Solid freeform fabrication by electrophotographic printing

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Abstract

A solid freeform fabrication technique is described where powder is deposited layer by layer using electrophotographic printing. In this process, powder is picked up and deposited using a charged photoconducting surface and deposited on a build platform. The paper describes a test bed that was designed and constructed to study the application of electrophotography to solid freeform fabrication. It can precisely deposit powder in the desired shape on each layer. The electric field required to transfer the powder on to the platform (or onto previously printed layers) was studied. A polymer toner powder was used to build small components by fusing each layer of printer powder using a hot compaction plate.

1. Introduction

Solid Freeform Fabrication (SFF) technologies are manufacturing / prototyping technologies that are characterized by layer-by-layer addition of material to fabricate components. These techniques are also known as layered manufacturing and rapid prototyping [1]. The layer-by-layer building approach allows significantly more complex parts to be built in one fabrication step than was previously possible thus simplifying process planning. SFF technology therefore can automate the process planning and fabrication of a part under computer control so that the only input needed is a solid model of the part.

Over the last decade many different technologies for Solid Freeform Fabrication have evolved. Broadly, the SFF techniques available currently can be classified as stereolithography, solid fusion and solidification, laminated object manufacturing, and powder based techniques. The stereolithography technique [2] selectively solidifies a liquid photopolymer while solid fusion and solidification [3], [4] fuses/melts the material and deposits it layer by layer. The laminated object manufacturing technology [5] cuts out laminates from sheets of part material and glues or fuses them together. In all these methods of SFF, special support structures are needed to support overhanging features of the part. The two main powder-based techniques that have been commercialized are Selective Laser Sintering and 3D printing. For powder based methods no support structures are typically required to create complex shapes. Powder is selectively consolidated into a part and the remaining powder can be removed. In the SLS process [6], a thin layer of powder is deposited in a workspace container and the powder is then fused together using a laser beam that traces the shape of the desired cross-section. The process is repeated by depositing layers of powder thus building the part layer by layer. In the 3D printing process [7], a binder material selectively binds powder deposited in layers. Ink-jet printing technology is used to print the binder in the shape of the cross-section of the part on each layer of powder.

Electrophotographic Solid Freeform Fabrication (ESFF) [8], [9], [10] is also a powder based freeform fabrication technology that builds parts by printing powder layer-by-layer using electrophotography process [11]. The electrophotography process is used in photocopiers and printers to print toner powder on paper. This technology is capable of printing powder with high accuracy and resolution. Each layer of powder is printed in the shape of the cross-section. Two different processes for using electrophotography for SFF are described in this paper. In the first approach the part powder is printed layer by layer in the shape of the cross-sections of the part and thermally fused to previous layers. In the second approach, a part powder is first deposited uniformly by spreading a thin layer of powder using a roller and then a binder powder is electrophotographically printed in the cross-sectional image. This process is similar to 3D printing except that the binder is in powder form and printed using electrophotography. The binder is then thermal fused so that it diffuses into and binds the part powder. The challenges associated with printing powder for these two approaches were studied experimentally on a test bed. This test bed was designed as a flexible experimental platform to study layer by layer electrophotographic printing.

The design and working principle of the ESFF testbed is described in section 2. Using this test bed powder, parts can be built directly by printing part powder layer by layer as described in section 3. A technique for printing binder powder on a bed of part powder is described in section 4.

2. Description of the test-bed

An ESFF test bed was built that enables layer-by-layer deposition of powder using electrophotography technology. This test bed consists of an electrophotographic printing system, an automated two axes deposition/build platform and control system as well as a thermal fusing and compacting system, all mounted on a structural frame. A model of the system is shown below in Fig. 1.

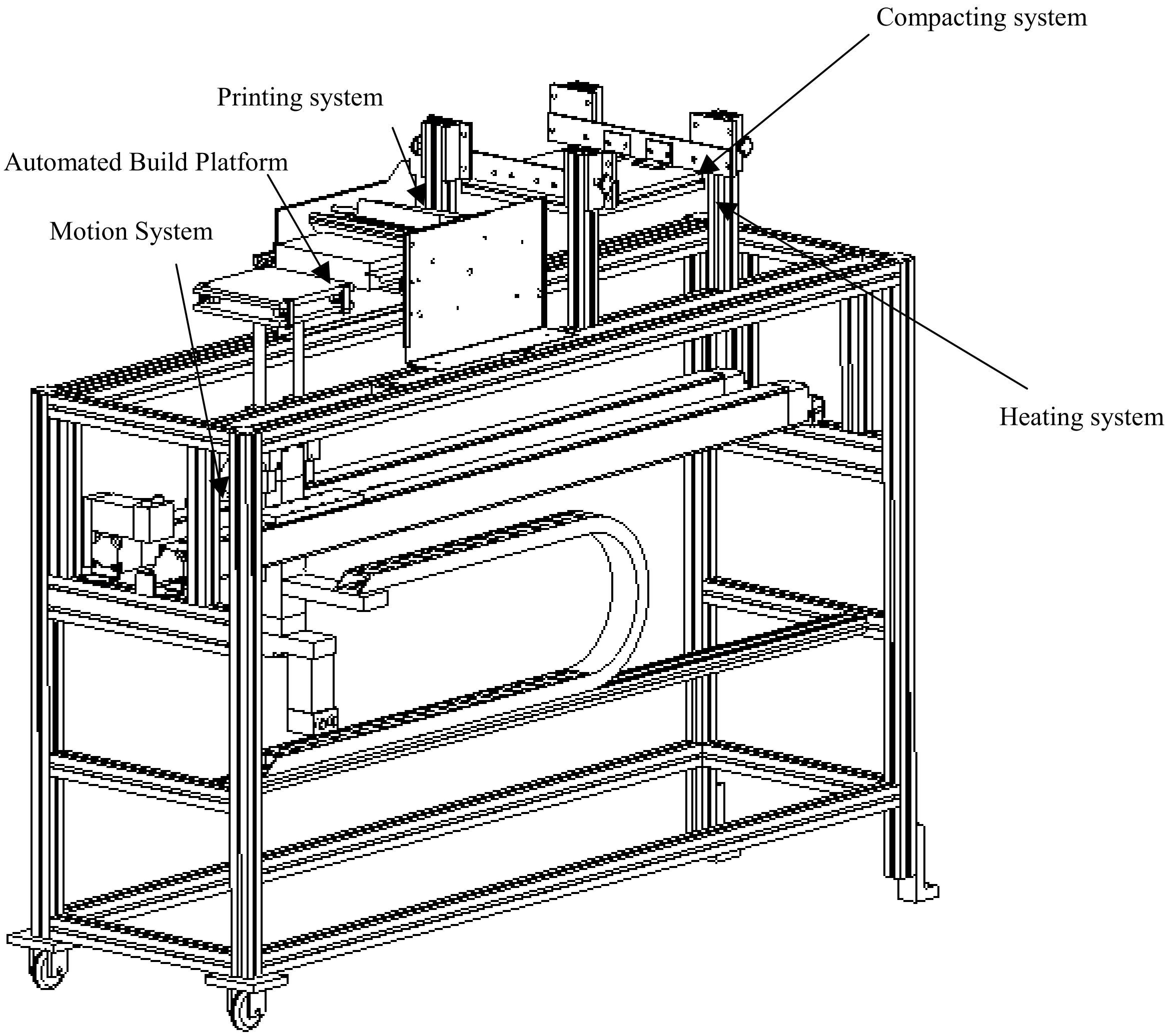

Figure 1: Model of the ESFF machine

A belt driven linear actuator moves the build platform in the horizontal (or x-) direction while a lead screw driven linear actuator moves the platform vertically (z-direction). Both the actuators are driven by servo-motors controlled by a digital control system. The printing system prints powder on the build platform as it passes below the printer. The cross-sectional images to be printed are computed by software that runs on a PC and can read in the solid model of the part to be fabricated in the STL format. The powder that is printed on the build platform is compacted and fused by the compacting system which is a heated non-stick plate mounted on a rigid frame.

The most important sub-system of the test bed is the electrophotographic printing system. Figure 2 shows the schematic diagram of the electrophotography engine used in a desktop laser printer from which components were taken to build the printing system for the test bed. The photoconducting drum is an aluminum drum that has a coating of photoreceptive material which is non-conductive in the dark and conductive when exposed to certain wavelength of light. When the drum rotates its surface is cleaned by the cleaner blade and then charged by the charging roller that is made of a conducting polyurethane on which a DC biased AC voltage is applied. The uniformly charged surface of the drum is selectively discharged by the laser image scanner that projects a UV laser on the drum surface. The region on the surface of the drum that is exposed to the laser beam becomes conductive and therefore gets discharged. A latent image is thus formed on the surface of the drum consisting of the discharged areas.

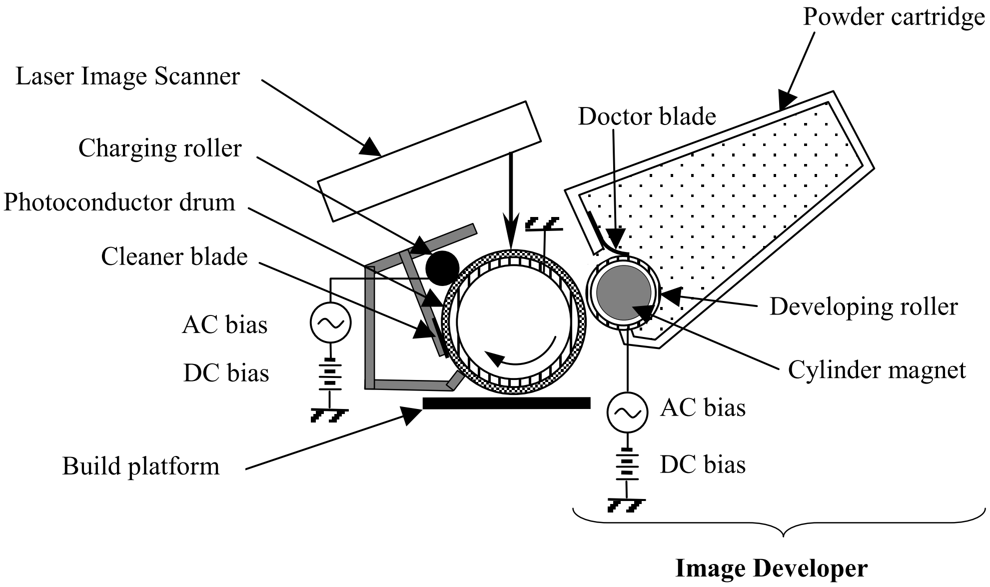

Figure 2: **Schematic of the electrophotographic printing system**

The latent image is converted into a real image when powder is electrostatically attracted (or developed) on to the discharged regions of the drum from the image developer. The image developer consists of the powder cartridge and the developing roller shown in Fig. 2. The developing roller is a hollow metallic roller which encases a cylinder magnet. The powder is magnetized so that it sticks to the developing roller. As this roller rotates a thin layer of powder squeezes out between the doctor blade and the roller. A DC biased AC voltage is applied to the roller to print this powder on to the photoconductor drum. The powder is electrically charged to the same polarity (negatively) as the surface of the drum so that the powder is only printed on to the discharged areas due the electric field between the developing roller and the photoconductor drum.

The image developed on to the photoconductor surface is transferred to the printing surface or the build platform of the test bed. A positive charge is applied to the surface of the platform. The field generated by this charge attracts the negatively charged powder on the surface of the drum to the surface of platform, and thus the real image on the drum surface is transferred to the platform surface. The control system synchronizes the printing with the platform motion. The platform is moved at a velocity equal to the tangential velocity of the drum so that there is no relative velocity between the two surfaces as the image is transferred from the drum to the platform.

3. Direct part printing

The test bed described above has shown the feasibility of printing powder layer by layer using the electrophotography method. As mentioned earlier, one method for implementing solid freeform fabrication is to print part powder layer by layer in the shape of the cross-section and then fusing the printed powder to previous layers. This approach has been referred to here as direct part printing. A polymer powder consisting of styrene with various additives, including ferrous oxide to magnetize the powder, was used for printing. The particles in the powder were approximately 5 microns in size. The surface to be printed on was charged using a corona charging device and a constant DC voltage of 1000V was applied to the aluminum build platform to enable transfer of the image from the photoconductor drum to the build platform. The layer thickness is dependent on particle size as well as parameters such as charge per unit mass of powder, speed ratio between photoconductor drum and developer roller etc.

The electric field between the photoconductor drum and the print surface was computed using Gauss's law as follows [12]:

$$E(p,\sigma_s)=\frac{V_{DC}+\rho_1\frac{p^2}{2K_1\varepsilon_0}+\rho_2\frac{d_2^2}{2K_2\varepsilon_0}-\rho_3\frac{d_3^2}{2K_3\varepsilon_0}+\frac{p}{K_1\varepsilon_0}\left(\sigma_s+\rho_2 d_2\right)}{K_2\left(\frac{p}{K_1}+\frac{d_2}{K_2}+\frac{d_3}{K_3}\right)} \tag{1}$$

In the above equation, V_{DC} is the potential applied to the build platform, p is the height of the part (or previously printed layers), d_2 is the thickness of the fresh powder layer, d_3

is the thickness of the photo-conducting layer. K_1, K_2 and K_3 are the relative permittivity of the fused powder layer, fresh powder layer and photoconductor material respectively. ρ_1, ρ_2 and ρ_3 are charge per unit volume in the fused powder, fresh powder layer and the photoconductor layer respectively and ε_0 is the permittivity of the air. σ_s is the charge per unit area deposited on the print surface. The equation shows that the field strength decreases with part height p, if the surface is not charged ($\sigma_s = 0$). Residual negative charge on the fused layers of powder ($\rho_1 < 0$) also can significantly decrease the electric field strength available for image transfer.

Figure 3 shows small parts built using the test bed. The parts were built simultaneously by printing powder over a thin layer of polymer sheet covering the aluminum platform. The parts are approximately 1 mm tall and took about 200 prints of polystyrene based powder. The print thickness is larger for the first few prints and then decreases to an average rate of approximately 5 microns per print. This low rate of printing can be improved by more efficient removal of residual charge from the previously printed layers and by increasing the charge density deposited by the corona charging device.

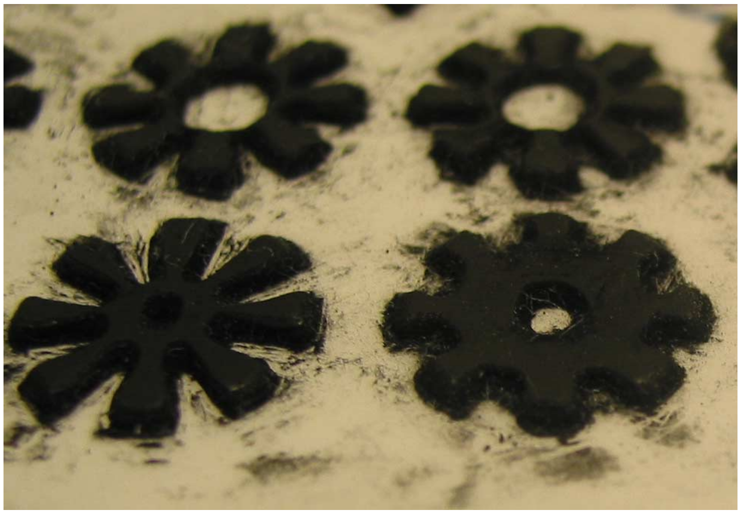

Figure 3: Parts made by the test bed

The printing system used in the test bed is capable of achieving up to 600 dpi. However, the accuracy and finish of the parts made using the process also depends up on the accuracy with which subsequent layers can be aligned over each other. Another factor that affects the part accuracy is the distortion that occurs during the fusing and compaction after each layer is printed.

4. Binder printing on part powder

An alternative way to build parts using electrophotography is to print a binder powder on uniformly deposited part powder as is done for 3D printing. The binder powder can then be fused thermally so that it diffuses into the part powder and binds the part powder together up on subsequent cooling and solidification. The success of this concept depends on the ability to deposit thin uniform layers of part powder and the efficiency with which the binder powder can be transferred on to the part powder bed. It is not feasible to transfer powder directly from the photoconducting drum on to previously deposited part powder bed because the charged regions of the drum will pick up some part powder. In other words, during the transfer process the part powder will get picked up by the photoconductor drum instead of the binder powder being printed from the drum to the powder bed. This can quickly damage the photoconductor especially if the part powder is abrasive. To protect the photoconductor drum and to minimize part powder reverse printing it is necessary to use either a transfer roller or a transfer belt. The ideas is that the binder can be first printed on to an intermediate transfer device and then subsequently transferred from this device to the part powder bed. Figure 4 shows the concept schematically where a transfer roller is shown between the photoconductor and the build platform. On the right an equivalent parallel plate model for the interface between photoconductor drum and transfer roller as well as the interface between the transfer roller and the print surface.

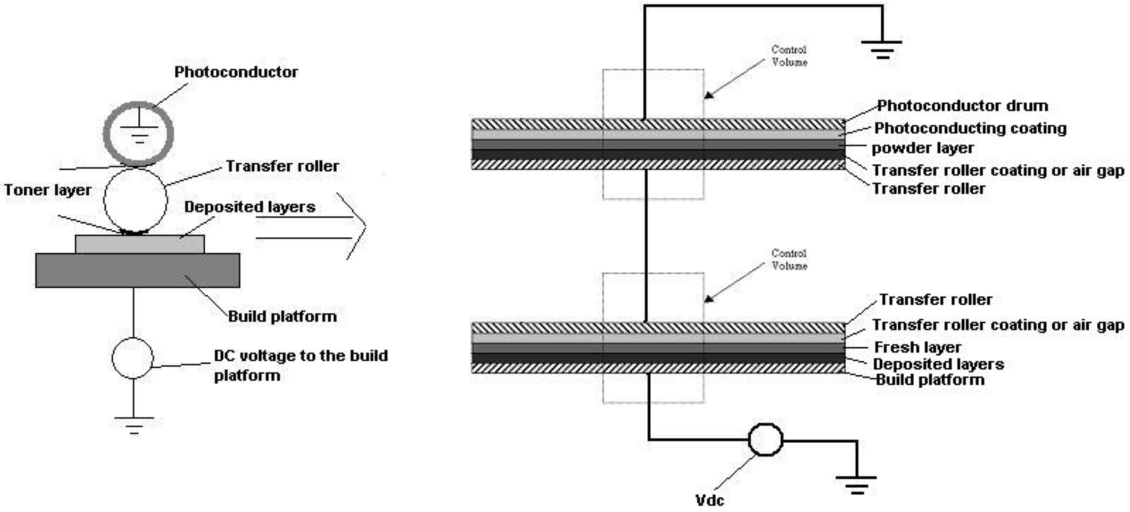

Figure 4: Parallel plate analogy for transfer device arrangement

Electric field is required at both interfaces to enable transfer of powder. A conductive (aluminum) drum was used as the transfer roller. The electric field for transfer can be created by applying a voltage to the build platform or by charging the top layer of the powder bed. Since the transfer roller is conductive its voltage is constant and the electric field created at one interface is transmitted to the other interface. The transfer roller rotates such that it has the same tangential velocity as the photoconductor drum so that the image can transfer from the photoconductor to the transfer roller. Similarly the build platform moves at the same velocity as the tangential velocity of the transfer roller to enable undistorted transfer of the image from the transfer roller to the platform.

If the part powder is metallic (conductive), it tends to get charged by the electric field and jumps back and forth between the transfer roller and the powder bed creating a powder cloud as shown in Fig. 5. The reason for this powder oscillation is that the powder particles are conductive and therefore loose their charge and get reversely charged due to the field as soon as they contact the transfer roller or the drum. This oscillation causes many problems including poor transfer of binder powder as well as distortion of the image. If the drum is covered with a thin insulator layer then the particles cannot loose charge to this layer and sticks to it resulting in reverse printing. Therefore this approach appears to be infeasible for conductive part powders unless some other means is used to hold down the part powder, such magnetic force if the part powder is magnetic.

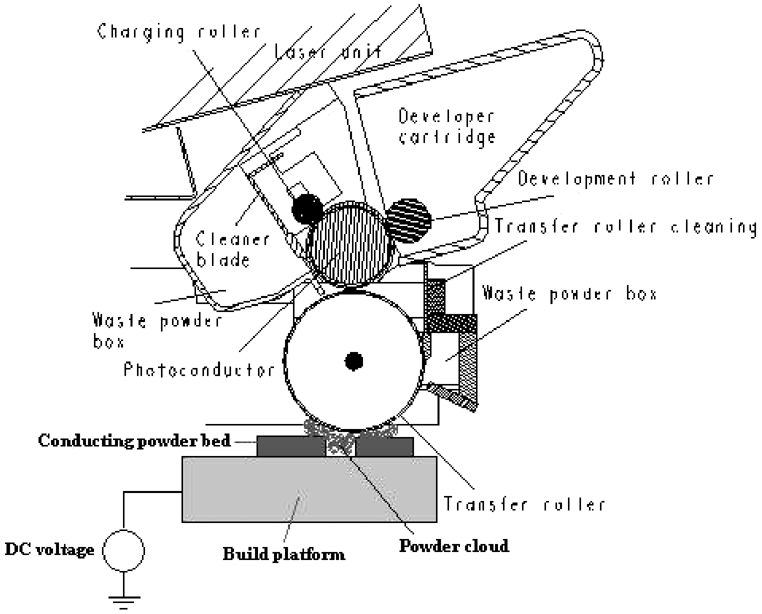

Figure 5: **Transfer roller system with conducting part powder bed**

For non-conductive part powders, the top surface of the powder bed must be charged to facilitate (or create the necessary field for) transfer of the binder powder. The charged particles on the surface need to be held down so that they do not get picked up by the transfer roller. Figure 6 shows a polystyrene binder powder printed on a ceramic (alumina) powder bed. The powder bed was created by spreading a layer of the ceramic powder uniformly and then it was compacted to impart green strength in order to minimize reverse printing. A thin polymer (insulator) cover was glued over the transfer roller to minimize chances of sparking between the photoconductor drum and the roller.

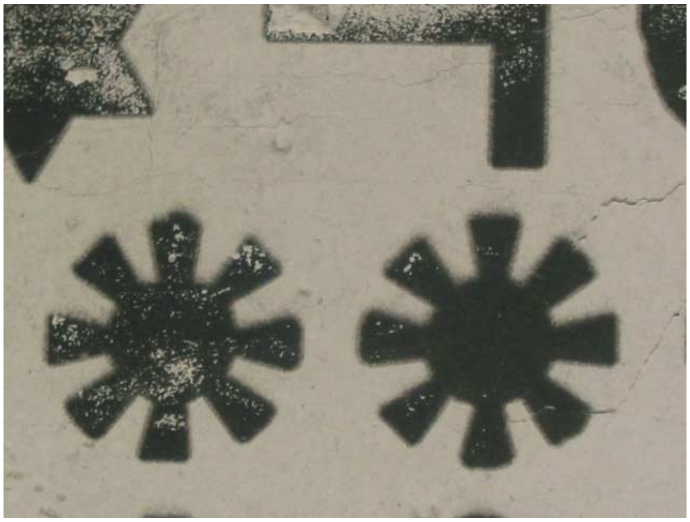

Figure 6: Toner powder on insulating alumina powder bed

In Fig. 6, the black binder powder is printed on alumina (white) powder bed. The white spots within the printed image were caused by reverse printing where the alumina powder was picked up by the transfer roller instead of the binder getting printed on the alumina powder bed. Another problem with this approach is that if the binder is too viscous after melting it may not diffuse into the part powder deep enough to ensure proper bonding between layers.

5. Conclusions

A test bed for studying electrophotographic solid freeform fabrication was built and used to show the feasibility of printing powder layer by layer in the shape of the cross-sectional images of a part to be fabricated. The test bed was fully automated and controlled from a program that reads in a solid model of the part, computes the cross-sectional images and prints them layer by layer on to a build platform. This approach appears to be a feasible method for rapid prototyping small polymer components. 3D printing was also attempted by printing polymer binder electrophotographically on a ceramic powder bed. It was necessary to use a transfer roller to print the binder powder. The transfer roller can not prevent reverse printing but it protects the photoconductor drum from damage. Printing binder powder for 3D printing has other disadvantages that traditional 3D printing does not have including the need for melting the binder and poor bonding between layers. Direct part printing on the other hand appears to be a promising approach for building tiny components as well as for constructing heterogeneous parts if multiple powders can be printed layer by layer. However, further research is required to develop technology for reliably charging and printing a variety of powders including ceramic and metallic powders. This work is currently in progress and initial results have been encouraging.

6. Acknowledgement

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7. References

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