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TEACHING PHOTOGRAPHY: INTERPLAY BETWEEN CHEMICAL KINETICS AND VISUAL ART

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ABSTRACT: This paper proposes photography experiments, which appeals to interdisciplinary teaching, where an effort is made to reveal the interactive relationships among two different fields, science and art. Such teaching can follow an interplay between chemistry and visual art establishing a relation between the appearance of a photographic image and the rate of a chemical reaction. The appearance of a photographic image is related to its *contrast*, which actually expresses the number of gray tones existing between absolute black and absolute white, and the chemical reaction is the reduction of silver halide to metallic silver. This interplay involves the two levels of representing matter: the microscopic and the macroscopic level. The macroscopic level that concerns visual art can be understood in relation to a chemical kinetic effect at microscopic level. Teaching photography within an Art Science frame provides the context for introducing chemical kinetics and studying the factors affecting the rate of a reaction. [*Chem. Educ. Res. Pract.*: 2003, 4, 55-66]

KEY WORDS: *chemical kinetics; photographic chemistry; silver halide reduction; photography; characteristic curve of negative film; contrast of an image; visual art*

INTRODUCTION

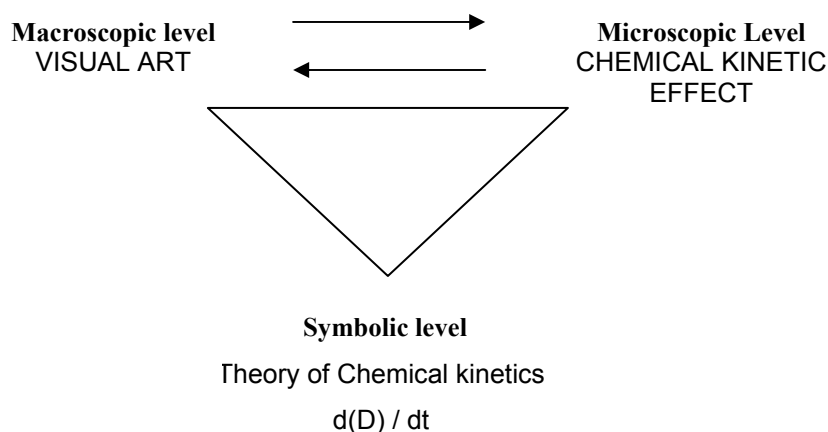
The post-modern point of view of cultural values, moral, aesthetics and scientific progress is based on positivist and reductionist approaches (Oliver, 1989). These approaches have affected education and have imposed a tradition, which views the various types of knowledge of different disciplines as having an antagonistic relation, and that leads to the fragmentation of knowledge and disintegration of meaning. In addition, the increasing need for specialization produces narrow views instead of holistic awareness of how the part fits into the whole. The strong commitment to disciplinary strength in chemistry or physics teaching has resulted in failing to develop links between science and social / life science or Art. On the other hand, research in science education has shown that there is a need for fostering interdisciplinary teaching approaches to provide learners with appropriate knowledge for dealing with the contemporary society's problems. (Zoller, 2000). Although most curricula follow the transitional way, there are some exceptions, where an effort has been made to focus specifically on the interactive relationship among Science, Technology, and Society (STS). The goals of these STS programs are to emphasize the social implications of the development of science and technology (McFadden, 1991). No matter how clear the educational goals and teaching objectives might be, a practical issue of a great importance

arises. That is, how to translate these objectives in a STS-oriented course into teaching strategies and assessment methodologies.

Concerning chemistry education, research has revealed the existence of barriers to learning basic concepts of the subject with direct implications on teaching. Those difficulties lie in the intrinsic nature of the subject as well as in human learning. In teaching, the complexity of chemistry arises from a threefold representation of matter that instructors employ. (Johnstone, 1982, 1991). Chemists can represent matter and describe chemical phenomena in three levels: the macroscopic, the microscopic, and the symbolic level. The first level, the *macro* level is the one observable by our senses. The second is the *sub micro* level of atoms and molecules, and the third is the representational use of symbols and mathematics. Even though experts can think at all levels, novice and learners have difficulty to connect these three representations. It has been pointed out that it is psychological folly to introduce learners to all three levels simultaneously because herein lies the origin of the students' alternative ideas and misconceptions (Gabel, 1999; Johnstone & Selepeg, 2001). However this concerns introductory chemistry teaching.

On the contrary, at a higher educational level, a switch or interplay between these levels of representation or levels of thought can serve as a teaching tool to create links between disciplines. Chemistry is usually taught with a strong commitment to its disciplinary strength. Fine Arts, on the other hand, are taught as a separate discipline having its own core-elements and its own defined boundaries. Contemporary Art is usually closely related to technology applications and artists need to understand science to an adequate level. Thus, links between these two disciplines would reveal an interactive relationship.

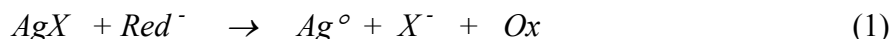
This paper provides a paradigm of conceptual connection between chemical kinetics and image formation. It provides an interdisciplinary teaching (Stamovlasis, 2001a) that can follow interplay between chemistry and visual art establishing a relation between the appearance of a photographic image related to its *contrast*, and the rate of a chemical reaction. This interplay involves the microscopic and the macroscopic level of representing matter. (Scheme 1). The macroscopic level that concerns visual arts can be understood in relation to a chemical kinetic effect at microscopic level. In addition teaching photography provides the context for introducing chemical kinetics and studying the factors affecting the rate of a reaction (Stamovlasis, 2001b).



SCHEME 1. The threefold representation of matter (Johnstone, 1991) in the interplay between chemical kinetics and Visual Art.

CHEMISTRY OF PHOTOGRAPHY

The black and white (*B/W*) photographic image as perceived is created by variation in the absorption of light in the photosensitive *AgX* emulsion, corresponding to the quantity of metallic silver *Ag* formed after exposure and development. When a photographic material is developed, those silver halide crystals, which have been exposed to light and bear a latent-image centre, are reduced to metallic silver *Ag* by a reducing agent:



where *Red⁻* is the developing or reducing agent, and *Ox* is its oxidized form. The developing or is an alkaline solution of hydroquinone, which is oxidized to quinone (Eaton 1957).

The amount of metallic silver formed on a developed transparent emulsion can be estimated by measuring its optical density, $D = -\log(I_0/I_t)$. (Lambert-Beer Law). Where I_0 is the radiant flux incident on a developed transparent emulsion and I_t is the radiant transmitted after absorption. The growth rate of the optical density $d(D)/dt$, can account then for the rate of increase of the concentration of metallic silver, keeping the amount of the absorbed light constant. The amount of the absorbed light is measured by the *Exposure H*, defined as $H = E * t$ (in lux*sec), where t is the exposure time in seconds.

The growth rate of the optical density is described according to the following equation:

$$\frac{d(D)}{dt} = K(D_\infty - D)$$

where D_∞ is the optical density after infinitely long development and K is a rate constant given by

$$K = k[Re dH]^a [OH^-]^b$$

where k is another rate constant and a and b are exponents with values between 0 and 1 (James, 1957). The exponents a and b have been determined under widely varying development conditions (Keller, 1992). The principal factors governing the development kinetics of a photographic emulsion are: 1) The size and the nature of the emulsion (grain size, packing density, contents of photosensitive material *AgX*, etc.). 2) The concentration and the nature of the developing solution (acceleration, restrainers, sulphide, pH, etc.). 3) The exposure conditions (intensity of light). 4) The temperature of development.

Thus the developing procedure can provide a context for a lot of experimental work and problem solving (Stamovlasis, 2000, 2001). In addition it serves as a teaching tool to demonstrate the effect of various factors on the rate of an heterogeneous reaction, that is, in our case how the above factors affect the growth rate, $d(D)/dt$, of the optical density D . In practical photography it is useful to find a convenient way of converting relative exposure differences into density differences. For that reason, within the normally exposed region, another parameter is defined, which is discussed in the following section.

EXPERIMENTAL PART 1: DEMONSTRATION OF THE KINETIC EFFECT

The purpose of the experiments is to demonstrate how factors, such as the amount of absorbed light, the development temperature and the concentration of reducing agent, affect the rate change of the optical density $d(D)/dt$. The experimental is the standard procedure of obtaining sensitometric data. (Keller, 1993; Stamovvlasis, 2000). The procedure could be divided into three steps: The exposure, the development and the optical density measurements.

The experimental data were limited in the range applied in the everyday practical photography. Temperature was limited also since above 30 degrees Celsius the photosensitive emulsion carrier (gelatin) is greatly affected. The calculation of the activation energy was conducted in the region of temperature studied.

Film-exposure

A negative B/W photographic film is placed in a camera facing a light source. Let the photometer indication be $V = 16$ relative units of exposure. This is the normal exposure. *The effect of exposure condition* is studied by varying the amount of light absorbed by the emulsion. This is controlled by the aperture or shutter speed. Table 1 shows the exposure units relatively to the normal exposure V . Short film strips are exposed to different light conditions and they are developed at the chosen conditions (temperature and/or concentration of reducing agent) for various developing times (from 3 to 10 minutes).

TABLE 1. Relative units of exposure. V is the normal exposure (photometer indicator).

	1	2	4	8	V 16	32	64	128	512
Exposure, H									
Log of Exposure Log (H)	0	0.3	0.6	0.9	1.2	1.5	1.8	2.1	2.3
Stop difference from V	-4	-3	-2	-1	0	+1	+2	+3	+4

NOTE: Let the photometer indication be $V = 16$ relative units of exposure, then one stop difference from V is the next aperture setting that permits double or half amount of light to pass through.

Film-development

The film is developed under the chosen conditions of temperature, developing time and concentration of reducing agent with the tank method. One can follow the instructions given by any film manufacturer. Note that agitation during development is important and should always follow the same method in order to obtain reproducible results. In addition, a temperature-control unit for solution-temperature regulation is necessary. The films must be washed and dried and the optical densities of the various exposures are measured.

Optical-density measurement: The optical density is measured by a densitometer.

Data treatment

The measured densities, the corresponding exposure units, and the development conditions (reducing-agent concentration, development time and temperature) are the data to be analysed. The experimental data can be recorded, tabulated and plotted. From the graphs of optical density D versus development time t , the slope can be obtained giving the rate $d(D)/dt$. Subsequently the values of the slopes $d(D)/dt$ can be plotted against the various factors. The data presented in Figures 1, 2, 3 and 4 are from experimental work on a negative B/W Kodak TMX100 film, treated with TMX-developer and fixed with Kodak T-fixer (Boas, 1988).

Specifically, Figure 1 shows the effect of exposure conditions: the growth rate $d(D)/dt$ of the optical density D is plotted versus the logarithm of Exposure [$\text{Log}(H)$] at 20 °C and constant concentration of the reducing agent (20% v/v). The rate $d(D)/dt$ increases with $\text{log}(H)$.

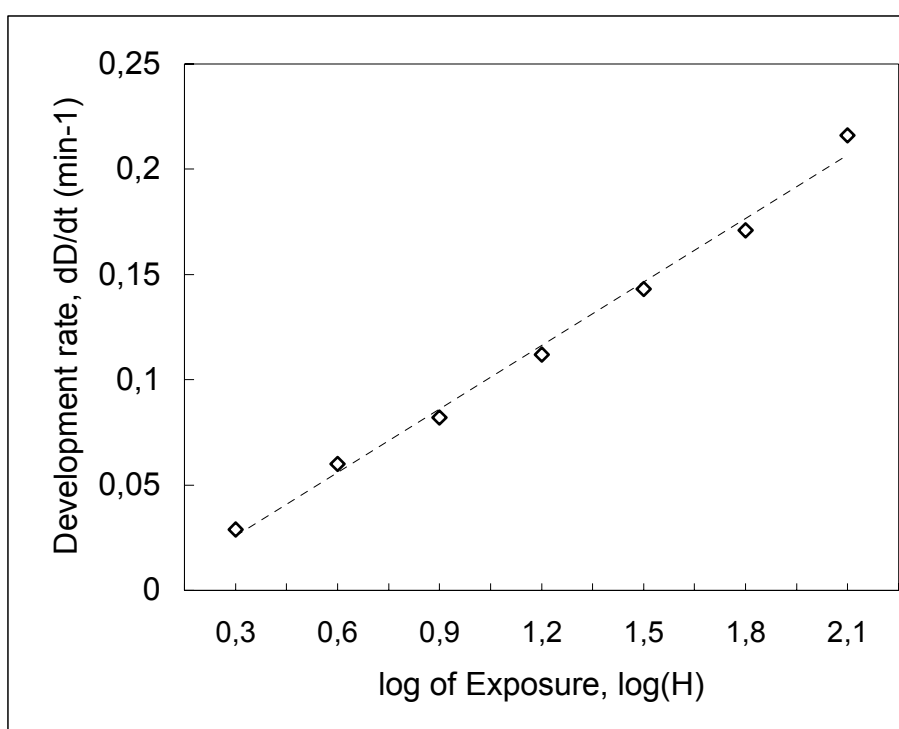


FIGURE 1. The development rate dD/dt versus the logarithm of exposure, $\text{log}(H)$, at 20 °C and constant concentration of the reducing agent (20% v/v).

Figure 2 shows the effect of development temperature. The growth rate $d(D)/dt$ of the optical density D is plotted versus the development temperature for fixed exposure [$\text{Log}(H) = 1,2$] and constant concentration of the reducing agent (20% v/v). The rate $d(D)/dt$ increases with increasing temperature.

Calculation of the activation energy (E_a)

The rate of the reaction is related to the activation energy (E_a) by the expression (Benson, 1982):

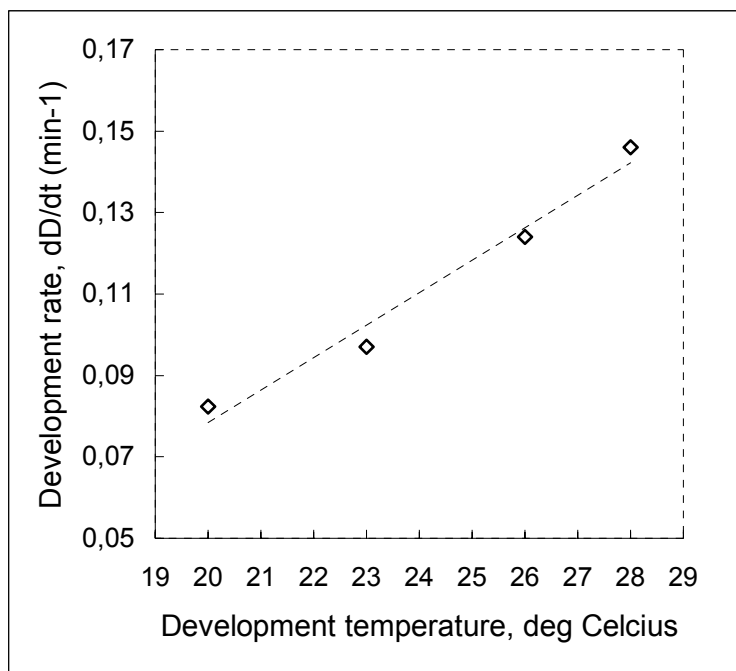


FIGURE 2. The development rate dD/dt versus development temperature, for exposure $\log(H) = 1,2$ and constant concentration of the reducing agent (20% v/v).

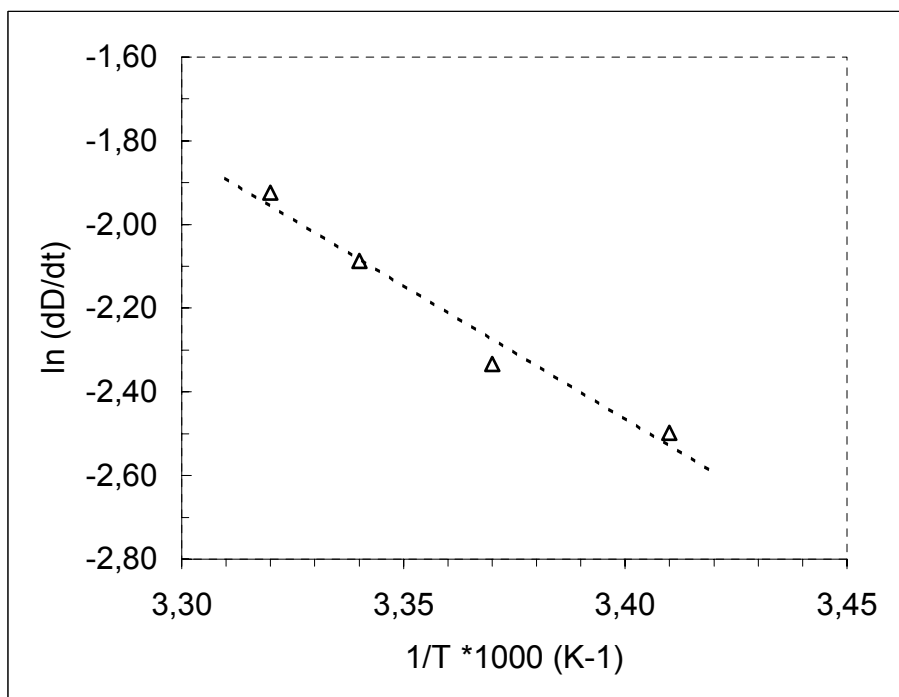


FIGURE 3. The $\ln(dD/dt)$ versus $1/T$. T is the temperature in Kelvin ($^{\circ}\text{K}$). The activation energy of the reaction can be calculated from the slope of the graph ($-E_a/R$).

$$dD/dt = Z \exp(-E_a/RT) \text{ or } \ln [dD/dt] = \ln Z - (E_a/R)[1/T]$$

By plotting $\ln(dD/dt)$ versus $1/T$ from the data of Figure 2 we obtain a straight line (Figure 3) with intercept the \ln of a constant (Z) and slope $-E_a/R$ from which the activation energy is calculated. Appendix A shows the statistics of the regression line and the calculations. The calculated value of the Activation Energy is 53,0 kJ/mole.

Figure 4 shows the effect of the concentration of the reducing agent. The plotted data correspond to experiments carried out at a fixed exposure condition [$\log(H)=1.2$] and constant temperature (20°C), with varying the reducing-agent concentration. The concentration of the reducing agent is expressed in % v/v (ml per 100 mL total developing solution). The rate $d(D)/dt$ increases with increasing the concentration of the reducing agent.

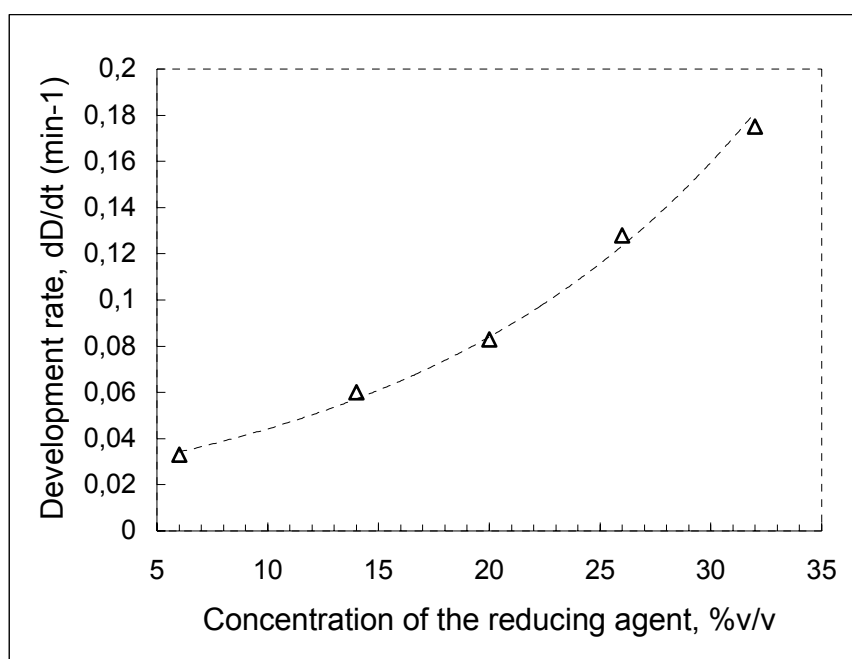


FIGURE 4. The development rate dD/dt versus concentration of the reducing agent, for exposure $\log(H) = 1.2$ and temperature 20°C

In addition to the above experiments, other experiments could also be carried out by varying other factors, such as the length of the filmstrip, which in kinetic terms represents the contact area, the nature of the emulsion by choosing different film, or the pH of the solutions.

Figures 1, 2 and 4 represent the effect of the exposure conditions, development temperature and concentration of the reducing agent, on the growth rate of optical density $d(D)/dt$, which accounts for the rate of the silver halide reduction to metallic silver. Thus the optical density difference between two parts of the photograph depends not only on the luminance-difference between the two corresponding parts of the scene, but also it depends on a kinetic effect during development. That kinetic effect has an impact on the appearance of the image, and that will be understood in the next section and can be visualised with the next experiment.

A mathematical aspect of visual art

An important feature of a photographic image is its *contrast*. The concept of *contrast* is related to the number of grey tones existing between absolute black and absolute white. The control of contrast serves as artistic expression. In determining how to record a scene, a photographer must decide whether the scene would be more appropriately portrayed as high contrast, low contrast, or somewhere in between, in the so-called normal range. Thus he should modify accordingly the camera settings, the developing procedures (kinetic effect) or both in order to control contrast. In black/white photography contrast is one of the foremost variables in the medium and one that has a great influence on the emotional impact of the picture.

“...Low-contrast images contain a closely grouped narrow range of tones and present all information on a more-less equal basis. They can impart a calm, moody and static atmosphere. On the other hand in high-contrast images details are eliminated by deep shadows or glaring highlights. They may relate a sensation of activity, intensity and strictly confine the viewer’s attention to critical scene elements.” (Taylor, 1987).

In mathematical terms *contrast* is defined as the slope *gamma*, γ of the linear portion of the characteristic curve (Figure 5) of the photographic film, which is obtained by plotting the optical density D , versus the logarithm of exposure $H = E * t$.

$$\gamma = dD / d(\log H)$$

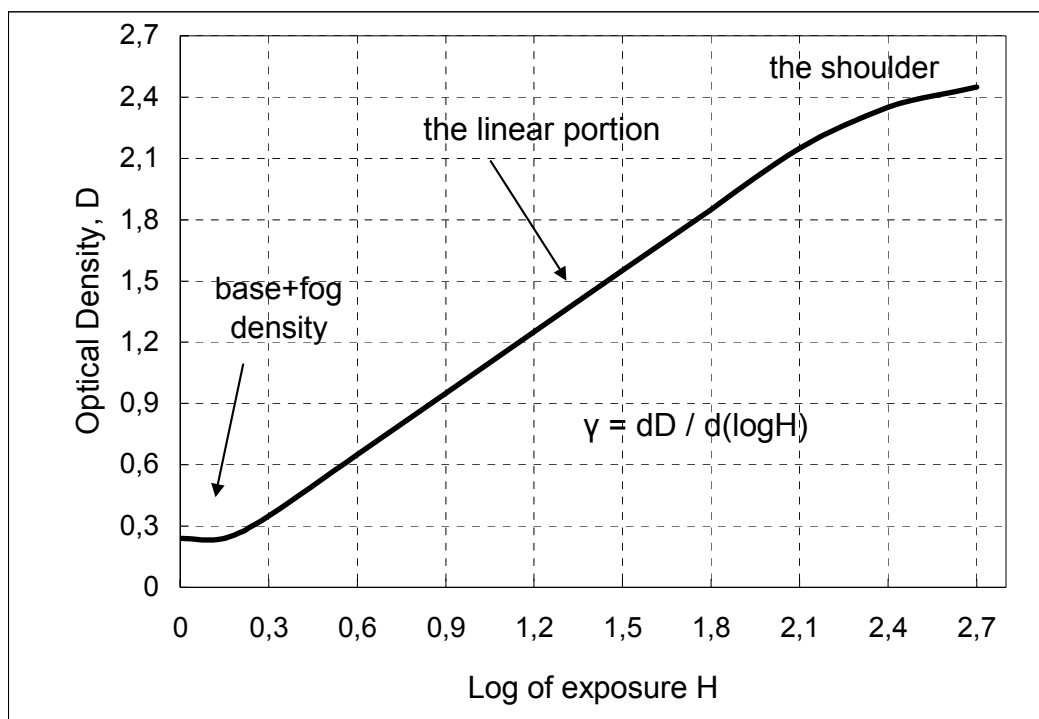


FIGURE 5. A characteristic curve of a photographic film.

The graph in Figure 5 is known as the *Hurter & Driffield (H & D) curve* (Hurter, 1890; Keller, 1993). *Gamma* corresponds to the normally exposed region and it is a measure of how relative exposure differences are transformed into density differences or density contrasts. *Gamma* provides an alternative way of studying the development rate of emulsions.

EXPERIMENTAL PART 2: DEMONSTRATION OF THE CONTROL OF THE IMAGE CONTRAST

The experiments that follow are development procedures at constant time and demonstrate how the development temperature and the concentration of the reducing agent can affect the parameter *gamma* and as a result the appearance and the aesthetic of the image. *Gamma* is a measure of how relative exposure differences are transformed into density differences or density contrasts, and it is related to development rate of the photosensitive emulsion. Thus we can create a link between the macroscopic appearance of the photographic image and the kinetic nature of the process creating that.

Part A. The exposure and development procedure is the standard procedure described in experimental Part 1. A negative B/W photographic film is placed in a camera facing a light source. Let the photometer indication be $V = 16$ relative units of exposure. This is the normal exposure. Eight additional exposures are taken, by controlling the aperture or shutter speed. Four exposures from one to five 'stops' differences above the normal exposure V , and four exposures from one to five 'stops' differences below the normal exposure V (see Table 1). A number of such filmstrips are exposed using this method. The films are developed at constant time (e.g. 6,5 min), under various conditions of temperature and concentration of the reducing agent. Figure 6 represents high and low contrast filmstrips. Then, for each frame the optical density is measured. When these optical densities are plotted against the logarithm of exposure, the slopes of the characteristic curves vary. The negatives can be classified relatively to a conventional normal contrast ($\gamma = 0,52$), as high or low contrast (Figure 7)

Part B. The same experiment of constant development can be carried out with two pictures of the same scene taken under the same exposure conditions but developed at different conditions by varying the development temperature and/or concentration of the reducing agent. Results are shown in Figure 8.

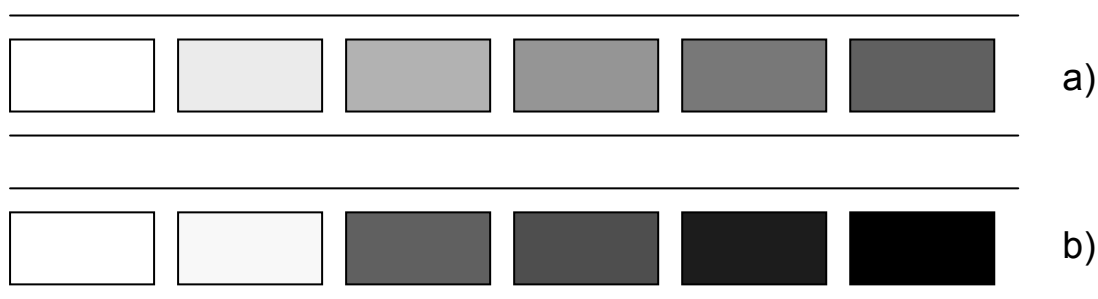


FIGURE 6. a) Low contrast filmstrip; b) high contrast filmstrip.

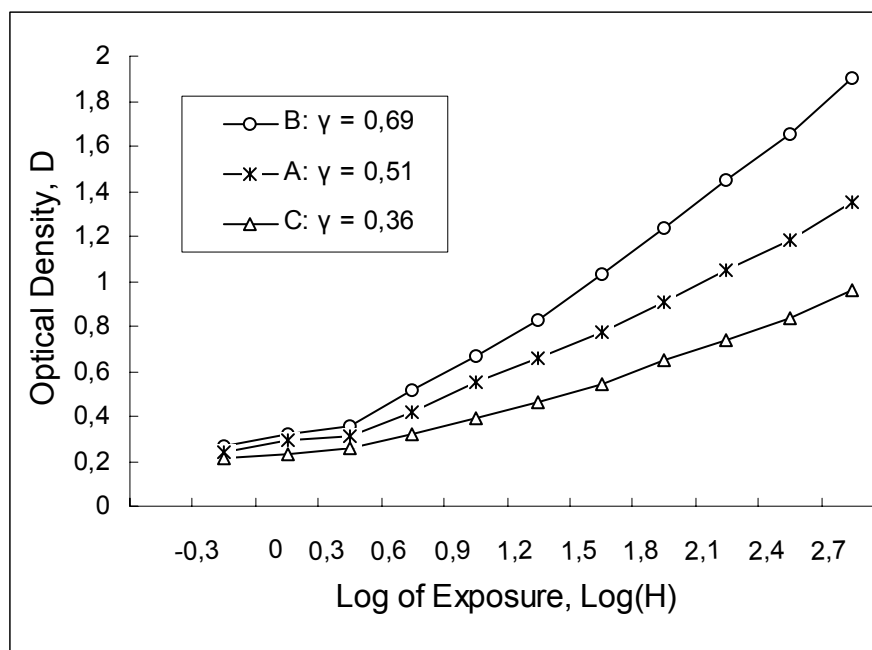


FIGURE 7. Plot of D versus log of exposure for low (C) and high (B) contrast B/W negative photographic films: A) Development time 6 min, development temperature 20 °C, and concentration of reducing agent 20% v/v. B) Development time 6 min, development temperature 26 °C, and concentration of reducing agent 20% v/v. C) Development time 6 min, development temperature 20 °C, and concentration of reducing agent 12% v/v.

SUMMARY AND CONCLUDING REMARKS

The goal of this presentation of constant time development procedures (experimental Part 2) was to present the kinetic nature of the image formation within an educational context. In practical photography, all the above factors affecting the development kinetics of a photographic emulsion are kept constant and the only variable is the development time.

We presented an application of photography experiments, which appeals to Art Science or STS curricula, but also to chemistry teaching within an interdisciplinary approach. The experiments introduce concepts of chemical kinetics and explore the factors affecting the rate of a heterogeneous chemical reaction, that of silver halide reduction. The proposed work gives also to the instructor the opportunity to introduce sensitometry and photographic chemistry. The film developing procedure can provide a context for experimental work and problem solving (Stamovlasis, 2001a). On the other hand the theme involves Visual Art aspects that concern the appearance of an image related to its *contrast*. Thus the instructor can integrate chemical kinetic concepts within an Art frame following interplay between Science and Visual Art (Scheme 1). This interplay involves the microscopic and macroscopic level. The macroscopic level that concerns Visual Art can be understood in relation to a chemical kinetic effect at microscopic level. In addition a connection with the symbolic level is made by involving the mathematical expression, which corresponds to a macroscopic property that of image *contrast*. Figure 8 shows two different macroscopic views of the same scene as a result of the kinetic effect. These pictures result at two different temperatures and/or with two different concentrations of the developing solutions (all other parameters kept constant).

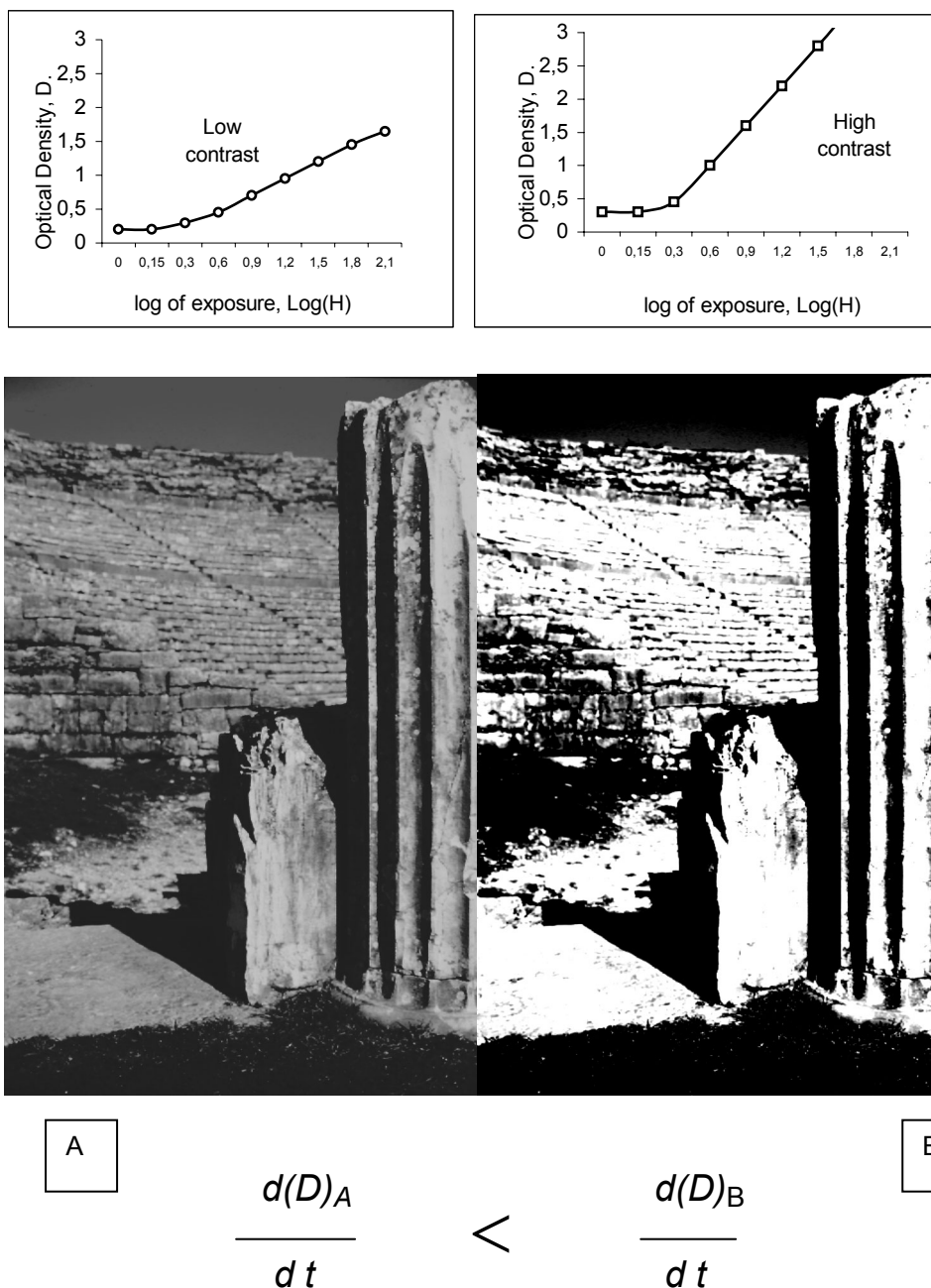


FIGURE 8. The two pictures A and B produced at the same development time have different *aesthetics*. Picture B demonstrates different *contrast*, a macroscopic property due to a kinetic effect at microscopic level. The rate of the silver reduction in picture B was greater, implying that the development temperature or/and the concentration of the reducing agent were higher.

Concluding, the current presentation draws patterns that connect Science and Visual Art; on the other hand provides supporting material in chemistry teaching. Such an interdisciplinary approach reveals the interactive relationships among different fields and makes a contribution towards the reduction of knowledge fragmentation.

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APPENDIX: MATHEMATICAL CALCULATIONS RELATED TO THE ACTIVATION ENERGY

The following Table provides statistical data for the regression line $Y=a*X +b$ (Figure 3).

Dependent variable Y. Loss=(OBS-PRED)**2		
Final Loss=0.00196, R=0.9949		
Parameter	a	b
Estimate	-6381.4	19.26
Std.Error	455.5	1.53
t	-14.00	12.57
p-level	0.005	0.006

It follows that $-E_a/R = -6381.4$ °K. Hence, the calculated value of the activation energy is $E_a = 53.0$ kJ/mol.

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