The Science and Technology of Electrophotography or Benjamin Franklin and Electrophotography

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Electrophotography

Technology used in
Copiers
Laser Printers

Multibillion Dollar Industry Based on Electrostatics

Its Roots go back to experiments of Benjamin Franklin
Woodcut illustrating the Leyden experiment from Park Benjamin, A History of Electricity, 1898 - reproduced from Winckler, 1746.

Franklin- from a painting by Stephen Elmer Bigelow 1904 Vol. VI frontispiece (public domain)
Franklin’s Experiments

- Rubbed glass rod with wool or silk to generate electrostatic charges – (2) insulator charge exchange. Used rod to charge a Leiden jar – first capacitor
- Observed sharp points work better than blunt points in drawing off the fire - electric field concentration
- Noted that the amount of “electrical fire” added to glass was lost by the wool. Introduced the one fluid theory of electricity, i.e. charge conservation
- Noted the attraction or repulsion of charged surfaces to each other – (3) electrostatic adhesion
- Defined the glass’s charge as positive, thereby defining the electron charge as negative
- Showed lightning is electrical in origin and designed the first lightning rods. This later led to (1) coronas
6 Steps of Electrophotography

1. Charge
2. Expose
3. Develop
4. Transfer
5. Fuse
6. Clean
Electrophotographic Process

Diagram showing the electrophotographic process:
- **Charge Corona**
  - Light imaging the photoreceptor
- **Transfer**
  - Transfer Corona
  - Paper Path
  - Magnetic Brush Development System
- **Develop**
- **Fuse**
- **Clean**
  - Clean Corona
  - Clean Lamp
  - Cleaning Brush
Schematic of a HeNe Laser Printer
Short History of Electrophotography (EP)

• 1938 – Invented by Chester Carlson
• Mid 1950s – Xerox (Haloid) - Battelle collaboration. Invented
  – a-Se Photoreceptor
  – Corona charging
  – Two component development
  – Electrostatic transfer
• 1959 – Xerox 914 copier introduced
• Mid-60s – Organic photoreceptor introduced by IBM led to IBM Copier I (1970) and first laser printer (1975)
• 1980 – Canon introduced magnetic toner, monocomponent development and cartridge (1983)
• 1985 – Ricoh introduced NON-magnetic toner, monocomponent development – used extensively in color EP
• 1986 – Canon introduced digital color
• 2001 – Xerox introduced image-on-image (IOI) architecture
• 2005 – Aetas introduced small volume, low cost IOI system
Lightning
Lightning and (1) Coronas

**Lightning**
- Franklin showed lightning is electrical in origin – electrical fire.
- Source of charge separation in clouds still under investigation.
- Consider the cloud and ground as a capacitor – 2 parallel plates.
- When the electric field in air is high enough (3 V/micron) for electrons to gain enough energy to ionize molecules by collision - creates a conductive path.
- Lightning (discharge of the cloud) follows the conductive path

**Corona**
- Consider a wire – plane geometry. Field is non-uniform - highest at the wire surface.
- Air is ionized near the wire. But far from the wire the field is too low to ionize the air.
- This creates a plasma near the wire, which can be used as a source of charged particles.
Corotron
Scorotron

Charging is self limited
Electrophotographic Process
2. Insulator Charge Exchange
Charging Toner Particles

Toner

Toner on Carrier
Two Component Development
Canon’s Magnetic Toner, Monocomponent Development System (1980)

Uses ac electric fields
Ricoh’s NON-magnetic Toner, Monocomponent Development System (1985)

Uses contact development
Toner Charge Distributions
Charge Measuring Tools

Cage Blowoff: $Q/M$

Vacuum Liftoff, Plate Blowoff: $Q/M$

Diagrams showing the processes involved in charge measuring tools.
Toner Charge Spectrometer
Low Density Surface State Model
Inconsistent with Data
Electric Field Theory
Consistent with all Experiments

\[ E = \frac{1}{4\pi\varepsilon_0} \left( \frac{Q}{r^2} + \frac{Q_e}{R^2} \right) \]

Toner charges until \( E = E_e \)
M/Q vs. $C_t$

(from Lee, Photo.Science, and Eng. 22, 228, 1978)
Comparison of Low Density and Electric Field Theories

- **Electric Field**
  \[
  \frac{M}{Q} = RC_t \left( \frac{\rho_c}{3eE_e} \right) + \frac{\rho_t}{3eE_e}
  \]
  \[
  \frac{S}{I} = \frac{R \rho_c}{r \rho_t}
  \]

- **Low Density**
  \[
  \frac{M}{Q} = RC_t \left( \frac{\rho_c}{3\Delta \phi eN_c} \right) + \frac{\rho_t}{3\Delta \phi eN_t}
  \]
  \[
  \frac{S}{I} = \frac{R \rho_c}{r \rho_t} \frac{N_t}{N_c}
  \]
Data Supporting Electric Field Theory
Theories of $E_e$ (10V/µm)

- If $E_e$ is associated with a work function or chemical potential, then $E_e = \Delta \Phi / ez$. $E_e = 1000 \text{ V/µm}$ for $z=1 \text{ nm}$, $\Delta \Phi = 1 \text{ eV}$.
- Correlation with “work functions” determined by charge exchange with metals. But the range of $\Phi$ small and $z$ not accounted for.
- Correlation with density of states of polymers suggested. But requires communication with bulk states and experiments could not be repeated.
- Correlations with Inverse Gas Chromatography recently shown. But $z=30 \text{ nm}$ is not unaccounted for.
- Basic understanding of $E_e$ is needed.
3. Electrostatic Adhesion and Color Electrophotography

• **Markets**
  - Low cost, desktop - $400, 4ppm - Canon, Samsung, Konica-Minolta
  - Midrange - $20-100K, 6-30 ppm – Many manufactures
  - Digital Production Printing - $500K, 100 ppm - Xerox, Kodak, HP

• **Technical Challenges**
  - Image Quality
  - Image Accumulation
Phaser 740 (Matsushita) (IOI means accumulation on the photoreceptor)
Image-on-Image (IOI) Technology Requires dc-Jump

Organic Photoconductor (OPC)

Cannot use ac electric fields because of contamination
Cannot use contact development due to image disturbance
Can only use dc electric fields
Physics of dc-Jump

Organic Photoreceptor (OPC)

Development occurs when QE > Fad
OPC charged to 700 volts, normally
Toner must be released at E=700 volts/gap
For IOI, release must be at E=400 volts/gap
Toner Adhesion from Literature
(Hays, J. of Adhesion, 51, 41, 1995)

\[ QE = Q \left( \frac{V_w}{L} > F_{ad} \right) = 2 \left[ \text{Measure(50%)} \right] \]

<table>
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<th>Diameter (µm)</th>
<th>Q/M (µC/g)</th>
<th>Adhesion (nN)</th>
<th>Measure(50%)/Calculated</th>
<th>( V_w ) (at 150 µm)</th>
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</table>
Numerical Calculation

\[ F = \frac{1}{4\pi\varepsilon_0} \frac{Q^2}{(2r)^2} \]

Underestimates adhesion
Numerical Calculation

Additional Adhesion is called the Proximity Force
Technology/Science Challenge: Minimize Toner Adhesion

Published Idea: Toner adhesion due to nonuniform charge distribution around the toner particle.

Aetas Discovery: Source of toner adhesion: Charge distribution on the toner is uniform, but discrete.

1. Toner adhesion is due to electrostatic proximity force (due to charge discreteness) -
2. Acting at each contact point (7-47 possible).
3. Toner adhesion is minimized if number of contact points is minimized. Control with nanoparticles (e.g. 10 nm silica) on surface.
Development Curve for 8 Micron Toner Measured at 150 µm Gap

Aetas Data
New dc-Jump Development System in a 4-Pass Printer
Aetas Printer

Volume = 27 liters

2.8 point Red
(magenta + yellow)
Ben Franklin and Electrophotography
Franklin Studied:

• **Lightning** – in a non-uniform geometry the same mechanism creates a corona (a plasma near the wire) which is useful as a source of charged particles. Used in two steps of EP.

• **Insulator Charge Exchange** – critical for toner charging. Insulators charging is described by Electric Field Theory. Need a theory of $E_e$.

• **Electrostatic Adhesion** – Its understanding (based on proximity force) has led to its minimization and a new EP dev. system that allows a small volume, low speed IOI system – a true desk-top color laser printer.

• **Franklin, who was a printer**, would have been proud to know that his electrostatic experiments evolved into a new printing technology called Electrophotography.