photoreceptor change, and the developed image is faint because it includes few particles. On the other hand, if the particles are large and lightly charged, many are needed to neutralize the photoreceptor charge, and the images of thin lines become wide and smudged in appearance. The key parameter here is the charge-to-mass ratio (q/m) of the toner. Once the charge is determined by the development force criterion, then the q/m ratio is selected so as to neutralize the photoreceptor charge with the volume of toner material that gives a good image. Typically it is on the order of 10 μC/g.

Once released from the donor, the toner is subject only to the coulombic force in the external field, so its deposition on the photoreceptor is controlled primarily by the electrostatic field in the vicinity of the image. The situation is not as simple as the attraction between two isolated charges, however, because the toner particle is influenced by the fields of all of the charges on the toner. A sketch of the field lines near the boundary between a charged and uncharged region of the photoreceptor (Fig. 14) illustrates this difference. Well inside the charged region, all of the field lines are directed down toward the ground plane, and the electric field above the photoreceptor is very weak. A charged toner particle above this part of the image experiences little or no force from the charges on the photoreceptor and thus does not complete the development step.

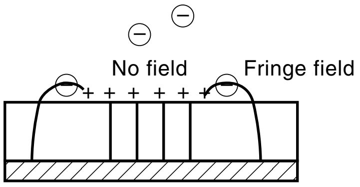


Figure 14. Fields near a charge image of finite width show fringing at the sides, which allows the fields to attract toner particles above the photoreceptor.

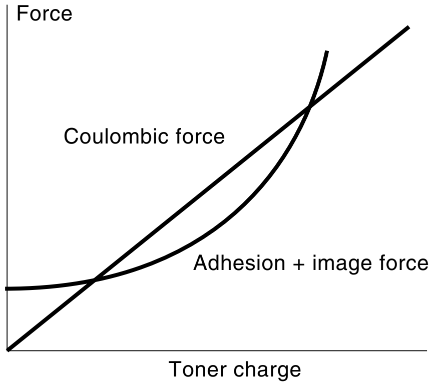


Figure 13. The attachment (adhesion and image) forces dominate over the development force for very large and very small toner charges. Transfer of toner is only possible over a limited range.

The situation is much different at the edge between the charged and uncharged regions. Here the field lines fringe out away from the photoreceptor before returning to reach the ground plane. If a charged toner particle finds itself in this region, it is attracted toward the photoreceptor, as indicated in the figure. The developed image that results is dense and dark along all the edges, but very light in the interior of the solid edges.

Edge development is a drawback in many imaging applications, but it has often been used to great advantage in electrophotography. The original market for copiers consisted primarily in the reproduction of textual documents, such as patents, correspondence, invoices, and related business communications. Text and line drawings consist mostly of edges, and edge development enhances the sharpness of edges. So documents copied in this mode often appear sharper and more legible than the originals. There are also important niche markets, such as mammography, where electrophotographic edge development produces a much more detailed image of soft tissue than is possible with traditional X-ray development.

Although edge development is preferable for certain documents, it is not suitable for general purpose printing and copying, and several methods have been devised to provide uniform development across solid areas of the image. All of these employ a second ground surface to direct some of the field lines into the air space above the photoreceptor. The simplest of these schemes, called a development electrode, is illustrated in Fig. 15. Only the interior of a uniform charged area is shown, where the photoreceptor ground plane is a distance b below the surface charge and the grounded development

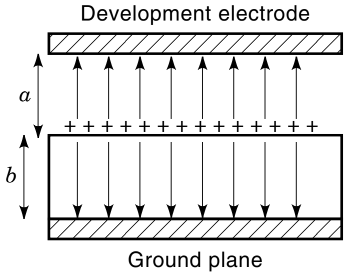
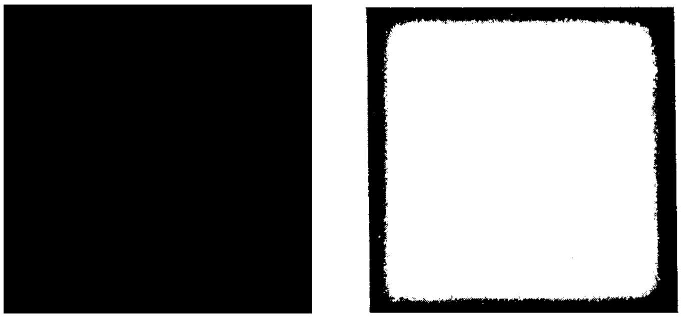


Figure 15. Fields near a development electrode are strong, giving good toner development over a wide area.



(a) (b)

Figure 16. Solid area development (a) with and (b) without a development electrode shows the effect of the development fields. (Courtesy L. B. Schein and Springer Verlag.)

electrode is a distance a above it. The electric field from the charge layer is divided between the upper and lower regions depending on their thickness and dielectric constant. The field in the region above the charge, given by

$$E_a = \frac{\sigma}{\epsilon_a}\left(\frac{\frac{a/\kappa_a}{b}}{b/(\kappa_b + a/\kappa_a)}\right) \tag{11}$$

depends on separation of the development electrode from the surface and also on the dielectric constants of the materials involved.

The ratio of thickness to dielectric constant (i.e., a/χ_a) that occurs frequently in electrophotography is given the name *dielectric thickness.* From the equation, it is clear that if the dielectric thickness of the upper layer is large, the field there is very weak, and development is slow. On the other hand, when the development electrode is close to the photoreceptor surface, the field is strong, and a solid image appears as toner is attracted there.

The effect of a development electrode can be seen in the comparison of the images of a solid area (Fig. 16) developed with and without a development electrode. The image using the development electrode [Fig. 16(a)] is uniform and dark across the entire area, whereas the other image [Fig. 16(b)] is dark only in the vicinity of the edges and almost disappears in the interior region.

Dual-Component Developer Systems

Toner is essentially a fine dust that can be very difficult to distribute uniformly across the photoreceptor during development. The process becomes much more controllable if the toner is transported on the surface of larger particles, called carrier beads. This combination, called dual-component toner, was used in the first commercial copier and is still used today in most large machines. The toner particles and carrier beads are mixed together in a hopper that charges them triboelectrically to opposite polarities. Then, being charged, they stick together, so that the toner coats the surface of the much larger carrier bead, as shown in the photomicrograph of Fig. 17.

The carrier bead on the order of 75 μm to 200 μm in diameter is usually composed of a relatively heavy material, such as carbon steel or ferrite. Magnetic properties are important because many development systems use magnetic forces to control the flow of carrier beads, especially in the vicinity of the development nip. The surface of the bead is usually coated with a different material (e.g., Teflon) that controls the triboelectric charging against the toner.

The toner/carrier combination is delivered to the photoreceptor in a number of ways. One of the oldest methods, called cascade development, uses a hopper/belt combination to lift the beads above the photoreceptor and then drop them so that they cascade over the photoreceptor in the vicinity of the image, as shown in Fig. 18. When this combination comes close to the photoreceptor, the charge on the photoreceptor competes with the charge on the carrier bead to capture the toner particles. The toner remains with the photoreceptor, and the carrier returns to the hopper to acquire more toner.

The collision of the carrier bead with the photoreceptor also provides inertial forces that help detach the toner particle. This is especially important when van der Waal's adhesive forces are strong. Cascade development was used in the earliest electrophotographic copiers but is less important today because it is difficult to bring a development electrode close enough to improve image quality without restricting the flow of toner.

A more common arrangement, called magnetic brush development, combines the detachment advantages of cascade development with the solid area performance of a development electrode. In this approach, the carrier beads, made of a magnetically soft material, are delivered to the development region by a rotating sleeve that encloses a magnet, as shown in Fig. 19.

Under the influence of the magnetic field, carrier beads chain together to form a relatively conducting chain extending out from the surface of the cylinder. The tips of the carrier chains (or bristles) just contact the surface of the photoreceptor as they pass, giving up some of the toner from the

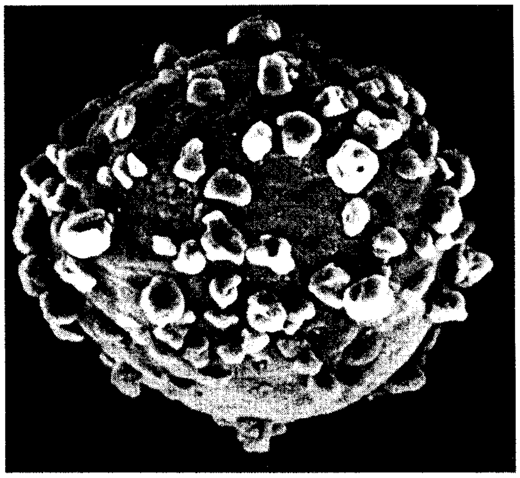


Figure 17. Toner particles are generally irregular in shape, and much smaller than the carrier bead. (Courtesy Xerox Corporation.)

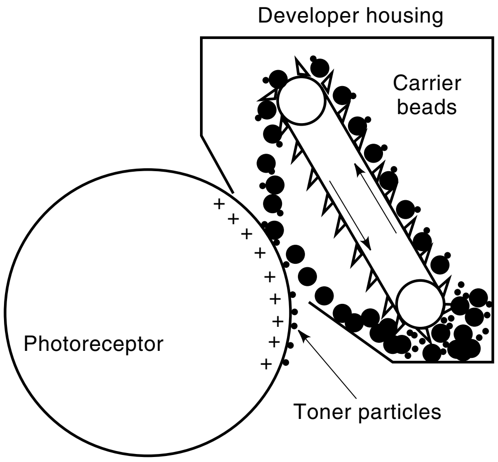


Figure 18. In cascade development the toner/carrier combination is conveyed to above the receptor and falls onto it. When it strikes the receptor, toner is dislodged and then attracted to the charged areas of the receptor.

outermost carrier bead to the charges on the surface of the photoreceptor. Because the magnetic bristle has low electrical resistance and extends all the way to the photoreceptor surface, it serves as a development electrode by attracting field lines from the latent charge image on the photoreceptor.

Monocomponent Developer Systems

Dual-component toner has some characteristics that make it inconvenient for small copiers and printers. The total mass of the carrier is much greater than the toner mass, so much more space is required to store the toner/carrier combination in the machine. If the toner is replenished while the carrier is reused, the operator must become involved in a messy procedure in which toner dust becomes airborne. This can be avoided by using the so-called "monocomponent" toner, which contains only pigmented toner particles. This is a compact toner system that is used in the majority of the copiers and laser printers, especially those with replaceable cartridges.

The need to have the development electrode spaced by a distance on the order of the dielectric thickness of the photoreceptor poses some practical problems because the dielectric thickness of the layer of selenium is not much larger than the diameter of a toner particle. One way of getting toner particles into this narrow gap above the photoreceptor is to carry them in as a single monolayer on a rotating sleeve that serves as the development electrode and the donor. This approach is used in many of the smaller, cartridge-based copiers and printers.

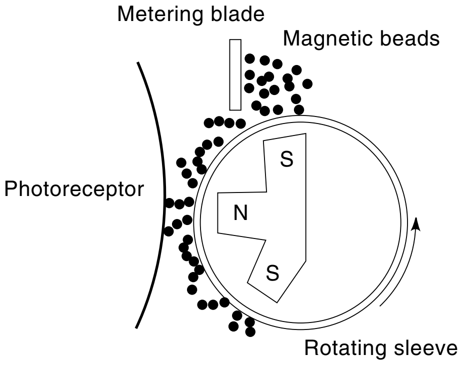


Figure 19. In magnetic brush development the carriers are transported by a magnetic field. The carriers also act as an electrical ground surface so that when toner is dislodged it is strongly propelled toward the charge on the photoreceptor.

An alternate method for overcoming the adhesion of the toner to the carrier is to apply a large alternating electrical field in the development region. This field is strong enough to detach the toner from either the donor surface or the photoreceptor, so that the toner bounces back and forth inside the development region. As it leaves, the alternating field weakens, and finally the steady development field causes it to remain on the photoreceptor surface (if the photoreceptor is charged) or on the toner roll (if the photoreceptor is uncharged).

TRANSFER

There have been a number of attempts to use special papers that include a photoconductive material and thus allow direct exposure and development of the image on a single substrate. These have always given such poor quality that they have been largely discarded. Virtually all electrophotographic copiers and laser printers develop the image on a photoreceptor drum or belt and then transfer the developed image onto paper. This allows optimizing the development system for good image quality, while providing an output document with the look and feel of ordinary paper.

Pulling a charged powder from intimate contact with a smooth charged surface and moving it onto the porous and irregular surface of paper is not an easy task. The physical force balance here is similar to that in development, but collision forces are not available to overcome the adhesive forces holding the particles to the photoreceptor. This requires physical contact between the toner and paper so that the adhesion forces from both sides are balanced. In addition, the electrostatic forces must also be overcome, usually by depositing large amounts of charge on the backside of the paper, as shown in Fig. 20. This charge has the same polarity as the charge on the photoreceptor but is much larger so that it can exert a net electrostatic force on the toner to pull it from the photoreceptor surface onto the paper. The charge is usually provided by a corotron similar to those used in the charging step described earlier.

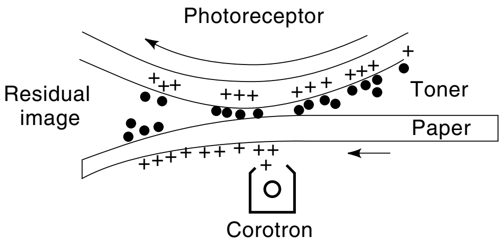


Figure 20. In a typical transfer step most of the charged toner is forced from the photoreceptor to the paper by a strong electric field.

The large charge on the paper is also beneficial because it presses the paper down toward the ground plane and thus helps to ensure good physical contact with the toner particles. This is especially helpful in duplex copying, where both sides of the sheet must be printed. Often the heating associated with the fusing step of the first side wrinkles or cockles the paper, so that it presents a very uneven surface for transfer of the second-side image. The high electric field from the charge on the back side of the paper helps to press the paper down and reduce the distance that the toner must traverse in the transfer nip.

In an ideal transfer nip, all of the toner moves to the paper, and none remains on the photoreceptor. In practice, some of the toner remains behind. Some transfer inefficiency can be tolerated because the residual toner is removed from the photoreceptor in the cleaning step, but very inefficient transfer leads to faint and/or nonuniform images and must be avoided. Although some inefficiency relates to paper roughness and the statistical nature of adhesive forces, the electrostatic forces on the toner play the most important role in determining transfer efficiency. The toner layer is itself charged, and it is placed between the photoreceptor and paper, which are also charged. The self charge of the layer, acting alone, splits the layer into two roughly equal thicknesses. Half transfers to the paper and half remains on the photoreceptor. The external field from the paper and receptor must be strong enough to overcome the self field of the toner layer to achieve good transfer.

FIXING TO PAPER

After transfer, the image is a dry powder held to the paper by electrostatic and adhesive forces alone. Neither of these is strong enough to provide the permanence associated with ink on paper, and the image is easily brushed off. To make a permanent document, the toner must be firmly attached to the paper fibers. This is usually accomplished in the fixing or fusing step. Typically the paper carrying the image is heated, softening the toner (which is a thermoplastic polymer). The individual toner particles coalesce and wet the paper fibers. When it cools, the toner rehardens into a continuous polymeric structure that is interlocked with the paper fibers and forms a permanent image.

A typical toner must be raised to about 180°C to flow. There are two ways to supply the heat needed for this step. The most common method is the hot roll fuser in which the paper is fed between two rollers before leaving the machine. At least one of the rollers (usually the one closest to the toner) is internally heated, and the pressure generated in the nip pushes the softened toner into the fabric of the paper. This approach is quite satisfactory at low speeds, but the reduced time in high-speed machines makes it difficult to heat the toner sufficiently in the nip without making the rollers so hot that they are damaged.

An alternate approach often used in high-speed machines is a lamp (usually a flash lamp) with a large heat output. These lamps heat a larger area of the paper than a roller nip, so that there is more time to reach the desired temperature. In addition, white paper reflects the heat, whereas most of it is absorbed by the black toner. This keeps the paper from dehydrating, which leads to the problems described below.

The power to run the heating elements of the fuser is often the largest component of the power required to operate a copier or printer. With the current demand for energy-efficient office machines, most copiers and printers include provision for heating only when it is required. This introduces an engineering trade-off between the convenience of making a single copy in a short time versus the energy cost of maintaining a heated roll indefinitely at a high temperature.

The high temperatures used in fusing have another serious side effect. Much of the moisture is driven out of the paper, which emerges from the fusing step as a dry and relatively insulative sheet. This dry paper often becomes charged triboelectrically and can stick to nearby objects or other sheets of paper with enough force to prevent its transport. In many of the more sophisticated copiers or printers, the sheet must be transported back into the machine to be printed on the other side, and then collected to be collated and stapled. It is not uncommon to find paper jams resulting from the electrostatic forces acting on dried paper. To avoid this problem, a variety of control measures ranging from conductive fibers ("tinsel") to corona-powered air ionizers are used to remove the charge from the paper. The high temperatures, coupled with the change in moisture content, can also lead to curling and cockling of the paper, another frequent source of jams.

CLEANING

Virtually all electrophotographic machines use the same photoreceptor drum or belt for thousands of cycles of printing. Before each cycle begins, however, all traces of the preceding operations must be removed so that they do not mingle with the next image. These remnants take many forms. The most obvious is the toner that remains after the transfer step. Because transfer is always less than 100% efficient, a shadow of the developed image remains on the photoreceptor. If the output document is smaller than the input image, all of the toner remains on the areas of the photoreceptor that do not actually come in contact with the paper in the transfer step. Thus large amounts of toner can be expected at any time. If left on the photoreceptor, they may block charge in the charging step, block light in the exposure step, and eventually be transferred to the paper.

Less obvious, but still important, is the charge on the photoreceptor that remains in the insulating regions that have not been exposed to light. If the photoreceptor enters the charging stage already partially charged, it charges to a level higher than its surrounding area and may leave some residual charge after the exposure step. Other contaminants, such as paper fibers, are also commonly found on the photoreceptor after transfer. All of these contaminants affect the succeeding image, and some, like untransferred toner, become permanently stuck to the photoreceptor, producing an image defect on every page printed in the future. It is the job of the cleaning station to remove all of these artifacts.

Cleaning the photoreceptor naturally divides into neutralization of charge and removal of particles. One simple way to remove the charge from a photoreceptor is to flood the entire

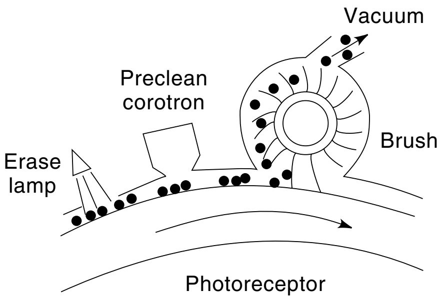


Figure 21. The cleaning step usually involves a light source to discharge the photoconductor by making it strongly conductive, a corotron to neutralize the remaining toner, and a brush or scraper to remove the toner.

surface with light, as shown in Fig. 21. The photoconductive material becomes conductive, and all of the charge is free to flow to the ground plane, leaving the free surface uncharged. Normally this does not remove the charge from the adhering toner particles, because they are insulating and do not make good electrical contact with the photoreceptor. To neutralize this charge, an ion flow is sometimes supplied by a corona device. Neutralizing the particles has the additional advantage of reducing the force holding them to the photoreceptor.

The particles are normally removed by a mechanical device, such as a blade or brush. Because the particles range down to 1 μm in diameter, the removal process must be carefully designed to operate satisfactorily over the lifetime of the electrophotographic engine. At low speeds, a doctor blade (oriented so as to scrape off the toner like a razor) is most commonly used. Because the clearance must be kept below 1 μm over the entire width of the photoreceptor, the blade is usually made of a soft, conforming elastomer for cleaning a hard photoreceptor like a selenium drum.

A blade typically fails when a small particle lodges under it at one point. This leads to 'tenting,' or raising of the blade so that nearby particles pass through. This defect manifests itself through streaks in the process direction. If the particle remains in place for many cycles, it softens from the frictional heat and adheres permanently to the photoreceptor resulting in a spot that is repeated on each subsequent copy.

If the cleaning device must last a long time, a rotating brush is usually chosen. Because the bristles strike different areas of the photoreceptor and stay in contact for only a brief time, the brush cleaner does not suffer from particles lodging at a particular point on the photoreceptor and is less likely to produce a streak in the image. The brushing action, however, makes the toner particles airborne after they are removed from the photoreceptor, and means must be provided to recapture them before they leak out of the machine or contaminate the other processing steps. Typically this is done by a vacuum system with filters. Because of the extra equipment and gentler action, brushes are normally used in high speed machines, which are normally larger and more expensive.

LASER PRINTERS

The other major application of the electrophotographic engine is the laser printer. Here there is no original document, and the image to be printed exists only as a collection of bits in a computer. In its most common form, the bit stream controls the light in a laser beam that sweeps across the photoreceptor drum. The beam is usually switched at a rate that allows it to address positions about 42 μm apart (600 dpi) and thus form a bit-mapped charge pattern. An alternate form of electrophotographic printer is based on an array of LEDs that cover the entire width of the photoreceptor and are individually switched to illuminate individual pixels.

Laser printers, like most computer-driven printers, use a dot matrix to form the image to be printed. This is necessary because the information is stored in the computer in a form that is meaningless to a human viewer. In a textual document, for example, the letter "A" is represented by the ASCII code number "01000001." A more complex document with tables, figures, photographs, and so on, requires an internal representation that is even less transparent to a human. Typical examples of these more complicated representations are PostScript and HPGL. Normally, laser printers are associated with an intermediate module that interprets the computer representation of the document and converts it to a dot matrix that controls the laser beam.

After the desired image becomes a two-dimensional dot matrix, it is still in electronic form and thus invisible to a human. The procedure for converting it to visible form is similar in many aspects to that used in television. The laser beam sweeps across the width of the photoreceptor to form a single horizontal line and then returns very quickly to the starting point. In the meantime, the paper has been slowly advancing, so that the laser beam starts its next sweep at the next line down. This procedure is called a raster scan.

In a laser printer, the raster is normally described by an array of one-bit numbers, indicating that the laser beam is either on or off at that point. This is adequate for textual and line illustrations but of course cannot represent gray levels or colors. It is characteristic of electrophotography that it is very difficult to produce a well-controlled gray spot, and all commercial laser printers are only capable of this one-bit operation. It is still possible to obtain images with gray levels, however, by trading resolution for gray scale. Rather than using a single bilevel pixel as the basis for the image, a larger superpixel containing many individual pixels is used. A simple example of a 4 × 4 superpixel is shown in Fig. 22.

If the superpixel is small enough, the individual pixels are not resolved by the eye, which therefore averages the brightness of all 16 pixels. If they are all white or all black, the image appears to be simply white or black. If half are black, then the image appears as a neutral gray. Thus 17 levels of gray are available, but the linear resolution of the image has been reduced by a factor of 4.

Once the desired image has been rasterized, it must still control the laser beam so that the light falls on the areas of the photoreceptor that are to be discharged. Because the

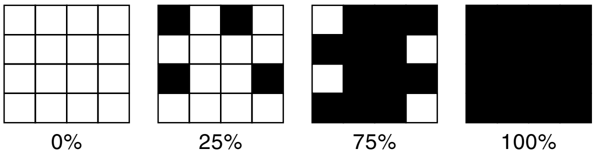


Figure 22. One way in which pixels can be arranged for gray level printing.

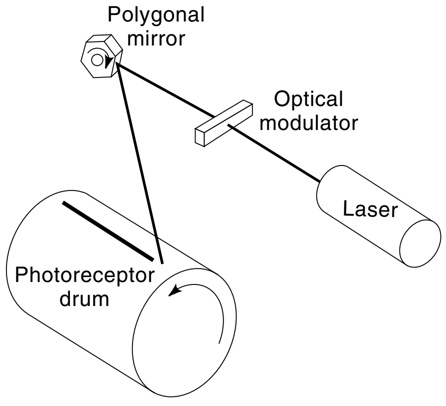


Figure 23. The optical path in a typical laser printer, in which the output of the laser is modulated, and then deflected by a rotating mirror so that it sweeps across the photoreceptor.

beam sweeps across the photoreceptor one row at a time, the image information is read from the raster array and fed to an optical modulator, as shown in Fig. 23.

This is the typical arrangement of a laser printer. The light comes from a continuous laser beam that passes through an optical modulator and then deflects toward the photoreceptor. The optical modulator switches the beam on and off depending on whether the light is to strike the photoreceptor. The speed and resolution of the printer determine the required switching speed of the laser beam. As an example, consider a laser printer with a resolution of 600 dpi. Each dot is approximately 42 μm in width. Assume that the printer operates at 100 pages per minute and that each page is approximately 0.3 m long and 0.25 m wide, a total area of

$$0.3(0.25) = 0.075\ \text{m}^2 \tag{12}$$

Then in one second, the beam must be able to address

$$\frac{0.075(100/60)}{(42.3 \times 10^{-6})^2} = 69{,}860{,}112\ \text{pixels} \tag{13}$$

so that the switching rate is approximately 70 million pixels per second. This is far too fast for a mechanical shutter, and so electro-optical methods are normally used to turn the light beam on and off.

By the way, these high switching rates are required of any printer using dot matrices and bit maps, if the same resolution and throughput are desired. In other related technologies, such as electromechanical printers and ink jet printers, optical modulation is not available, and much slower switches employing mechanical motion of objects on the orders of a millimeter must be used. The relatively large inertia associated with these switches prevents them from operating at such high rates. As a consequence, laser printers enjoy an advantage for high-speed, high-resolution printing.

Gas lasers operate in a continuous mode that always requires an optical modulator. Some solid-state lasers, however, can be pulsed on and off quickly enough to provide their own modulation. Such a laser (for example, GaAlAs) can greatly simplify the optical section of a laser printer.

In a laser printer, there is no need to supply a full spectrum of colors in the light source because there is no original document to image. This is a good thing because the output of a laser is typically a single wavelength of light that can be matched to the peak sensitivity of the photoreceptor and provide better charge control with a lower light level. Some of the photoreceptors, such as selenium, have relatively simple chemical structures and a definite spectral range of sensitivity. For example, amorphous selenium, which has been used in many of the machines made by the Xerox Corporation, responds well to the light emitted from a HeCd/Ar laser.

Other photoreceptors, especially organic photoreceptors, can be tailored to respond to a specific laser by adjusting the chemical moieties in the organic molecule. This allows the use of lasers with other advantages, such as the low cost of a HeNe laser or the switchability of a GaAlAs laser. This latter combination is used in many laser printers based on the Canon LBP-CX cartridge.

Once the laser beam has been separated into pulses, it must still be deflected to the proper location on the photoreceptor. The deflection method depends on the resolution and speed of the process. If the printer produces 100 pages per minute and each page is about 0.3 m long, the paper must advance at a velocity of

$$\frac{0.3}{(60/100)} = 0.5\,\text{m/s} \tag{14}$$

With a resolution of 600 dpi (42.3 μm lines), the beam must sweep out each line in a time on the order of

$$\frac{42.3 \times 10^{-6}}{0.5} = 8.46 \times 10^{-5}\,\text{s} \tag{15}$$

or about 85 μs. If the paper is 0.25 m wide, this implies a writing velocity of

$$\frac{0.25}{8.46 \times 10^{-5}} = 2955.0827\,\text{m/s} \tag{16}$$

almost 3 km/s the (the speed of sound in air is about 0.33 km/s). Direct physical motion across the page, as used in some typewriters and ink-jet printers, is clearly impractical for commercial devices. Instead, the laser beam is deflected by a rotating polygonal mirror, as shown in Fig. 23. As the mirror rotates, one facet intercepts the beam and reflects it across the width of the paper. When this reflected beam leaves the paper, the next facet of the mirror reaches the position at which it intercepts the beam, and the transverse sweep is repeated. The beam sweeps across the photoreceptor at a much faster velocity than the mirror is moving because of the nature of the reflection process.

The rotating polygonal mirror was the first solution to the problem of high scanning speeds in the laser printer. Other solutions based on optical effects have also been employed. One example is the Bragg effect, in which reflection is controlled by the spatially periodic variations within a crystal. Another approach to illuminating the photoreceptor avoids the laser beam altogether and relies on an array of small light-emitting diodes (LEDs) that cover the entire width of the photoreceptor. Each diode illuminates a particular spot on the photoreceptor and is turned on or off according to the information stored in the image bit map. This approach avoids the problems of scanning and high-frequency modulation of a single laser beam because it relies on the array of thousands of LEDs to share the writing load. As a result, each light emitter can be directly addressed at a much lower rate, which allows the use of relatively inexpensive devices. On the other hand, LED arrays must overcome the problem inherent in any addressing array, namely, the failure of a single LED out of the thousands in the array leads to a noticeable white or black line running along the entire length of the paper.

COLOR ELECTROPHOTOGRAPHY

The systems described above represent the standard black-and-white copiers and laser printers used throughout the world. The technology is based on dry toner particles of a single color and a charging process modulated by light. The increasing demand for colored printing has led to modifications of this technology that significantly affect the design and operation of electrophotographic machines. This section discusses three of the most important extensions. The first is the modifications required for any color printer, followed by the use of liquid toners, and then charge imaging without light.

Color Printing

Color printing is a broad term that covers several distinct categories, each of which imposes different requirements on electrophotographic technology. The simplest is to print in a single color, but that color is not black. This type of color printing is often used in advertising and can be quite effective when combined with colored paper and gray-scale output. It requires no modification of the electrophotographic process, except for replacing the black toner by a colored toner with similar physical and electrical properties. It is commonly offered in even the smallest and least expensive copiers, where it is implemented by simply replacing the cartridge.

A second level of complexity is the use of second (or highlight) color in the same machine. Typically most of the image is black, whereas a second color (usually red) is used to add emphasis or to distinguish between similar images. Typical examples are advertising (to call attention to benefits) and financial reporting (to distinguish negative numbers). From an electrophotographic viewpoint, two colors can be implemented by using two polarities of toner particles (positive and negative) for the two colors. If the image is formed on the photoreceptor with positive and negative areas, then toner of one color is attracted to the positive areas, whereas the opposite color goes to the negative areas. Thus both colors are developed in a single step.

Beyond these one- and two-color schemes is full color printing. Following the traditional printing theory of subtractive color, the image must contain at least three separate colors, chosen so that their combinations give the widest possible range of colors. These three colors are usually a cyan, a magenta, and a yellow. Then the images of each color are printed at the same location on the paper, where they combine to give the appearance of a different color. For example, cyan and yellow combine to give green.

When the three colors are combined in equal amounts, they give a gray scale ranging from white to black as the amount of color is increased. Normally the grays obtained in this way have a slight color cast, so a fourth color, black, is added to give better quality grays. The addition of black has additional benefits because a single layer of black toner replaces three layers of colored toners. This is less expensive and also reduces the height of the toner layer, an advantage in handling and appearance. Additional colors may be added for higher quality or special effects (like metallic printing), but in general the four color (CMYK) process is capable of handling all color printing requirements.

Unlike the highlight color printer, the four color electrophotographic process is always implemented by using four separate development units, one for each color. A schematic of a typical arrangement is shown in Fig. 24. This illustrates a drum architecture very similar to the standard monochromatic process, including the charging, exposure, transfer, and cleaning steps.

The exposure system in this example uses a laser beam, implying that this is a laser printer. In practice, virtually all color electrophotography is based on the laser printer, rather that the light-lens copier, whether it is sold as a copier or a printer. In fact, color copiers are basically color printers with a color scanner to capture and digitize the input document and a computer to process the image and send it to the laser. In the earlier direct color copiers it was quite apparent that the requirements of panchromatic photoreceptors and toners placed too much of a burden on the process for high-quality optical copying. The scanner/computer/laser combination allows individual control of each color channel, and the photoreceptor receives a single wavelength of light.

Color electrophotography introduces several problems not present in monochromatic printers and copiers. One is the need to place all four images in exact registration with each other to prevent objectionable color halos around image segments. Plain paper is not dimensionally stable enough that the four images can be placed in sequence, so alternate techniques must be used. In the example of Fig. 24, the four images can be developed on the photoreceptor drum in four successive revolutions, using the same laser. In the first pass, the yellow information is written as a charge image on the drum, and the yellow developer is pushed in to contact the drum. At this point, the transfer and cleaning stations are inactive, so the yellow image remains on the drum and rotates with it. As it passes the laser, the next color is imaged, and the process repeats. When the last color has been devel-

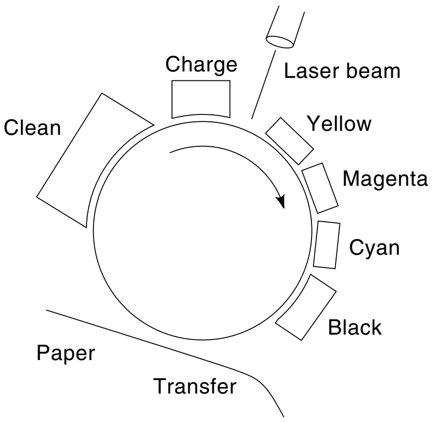


Figure 24. One method for obtaining color prints from a laser printer by using four colors (CMYK).

oped, the transfer station is activated, and the entire four-color image is transferred to the paper.

The drum is rigid, so the four images remain in good registration throughout, but each successive image must be written and developed in the presence of the earlier images. This can cause some problems in uniformity of response, so an alternate architecture involving an intermediate drum or belt is often used. In this arrangement, each image is transferred from the drum to some temporary holding place, allowing the drum to be cleaned before the next image. This makes it much easier to obtain good individual color images but adds the problem of transferring the image twice (once to the intermediate and again to the paper). A third method, and the most common in practice, is to build the image on the paper by transferring each color as soon as it develops.

Although not as obvious, the use of color presents some special considerations for the toner formulation. Colored tones, by definition, absorb some wavelengths and pass others. This rules out the use of some magnetic development systems that require magnetizable toners, because magnetic materials are usually black and/or opaque.

An additional consideration is the need to overlay four layers of toners in some parts of the image. This leads to an image that is four times as high as a conventional monochromatic image and much more likely to be disturbed by air currents, vibration, electrostatic charge repulsion, and other effects before it is fixed. After fixing, the image is still thick and may wrinkle or curl the paper because of differential contraction as it cools. These problems can be ameliorated by using toners that are much smaller in particle size than conventional black toners. In practice, however, the toner can not be much smaller that approximately 5 μm before it becomes very difficult to control in the air currents that always exist near the development nip and entrain small particles.

Liquid Development

Although it is difficult to keep small particles from becoming airborne, it is very easy to control them in a liquid. As a result, liquid electrophotographic development has undergone a great deal of study, and high quality color printers using this approach are commercially available. Although some changes must be made in all process steps in liquid electrophotography, the major modifications occur in the toner and development. The toner itself consists of small particles (typically on the order of 1 μm or less) suspended in an insulating liquid. The particles are charged by the zeta potential mechanism, leading to a separation of charge across the interface between the solid toner particle and the liquid. This effect is similar to the electrochemical potential difference that separates charge in a battery or to the contact potential difference that leads to triboelectric charging. Usually charging of the particles is controlled by the addition of chemicals (charge control agents) that promote charging of a particular polarity.

Because the particles are charged, they respond similarly to charged toner particles in air, except that their motion through a liquid is much slower than through air because of the increased drag. As a result, the liquid usually flows over the surface of the photoreceptor so as to bring the particles as close as possible before relying solely on electrostatic attraction to develop the charge image.

Some of the modifications needed to accommodate liquid development are obvious. The development unit, for example, is usually placed below the photoreceptor so that the fluid does not run out. Some are less obvious. For example, if the fluid itself is slightly conductive, and a thin layer (less than 1 μm) is left on the photoreceptor after cleaning, it can short out the next charge image. In addition, many photoreceptors are attacked chemically by the liquids used to suspend the toner, so that the choice of photoreceptors is much narrower than in dry electrophotography.

Electrography

All of the applications described so far involve electrophotography in the strict sense, that is, they rely on light to modify a charge distribution. There is an alternative, however, that does not rely on light and therefore is called electrography. In this approach, charge is deposited directly onto an insulator. All requirements for photoconductivity are eliminated, which means that a much wider range of materials can be used. The most common application of this technique is the electrostatic plotter, often used to produce multicolored engineering drawings, posters, and other wide formats.

Because the receptor does not need to be a photoconductor, it is possible to form the charge image directly on the output document. This is a particular advantage for color because it avoids the transfer steps that often lead to poor registration. The image is developed with either dry powders or liquid toners. Both approaches are represented in commercially available printers.

The major problem to be faced in direct electrography arises from the charge deposition step itself. Charge is deposited only where an image is desired, so means must be provided to address every pixel with a voltage large enough to deposit charge. In air, this voltage is on the order of several hundred volts. Thus a 600-dpi printer 10 in. wide requires thousands of individual electronic switches operating at several hundred volts. The expense of this electronic array has limited electrography to high-end applications.

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Electrostatic Applications

ELECTRORHEOLOGICAL FLUIDS. See ELECTRORHEOLOGY.