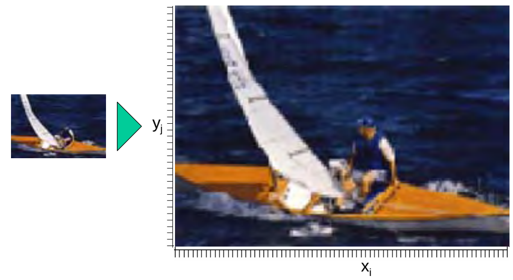
Digital printing:

where physics and chemistry merge

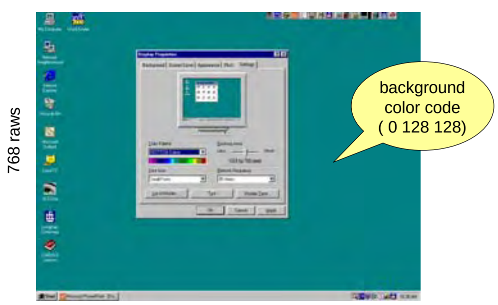
Boris Zhmud

Image as a bitmap

Position (x_i, y_j) + Color (R_k, G_l, B_m)



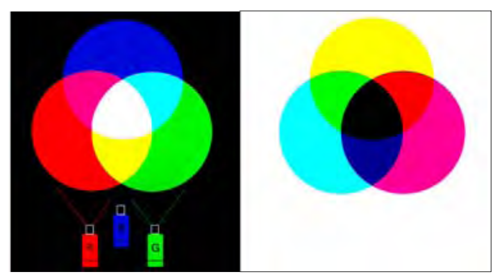
Windows NT desktop as a digital image



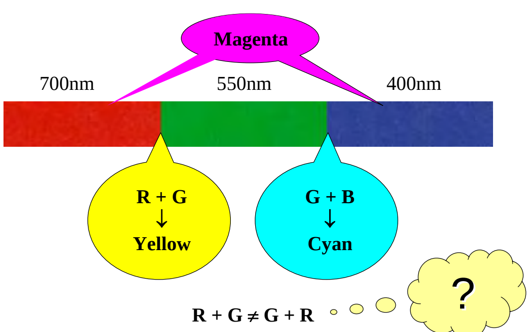
Color reproduction

Additive and subtractive colors

Can it be that 1 + 1 + 1 equals 16,777,216?



Blending colors gives more colors



R + G ≠ G + R

• *The summand order may alter the sum*

Adding and subtracting:

Simple arithmetic

Why grass is green?

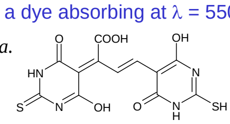
- *Chlorophill absorbs red and blue light.*

How would a blue Volvo look under yellow lighting?

- *Black.*

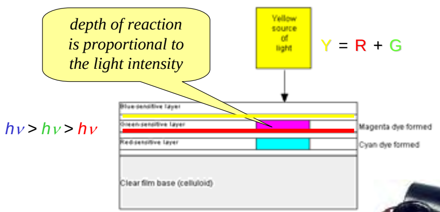
What color has a dye absorbing at λ = 550nm (green light)?

- *Magenta.*



Before the world has become digital

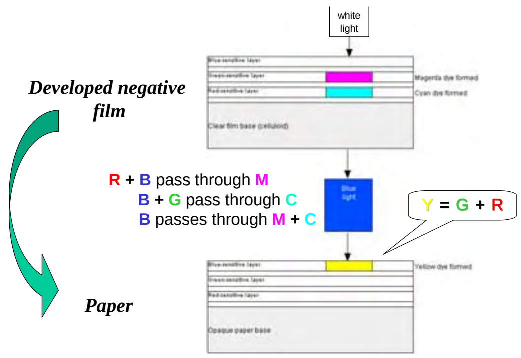
Color photography



$$AgCl + e + h\nu \rightarrow Ag + Cl^-$$

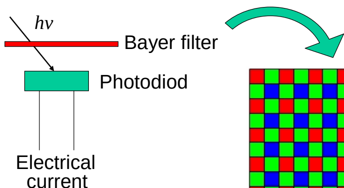
- Spectrally-sensitized AgHal crystals are used

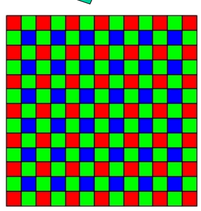
Negative-positive process



After Woodworth, Eastman Kodak Co.

Digitalizing colors





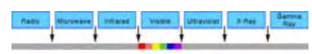
Color depth

$2^8 = 256$ (*gray scale*)

$2^{24} = 2^8 \times 2^8 \times 2^8 = 16{,}777{,}216$

Remember what the Windows desktop background color code was?

Why is it the visible light that is visible?

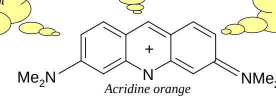


- Life is built around organic compounds
- Chemical identity is determined at a molecular level
- Electron structure of molecules determines the light absorption spectrum.
- The light absorption should not change the chemical identity of molecules.

IR can't be used by haemotherms

water is transparent for visible light

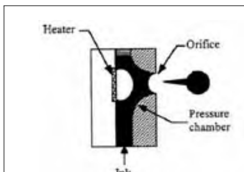
UV/vis spectrum is less sensitive to the effect of environment than e.g. IR spectrum



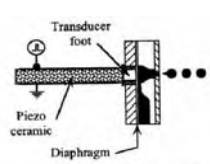
Acridine orange

Inkjet printing

Printer	DeskJet 850C	DeskJet 722C	DeskJet 2000C
Nozzle spacing (dpi)	300	300	600
Number of nozzles	64	64	300
Firing frequency (kHz)	6	12	12
Drop size (μm)	20	13	12



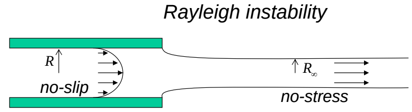
roof-shooter thermal inkjet pen



piezoelectric inkjet pen

Drop generation mechanics:

Rayleigh instability



Poiseuille flow profile:

$$F = -\eta S \frac{dv}{dr}$$

$$F = p \cdot \underbrace{\pi r^2}_{\text{cross-section area}} \quad ; \quad S = \underbrace{L \cdot 2\pi r}_{\text{wall area}}$$

$$\frac{p}{2L\eta} = -\frac{dv}{rdr} = -\frac{2dv}{d(r^2)}$$

$$v(r) = \frac{p(R^2 - r^2)}{4L\eta} = 2\bar{v}\left(1 - \frac{r^2}{R^2}\right)$$

Uniform flow profile:

$$v(r) = v_\infty \quad (0 < r < R_\infty)$$

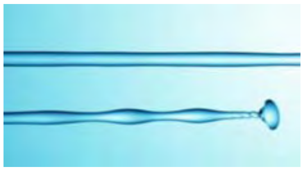
Jet contraction ratio:

$$v_\infty R_\infty^2 = \bar{v} R^2$$

$$\int_0^R v^2(r) r dr = v_\infty^2 \int_0^{R_\infty} r dr = \tfrac{1}{2} v_\infty^2 R_\infty^2$$

$$\frac{R_\infty}{R} = \frac{\sqrt{3}}{2} \approx 0.87$$

Rayleigh instability (cont'd)



Free area change on replacing $R_\infty \to R(x) = R_\infty + \varepsilon \sin\frac{n\pi x}{L}$

$$S = \int_0^L 2\pi R(x)\sqrt{1+[R'(x)]^2}\,dx$$

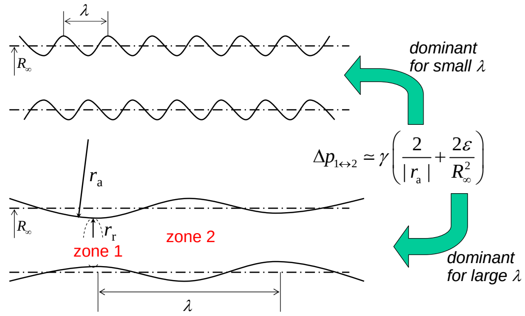
$$= 2\pi R_\infty \int_0^L \left(1+\frac{\varepsilon}{R_\infty}\sin\frac{n\pi x}{L}\right)\sqrt{1+\frac{\varepsilon^2 n^2\pi^2}{L^2}\cos^2\frac{n\pi x}{L}}\,dx$$

$$\approx S_0 + \varepsilon\left[\underbrace{2L(1-\cos n\pi)}_{0 \text{ if } n=2k} + \varepsilon\pi^3\frac{R_\infty n^2}{2L}\right]$$

this doesn't work because L was assumed constant

Rayleigh instability (cont'd)

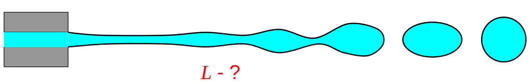
Surface tension effect revisited



$$\Delta p_{1\leftrightarrow 2} \simeq \gamma\left(\frac{2}{|r_a|} + \frac{2\varepsilon}{R_\infty^2}\right)$$

Break-up length evaluation

based on the dimensional analysis



$$\Delta p \sim \frac{\varepsilon\gamma}{R^2}; \quad F \sim R^2\Delta p \sim \varepsilon\gamma$$

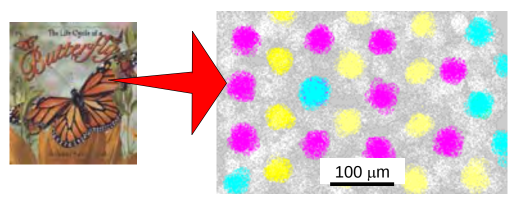
$$a \sim \frac{F}{m} \sim \frac{\varepsilon\gamma}{\rho R^2\lambda}$$

$$\tau \sim \sqrt{\frac{\lambda}{a}} \sim \sqrt{\frac{\rho R^2\lambda^2}{\varepsilon\gamma}}$$

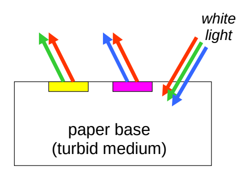
$$L \sim v\tau \sim \sqrt{\frac{\rho v^2 R^2\lambda^2}{\varepsilon\gamma}} \sim const\sqrt{\frac{\rho v^2 R}{\gamma}} \sim We^{1/2}$$

F – force
a – acceleration
τ – break-up time
L – length traveled for time τ

Digital image reproduction



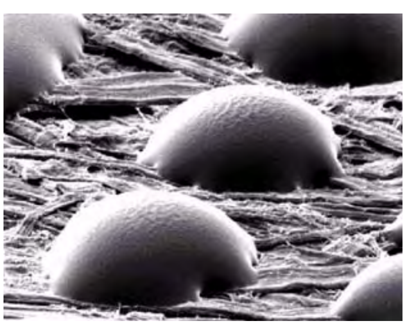
720 dpi, e.g. Epson Stylus



Possible physical problems:

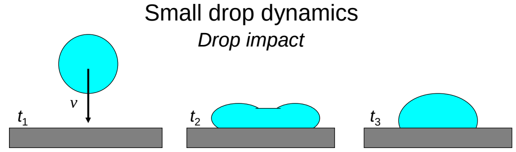
- Refraction and diffraction in an anisotropic stochastic medium
- Rayleigh scattering
- Fluorescence
- Heat transfer

Ink-media interactions



Small drop dynamics

Drop impact



$$\frac{E_{kin}}{E_{surf}} = \frac{R^3\rho v^2}{R^2\gamma} \sim \frac{R\rho v^2}{\gamma} \equiv We$$

$$\frac{E_{kin}}{E_{visc}} = \frac{R^3\rho v^2}{\eta\times\frac{v}{R}\times R^2\times R} \sim \frac{R\rho v}{\eta} \equiv Re$$

$$\frac{E_{pot}}{E_{surf}} = \frac{R^3\rho g R}{R^2\gamma} \sim \frac{\rho g R^2}{\gamma} \equiv Bo$$

(v, R, η, g, γ)

$$Ca \equiv \frac{E_{visc}}{E_{surf}} = \frac{E_{visc}}{E_{kin}}\frac{E_{kin}}{E_{surf}} = \frac{We}{Re}$$

$$Fr \equiv \frac{E_{kin}}{E_{pot}} = \frac{E_{kin}}{E_{surf}}\frac{E_{surf}}{E_{pot}} = \frac{We}{Bo}$$

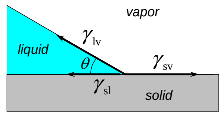
Small drop dynamics

Drop spreading

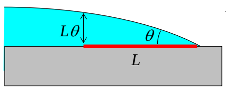
✓ Spreading force

$$\gamma_{\mathrm{sv}} - \gamma_{\mathrm{sl}} = \gamma_{\mathrm{lv}} \cos\theta$$

$$\frac{F}{\text{unit length}} \sim \gamma_{\mathrm{lv}}[\cos\theta_{\mathrm{eq}} - \cos\theta(t)]$$



✓ Useful asymptotic relations for the case of complete wetting:



$$L\eta\nabla v = \gamma_{\mathrm{lv}}(1-\cos\theta)$$

$$\nabla v \simeq v / L\theta$$
$$\cos\theta \simeq 1 - \theta^2/2$$
$$V \simeq \tfrac{1}{4}\pi r_{\mathrm{b}}^3\theta$$

$$v \sim \frac{\gamma_{\mathrm{lv}}\theta^3}{\eta}; \quad r_{\mathrm{b}}(t) \sim t^{1/10}; \quad \theta(t) \sim t^{-3/10}$$

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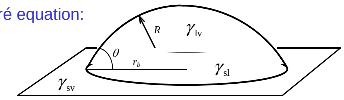
Wetting control

Young-Dupré equation:



$$E = E_{\mathrm{lv}} + E_{\mathrm{sl}} + E_{\mathrm{sv}}$$
$$E_{\mathrm{lv}} = \gamma_{\mathrm{lv}} S_{\mathrm{lv}} = 2\pi R^2 \gamma_{\mathrm{lv}}(1-\cos\theta)$$
$$E_{\mathrm{sl}} = \gamma_{\mathrm{sl}} S_{\mathrm{sl}} = \pi R^2 \gamma_{\mathrm{sl}} \sin^2\theta$$
$$E_{\mathrm{sv}} = \gamma_{\mathrm{sv}} S_{\mathrm{sv}} = const - \pi R^2 \gamma_{\mathrm{sv}} \sin^2\theta$$

$$R(\theta) = \sqrt[3]{\frac{3V}{\pi(2 - 3\cos\theta + \cos^3\theta)}}$$

$$\min_{\{\theta\}} E\big|_{V=const} \Rightarrow \cos\theta = \frac{\gamma_{\mathrm{sv}} - \gamma_{\mathrm{sl}}}{\gamma_{\mathrm{lv}}}$$

Effect of surfactants on wetting:

$$\cos\theta(c) = \frac{\gamma_{\mathrm{sv}} - \gamma_{\mathrm{sl}}(c)}{\gamma_{\mathrm{lv}}(c)} = \frac{\gamma_{\mathrm{sv}}^0 - \gamma_{\mathrm{sl}}^0 + k_{\mathrm{B}}T\int \Gamma_{\mathrm{sl}}(c)\,\mathrm{d}\ln c}{\gamma_{\mathrm{lv}}^0 - k_{\mathrm{B}}T\int \Gamma_{\mathrm{lv}}(c)\,\mathrm{d}\ln c}$$
$$= \cos\theta(0)\left\{1 + \frac{k_{\mathrm{B}}T}{\gamma_{\mathrm{lv}}^0}\int_0^c [\Gamma_{\mathrm{sl}}(c) + \Gamma_{\mathrm{lv}}(c)]\,\mathrm{d}\ln c + \ldots\right\} > \cos\theta(0)$$

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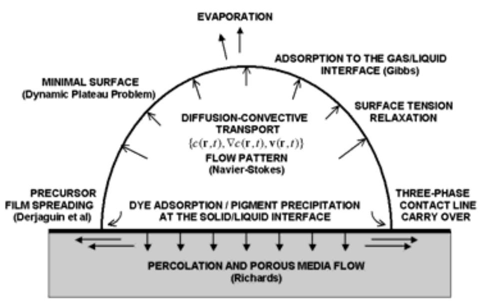
More physics for dedicated folk

Isn't it here that the physics and chemistry merge?



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