The Invention of Mountable Camera Device for Photo Taking of Light Spectra Diffracted from Grating

Buncha Silskulsuk*, Thanikan Sritonwong and Arunee Intasorn

Department of Physics, Faculty of Science, Srinakharinwirot University, Bangkok Thailand

Abstract

The device is consisted of five simple convex lenses with various focal lengths, a collimator system, a transmission grating and a CMOS (Complementary Metal Oxide Semiconductor) detector in DSLR (Digital Single Lens Reflex) camera. They are mounted on optical bench covered with PVC horizontal cylinder which is portable. The obtained images stored as .jpeg file format are transferred from camera to PC for data acquisition and analysis. This work shows how to invent the device which light color spectral image can be displayed together with the quantitative values of the light intensity analysis. The obtained results of wavelength values compared with the standard ones are in the range from 0.03% to 1.55%. The benefits of this device are the provision of light color spectral images from experiments to support the observations and analysis of diffraction color spectra in optical experiments, and it can be utilized as a teaching media as well.

Keywords: CMOS sensor, transmission grating, Fraunhofer diffraction pattern, spatial light intensity distribution analysis, light color spectral display.

1. Introduction

According to study the optical phenomena in physics, there are many methods and instruments for recording measurement data. Generally in laboratories; the expensive and large instruments are available, whilst the portable ones will be useful and easy for setting the experiments in class. Moreover conventional optical experiments are normally observed using a display on a projection screen without permanent records, and without obtainable exact quantitative values of light intensity. Therefore this work is focused on an invention of a portable and low cost device that light color spectral images can be taken and also the spatial intensity distribution of light can be computerized analysis. The advantage of this device is to be used conveniently by mounting theset to DSLR (Digital Single Lens Reflect) camera without any recalibration. Then one is able to hand-hold this device for photo taking. Grating is an important optical element which has been used widely for spectroscopy investigation [1]. Diffraction patterns from gratings are usually described by the rigorous diffraction theory [2]. The differential equations have to be solved with

* Corresponding author: Tel: 081-4999350 Fax: 0-2469-5598

E-mail: buncha@swu.ac.th

grating surface as boundaries to obtain the diffracted electromagnetic fields. Our main goal is to be able to display visible light diffraction patterns obtained from transmission grating and to analyze the spatial intensity distribution of light peaks. Additionally, the device is well equipped with something commonly available in markets which will be useful for teachers and their pedagogical experiments.

Gao *et al.* [1] analyzed diffraction properties of the transmission phase grating in terms of the Fourier optics theory. The diffraction angle corresponding to each diffraction order can be calculated. Their results show that diffraction intensity distribution of the transmission phase grating is not only determined by the grating period and slit width, but also closely related to the optical thickness of the grating and the wavelength of incident light. Their experiments used the lens of 28 mm focal length, the CCD (Charge-Coupled Device) and bromine-tungsten lamp as a white light source and also a frequency stable He-Ne laser as the monochromatic light source. The results show that, for monochromatic incident light, more than 80% of the diffraction energy will concentrate to first diffraction order under certain condition that the zero diffraction order vanishes depending on the grating thickness, and for white incident light, the energy of the first order of diffraction spectrum may be much higher than other orders. In 2007, Ramil *et al.* [3] introduced a simple methodology employing digital photography and image processing techniques to do a quantitative study of diffraction patterns from a single slit, a double slit and a circular hole. They recorded the intensities by using a CCD camera without saturation.

In 2009, Stich *et al.* [4] presented a novel approach for signal separation of multiple sensors, based on the fundamental setup of color cameras. It utilizes the basic setup of color CCD and CMOS (Complementary Metal Oxide Semiconductor) cameras. CMOS integrated circuits are inherently monochromatic (black and white) devices [5]. Color is detected either by passing the incident light through a sequential series of red, green and blue filters, or with miniature transparent polymeric thin-film filters that are deposited in a mosaic pattern over the pixel. Then each of three different types of pixels or layers sensitive towards different wavelength ranges. The different colors are absorbed and detected in different layer and then the information is transported in three distinct channels (one for each color) and recombined, resulting in a color image. CMOS sensors used for photons detection are organized as arrays of photodetectors that deliver an electric signal related to amount of photons that fall on the pixel surface during the integration time [6]. It uses the photoelectric effect in silicon, in either a photogate or a photodiode detector. Most of CMOS sensors operate in charge integrating mode, and both photogate and photodiode can be used for photon detection. The effective integrated electron charge is translated into a voltage signal that can be measured. The measured voltage is then passed through an analog-to-digital converter, which forms a digital electronic representation of scene imaged by the sensor. CMOS detectors have intrinsic advantages, i.e., low power consumption, readout rate, noise, radiation hardness, integration capability, that make them well suited for several applications.

2. Materials and Methods

2.1 Design and Experiments

Grating of 500 grooves per millimeter (N: 500 g/mm) is used as beam splitters divided one wave front into many wave fronts based on Huygens-Fresnel principle. The directions of these beams depend on the grating spacing and the wavelength of light so that the grating acts as a dispersive element. In the paraxial approximation, diffracted beams of plane waves are directed at the lens at different angles [7]. These beams are refracted and are focused by the lens into a series of diffraction patterns in the focal plane. Diameter of the lens plays a crucial role in the quality of the image.

DSLR (Digital Single Lens Reflex) camera of K 20D PENTAX with exposure time ranging from 1/4000 to 30 s and consists of CMOS sensor with an active area of 23.40 mm x 15.60 mm, and Flange Focal Distance (FFD) of 45.46 mm was utilized for photo taking. It means that, in order to project the image on CMOS sensor, the distance between position of the lens next to CMOS sensor and position of CMOS sensor must be longer than FFD, and the width of diffraction image must be smaller than 23.00 mm. As we know, whenever a plane wave is incident normally on grating, each slit in grating acts as a point source propagating in all directions. Hence, with geometrical optics study including the adjustment of the system to provide diffracted beam of red light situated in the boundary of an active area of CMOS sensor, a set of 4-lens combination with diameter of 25 mm (L_1, focal length: 50 mm), 50 mm (L_2, focal length: 100 mm), 50 mm (L_3, focal length: 100 mm) and 25 mm (L_4, focal length: 50 mm) are then designed to place next to grating finally. Figure 1 presents geometrical optics method of the arbitrary rays and principal rays [8] to locate images formed by the 4-lens combination.

The layout of the optical device is shown schematically in Figure 2. Hydrogen lamp is used as a calibrated light source of polychromatic beam, whilst Helium lamp is used for the investigation. All PVC ring holders are mounted on optical bench of 30 cm long and covered with PVC horizontal cylinder. When light is exposed into the horizontal cylinder, it is collimated through a collimator system (C) comprised of rectangular slit of 0.08 mm width and a converging lens of 20 mm diameter and 25 mm focal length, providing incident plane wave normally on the grating (G). Owing to the image projection of diffraction pattern on CMOS sensor (14.6 million pixels) in DSLR camera, the part of the camera lens was removed before mounting the camera on the device. The proper exposure time is tuned up with individual light source for provision of sharp displays of first diffraction order of different colors.

The obtained images on CMOS detector stored as .jpeg file format are transferred from camera to personal computer. Data acquisition method is carried out with a program written in VISUAL BASIC VI which the output displays the diffraction spectrum image and the quantitative analysis of spatial intensity distributions (peak-intensity) of diffraction field with the plot of light intensity as a function of pixel column number of the image and then wavelength determinations of each color fringe are performed. In order to readout only output data file, the output data is transferred to Microsoft Excel program and expressed in forms of tables which can be used to determine any relevant parameters manually via Microsoft Excel program for alternative data handling. Flowchart of the analysis procedure of sample data is shown in Figure 3. Each pixel in the array resulted from image digitization is represented by a coordinate-pair in a Cartesian coordinate system, i.e., a pixel located at (300,500) would be positioned where the 300^{th} column and 500^{th} row intersect. A digital image consists of an array of rectangular pixel intensities distributed through simple (x, y) addressing techniques.

2.2 Theoretical Background

In peak-intensity analysis, the maximum peak height intensity of light (I_0) is set to be 1 for the central maximum of diffraction image and thus the diffracted intensity of the m^{th} secondary peak height (I_m) is given by

$$I_m = \frac{\text{Readout the } m^{th} \text{ secondary peak height intensity}}{\text{Readout the central peak height intensity}} \qquad (1)$$

Since pictures must be converted to 8 bit grayscale, which is 256 levels (the grayscale values are in the range from 0 to 255). Both diffraction angle and the peak intensity of each diffraction order

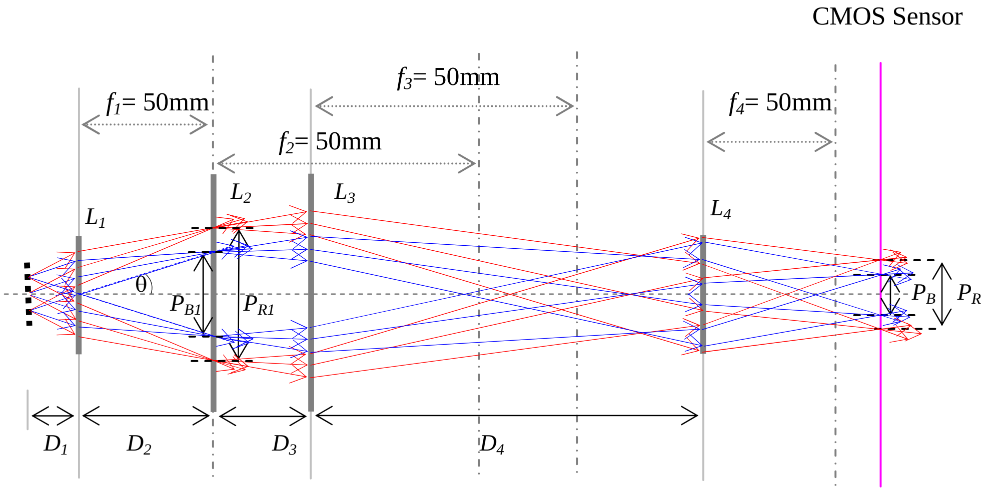


Figure 1 The geometrical optics of image formation for the device.

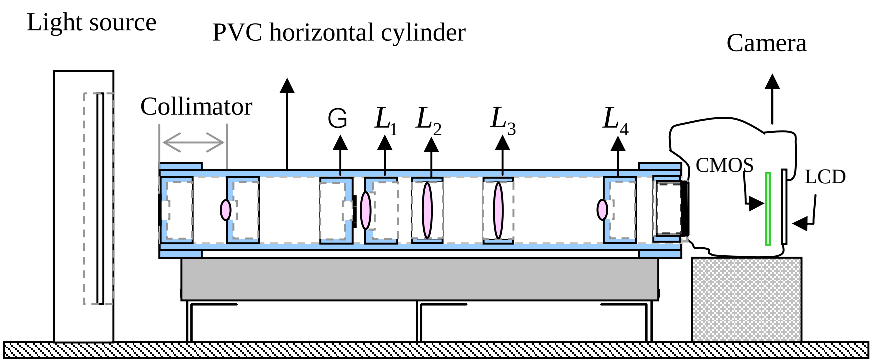


Figure 2 The layout of the device.

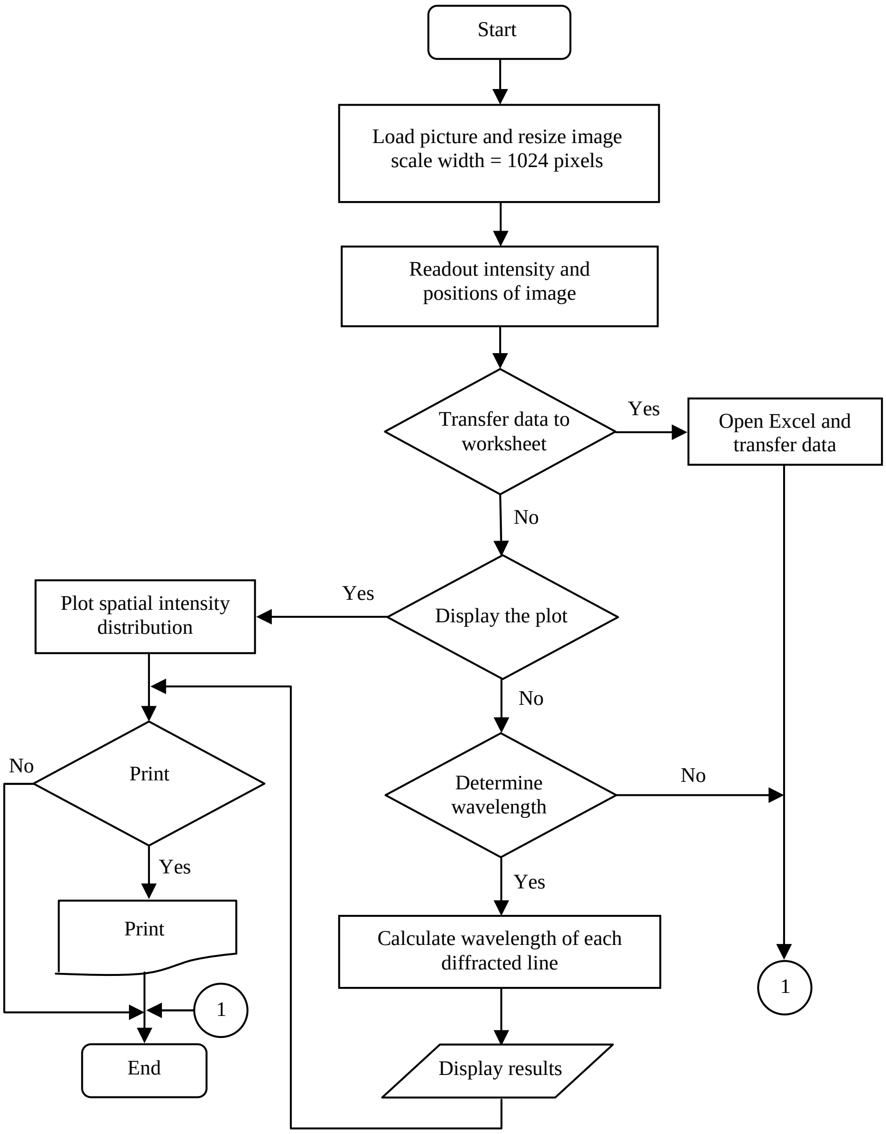


Figure 3 Flowchart for peak-intensity analysis of a digital image.

are wavelength dependence. If a plane wave is incident at an angle θ_i, and θ_m is the diffraction angle for the m^{th} order, the grating equation is

$$d(\sin\theta_m - \sin\theta_i) = m\lambda \qquad (2)$$

Where d = grating period or grating spacing (mm) = 1/ N, and λ = wavelength of incident light. In this study only the first diffraction order of different colors is observed, and the reliability of the device, is determined by analyzing the wavelength of each color with the first diffraction order peaks. For normal incident light, wavelength of the first diffraction order peak can be written as

$$\lambda = d\sin\theta \qquad (3)$$

By using the geometrical study as seen in Figure 1 for the first order diffracted blue color peak, if we started from the lens L_1, it yields

$$P_{1B} = 2f_1\tan\theta \qquad (4)$$

where P_{1B} = distance between both first order diffracted blue color peaks when refracted from lens L_1 and f_1 = focal length of L_1. We, finally, got a distance between both first order diffracted blue color peaks on CMOS sensor (P_B) = $m_2 m_3 m_4 P_{1B}$, where m represents the magnification power of lens. Then

$$P_B = 2D\tan\theta \qquad (5)$$

Here D = $m_2 m_3 m_4 f_1$, hence

$$\sin\theta = \frac{P_B}{2\sqrt{D^2 + \left(\frac{P_B}{2}\right)^2}} \qquad (6)$$

Then

$$\lambda = d\frac{P_B}{2\sqrt{D^2 + \left(\frac{P_B}{2}\right)^2}} \qquad (7)$$

It can be seen that D is proportional to f_1 and image magnification. Whenever the image is resized, D is therefore changed with the same scale. In order to provide D value, Hydrogen light source was utilized to calibrate the value of D expressed in Eqn. (7).

3. Results and Discussion

Figure 4 is a picture of experimental arrangement of the invented device. It can be seen that the whole set of the device closed with its cover is able to be used everywhere as a camera for hand-holding in photo taking of the color light spectrum images. The experimental results of color diffraction spectra of Hydrogen and Helium light sources displayed respectively three and five distinct colors of the first order of Fraunhofer diffraction are presented in Figure 5 for ISO 1600 with exposure time of 6 s and ISO1600 with exposure time of 2 s. They show that peak-separation due to the different colors of the displays express the good results of resolution obtained from the device. Figure 6 shows the plots of light intensity distribution versus pixel column number of diffraction spectra using both light sources. Each peak position of the spatial intensity distribution corresponds to an angle θ of sine function in Eqn. (6). Consequently, the wavelength λ of each peak can be determined from Eqn. (7) with the experimental value of P for

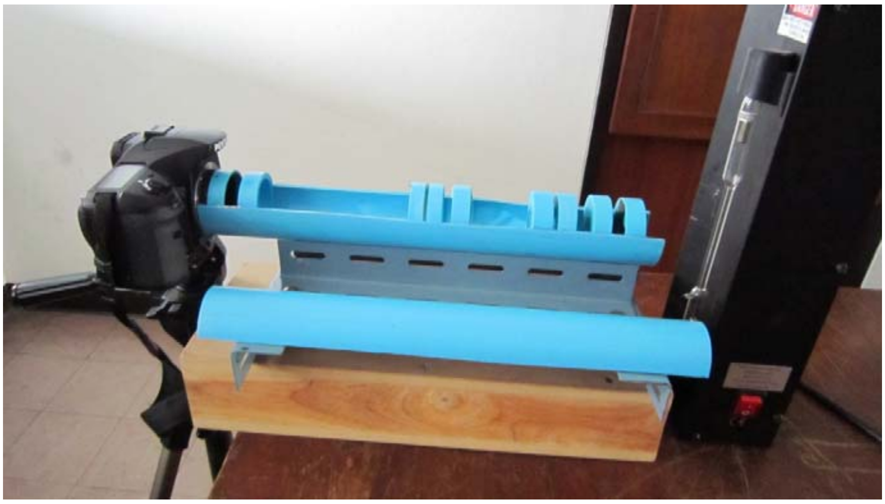
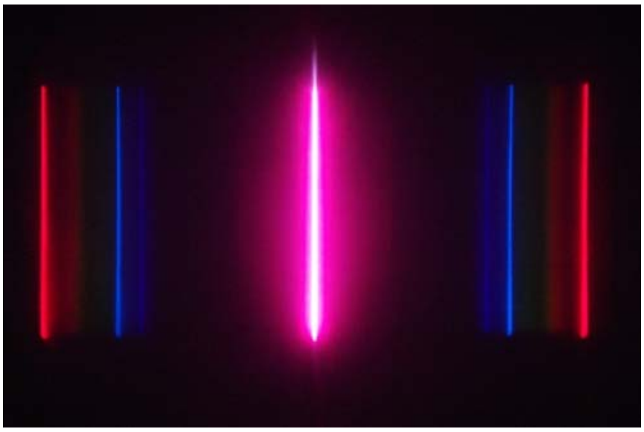
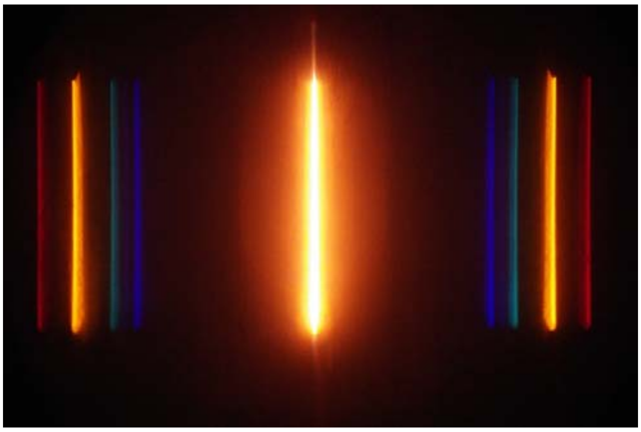


Figure 4 Picture of experimental arrangement of the invented device.

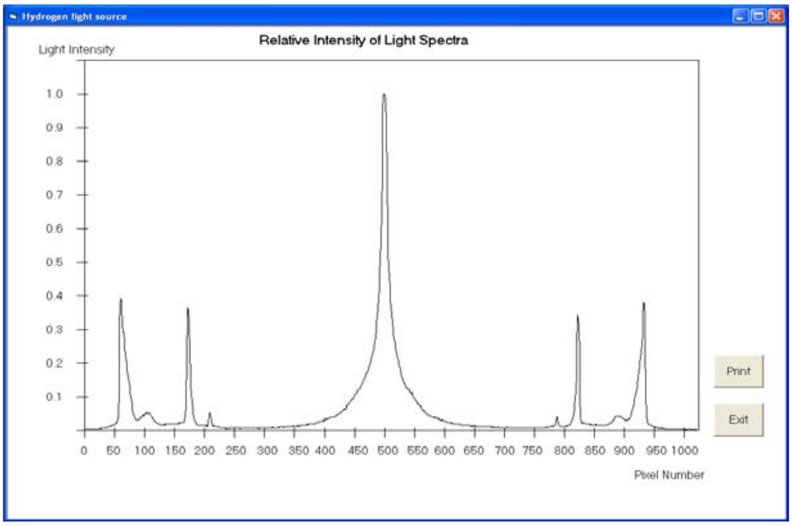


(a)

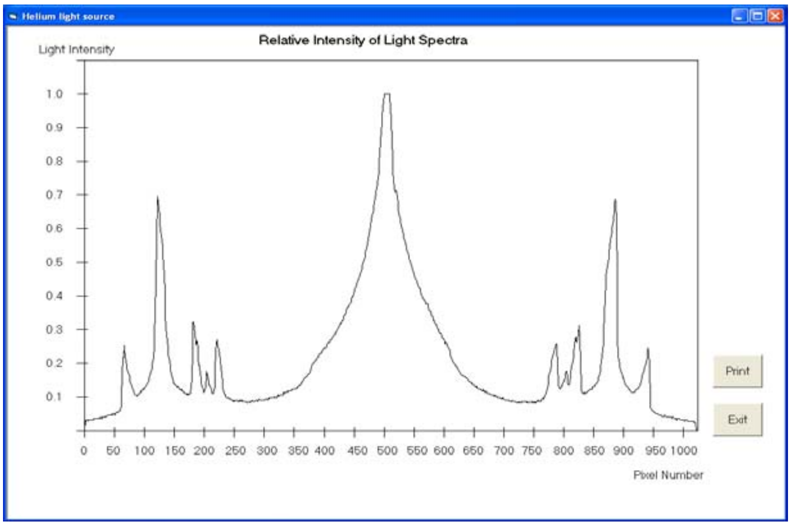


(b)

Figure 5 The diffraction image displays using (a) Hydrogen lamp and (b) Helium lamp as incident light sources.



(6a)



(6b)

Figure 6 Example of the plots between light intensity and pixel number for (a) Hydrogen light source, and (b) Helium light source.

each color fringe. Owing to monitor results of the diffraction studies, the obtained wavelength value of each color is matched to general wavelength information of Helium light sources [9] as reported in Table 1. Moreover, the experimental values of the secondary maxima for diffracted intensity perform the reasonable results of the relative intensity I_1 / I_0. It is noted that, these values are higher than it should be, since the real value of I_0 is over upper limit of this measurement, as a result, the measured value is too low. In addition, the different value of wavelengths between the results and the standard ones are in the range from 0.03 % to 1.55%.

Table 1 Experimental result with Helium lamp as incident light source.

The 1st diffraction order	Relative peak height intensity I_1 / I_0	Half of the distance between two same color lines (pixel number)	λ_{exp} (nm)	λ_{theo} (nm) [9]	% diff
He-dark blue	0.23	288	446.3	447.1	0.18
He- blue	0.15	309	478.6	471.3	1.55
He-green	0.26	325	501.2	501.5	0.06
He-yellow	0.65	386	587.9	587.6	0.05
He-red	0.20	443	668.0	667.8	0.03

4. Conclusions

The results show the good displays of diffracted beams without overlapping of first diffraction order of distinct colors, then this can be summarized that it is possible to focus the spatial intensity distribution in particular order for a given wavelength with good resolution as presented in Figure 6. Importantly this device is able to be used as a portable spectrometer of light in the whole visible range and the spectral images are recorded shortly without time consuming in the alignment and calibration of the system for individual run. In addition it is easy to invent with very low cost equipments which will be suitable as a pedagogical experimental setup in a laboratory course. With the ability of this technique and device of performing all valid experimental results, we would like to recommend developing this methodology for further diffraction study with other experimental conditions or other pedagogical experiments for provision of reliable quantitative data.

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