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Using LEDs as solar cells is a useful tool for teaching about photovoltaic phenomena

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The world faces a global concern of replacing fossil fuels with renewable and clean energy sources due to the harmful carbon emissions that contribute to climate change and the depletion of these non-renewable resources. To combat this issue, there is a worldwide effort to find alternatives to fossil fuels and develop new energy generation technologies. One promising alternative is solar energy, which several countries include as an energy source. While photovoltaic power has been used, expanding knowledge in this area is needed. Educating people about the importance of critical thinking regarding renewable, carbon-free energy technology like solar energy can highlight its significance in the contemporary world. In this study, we use light-emitting diodes (LEDs) to simulate the behaviour of a photovoltaic solar cell when exposed to sunlight and describe the relationships among electrical quantities, such as potential difference, current, and power.

Keywords: LED set as solar cell experiments, Photovoltaic solar cell teaching, Characteristic curves.

1. Introduction

Experiments involving photovoltaic phenomena could provide introductory concepts to students in modern physics, either involving photovoltaic cells [1] or light-emitting diodes [2] (LEDs) and stimulate critical thinking about sustainability issues. On the upside, LED and solar cells are both *p*-*n* junction diodes; LEDs are cheaper, easy to use, and can be used in experiments in almost every unit of a physics course [3, 4], so why does LED not be used in educational experiments that demonstrate the photovoltaic phenomenon?

LEDs are *p*-*n* junction diodes composed of doped semiconductor wafers with different element impurities, as shown in Figure 1.

As with other diodes, the current flows easily from the *p*-side to the *n*-side but not in the reverse direction. Charge carriers, electrons and holes, flow to the junction of the electrodes at different potential differences. When an electron finds a hole, it decays to a lower energy level and releases energy in photons [5].

Manufacturers of these components generally adopt an identification code in which the *p*-type side is identified by the letter **A** (anode) and with a longer terminal. The *n*-type side is identified by the letter **K** (cathode) and has a shorter terminal, as shown in Figure 2.

Solar cells are *p*-*n* junction diodes with a large area specially prepared for the photovoltaic phenomenon. The sunlight entering the cell produces current and potential difference to generate electrical power, as shown in Figure 3. This process requires a material in which light absorption raises an electron to a higher energy state and moves this higher energy electron from the solar cell into an external circuit. The electrons then dissipate their energy in the external circuit and return to the solar cell [6].

The three most relevant electrical quantities in the dimensioning of photovoltaic systems are power, potential difference and current. Understanding the behaviour of these quantities as the dependence of the weather and the panel's position about the sun is very important when designing a photovoltaic solar energy generation system.

On cloudy days, the current supplied by the panel is much smaller than that on sunny days, and the current depends directly on the radiation that falls on the panel. On the other hand, potential difference is more influenced by the temperature variation. The potential difference across the panels is lower on hotter days than on colder days. The power, in turn, is defined by the incidence of solar radiation and temperature, which influences the current and potential difference, respectively.

Positioning the panels facing the sun's passage throughout the day also influences energy transformation. In this sense, finding the best angle of inclination of the panel about the horizontal plane (β) and the surface azimuth angle (γ) maximises the harnessing of solar radiation and, consequently, generates electrical power. In Figure 4, we illustrate the inclination angle β, surface azimuth angle γ, elevation angle α_S and zenith solar angle θ_Z.

The photovoltaic phenomenon applies to various levels of education, including engineering and physics courses

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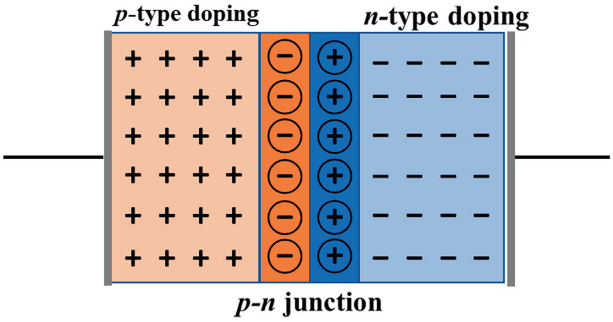

Figure 1: Representation of *p-n* junction diode.

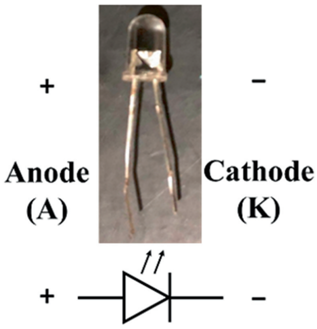

Figure 2: A LED picture in which the longer terminal indicates the anode (**A**), and the shorter terminal indicates the cathode (**K**). At the bottom is its symbology.

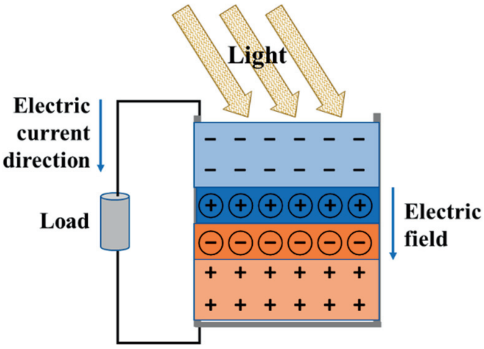

Figure 3: Electrons flow through a conductor interconnected between the *p-n* terminals of a photovoltaic cell.

as well as high school curricula. The concepts related to this phenomenon can be utilised to explore fundamental semiconductor concepts. Additionally, studies that focus on practical applications, such as training for the assembly and installation of photovoltaic systems, require didactic strategies to facilitate comprehension of the photovoltaic phenomenon. As LED and photovoltaic solar cells are both p-n junction diodes, it may be more cost-effective and accessible to use LEDs in educational experiments to replicate photovoltaic phenomena.

To show that the "solar cell" built with LEDs can be used to simulate a commercial photovoltaic panel for educational purposes, we propose four experiments in

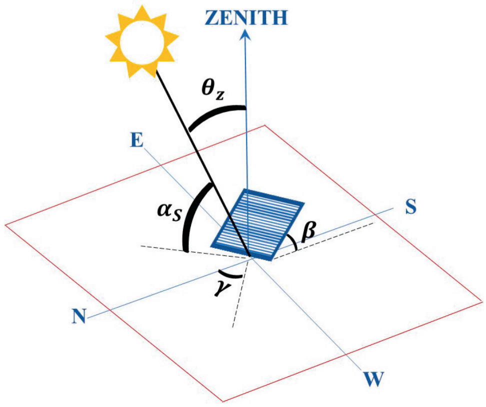

Figure 4: Solar angles. α_S is the elevation angle, β is the inclination angle, γ is the surface azimuth angle, and θ_Z is the zenith angle.

Section 2. The first, a "solar cell" generating energy, demonstrates that it can turn on a digital clock when exposed to a light source, converting light energy into electrical energy. The second, variation of energy transformation by the "solar cell" as a function of its position about the light source, seeks to reproduce the behaviour of the solar panel against variations in the position of the roof in which it is installed. Third, the characteristic current *versus* potential difference (I-V) curve and electric power *versus* potential difference (P-V) curve of the "solar cell", and fourth, the variation in energy transformation by the "solar cell" due to the presence of a screen made of translucent paper between it and the source.

Section 3 presents the discussions and conclusions.

2. Experimental setup apparatus, experiments, and results

The experimental apparatus consisted of one 1000 W halogen floodlight as the light source, 12 high-brightness red LEDs, two variable resistors, both from 0 to 1 MΩ, a breadboard, a multimeter, and a screen made of translucent paper. (see Figure 5).

The choice of a "solar cell" with 12 LEDs was sufficient to turn on the digital clock in an attempt to measure the current from our available multimeter and two variable resistors of 1 MΩ to provide an adequate variation in the resistance required to trace the current *versus* potential difference curve. The 1000 W halogen lamp was used because of the need to perform the experiments indoors and because this value is the average radiation power coming from the Sun on the Earth's surface.

We chose to use the red LED based on the work from Reference [7] about the efficiency of LEDs in energy transformation. Among the green LED, the white LED, the yellow LED and the red LED, in measurements made in the laboratory (indoor), the red LED had the best

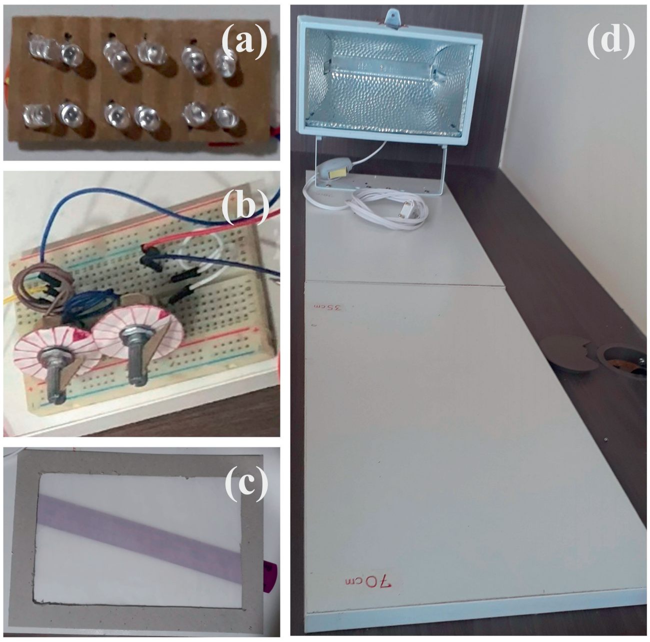

Figure 5: (a) 12 LEDs attached to a cardboard plate, **(b)** two 1 MΩ variable resistors (rheostats), **(c)** screen built with translucent paper, and **(d)** a 1000 W halogen lamp floodlight fixed to a wooden support.

performance in generating energy by the photovoltaic effect.

The light source consisted of a 1000 W halogen lamp floodlight fixed on a wooden base, which supported the experiments. The 12 LEDs used as "solar cells" are high gloss in red colour, and they are attached on a cardboard plate with dimensions 3 cm × 6 cm and connected in parallel. The reason for connecting the 12 LEDs in parallel is the low electrical current that an LED can provide, so it is impossible to read on a usual ammeter from a didactic laboratory. In this sense, the LED set can provide a higher current by connecting them in parallel. The connection diagram of the LEDs is shown in Figure 6.

A 70 cm distance between the LED set and the light source was adopted. Two 1 MΩ variable resistors (rheostat) were connected in series. A schematic diagram

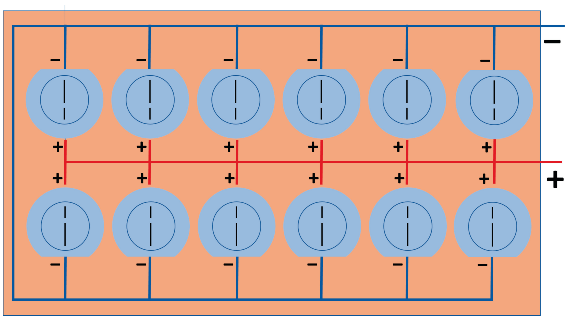

Figure 6: The 12 LEDs parallel connection diagram.

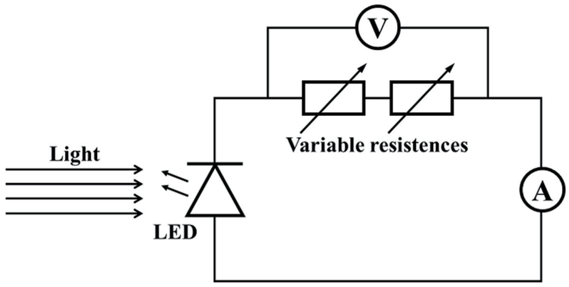

Figure 7: Schematic electric circuit diagram for measuring the potential difference and current from the variable resistors. **A** denotes the ammeter and **V** the voltmeter. Here, the LED symbol represents the 12 LEDs used in the present experiment.

of the electrical circuit for measuring the potential difference and current from the variable resistors is shown in Figure 7.

The translucent screen was constructed with a cardboard frame and a sheet of translucent paper and was used to simulate cloudy weather.

2.1. Led set as "solar cell" experiment — a source of electric energy transformation

The energy transformation from a set of LEDs can be verified through an experiment in which a digital clock is powered by it, as shown in Figure 8. This experiment replaced both variable resistances with a clock, as indicated in Figure 7. To carry out this experiment, the light source, a 1000 W halogen lamp reflector, was positioned 70 cm from the LED set, and a 1.5 V digital clock was wired to the LED set using a breadboard (Figure 8.a). The electrical circuit diagram of the assembly is shown in Figure 8.b.

Our measurements indicate a potential difference of 1.7 V across the digital clock and a current of 6.3 μA through the digital clock, even though the experiment from Figure 8 is qualitative.

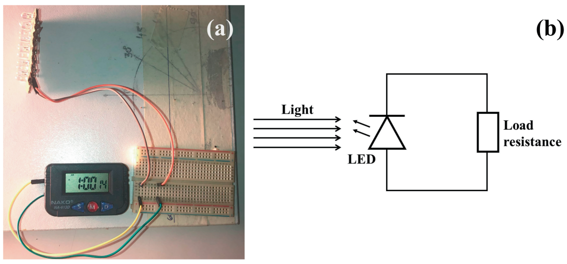

Figure 8: Load resistance (digital clock) powered by illuminated LED set. **(a)** Red 12-LEDs illuminated by a 1000 W halogen floodlight and distanced 70 cm between them. A 1.5 V digital clock is wired to the LED set via a breadboard. **(b)** Schematic electric circuit diagram. The LED symbol represents the LED set, and the load resistance means the digital clock.

2.2. Variation of energy transformation by the "solar cell" as a function in the light source experiment

In this experiment, we attempted to simulate the dependence of power generation by solar panels on the angular position in which they are installed on roofs or surfaces. For this, a multimeter verified the current's variation and the potential difference's behaviour by changing the angular position of the LED set ("solar cell") about the light source ("the Sun").

We consider the light source from the horizontal surface for simplicity, corresponding to the zenith angle $\theta_Z = 90°$. Even bearing in mind the effects that may occur due to the dome of the semiconductor element in the LED affecting the angular dependence, we do not take this into account since we are interested in results that present the tendency of dependence on energy transformation about the angular position of the "solar cell" about the light source.

The setup of this experiment is similar to the one present in section 2.1, but here, we replace the clock with a multimeter. We carried out the check of the "solar cell" behaviour from the generated electrical current variation in two situations: from the inclination angle β (Figure 9) and the surface azimuth angle γ (Figure 10).

2.2.1. The inclination angle β variation

This part of the experiment simulates the variation that occurs in the energy generation of a solar panel owing to the different slopes of the roofs or surfaces on which the solar panels are installed.

As shown in Figure 9, when varying the inclination angle (β), the position of the "solar cell" about the horizontal plane, both potential difference and current present smaller values as (β) decreases.

In Table 1, we explicit those values for potential difference and current.

Table 1: Inclination angle β dependence on potential difference across in V and on electrical current in μA, considering $\theta_z = 90°$.

β	Pot. difference (V)	Elec. current (μA)
90°	1.381	6.0
45°	1.290	1.3
0°	1.127	0.1

2.2.2. Azimuthal angle variation (γ)

This second part of the experiment simulates the variation that occurs in the energy generation of a solar panel

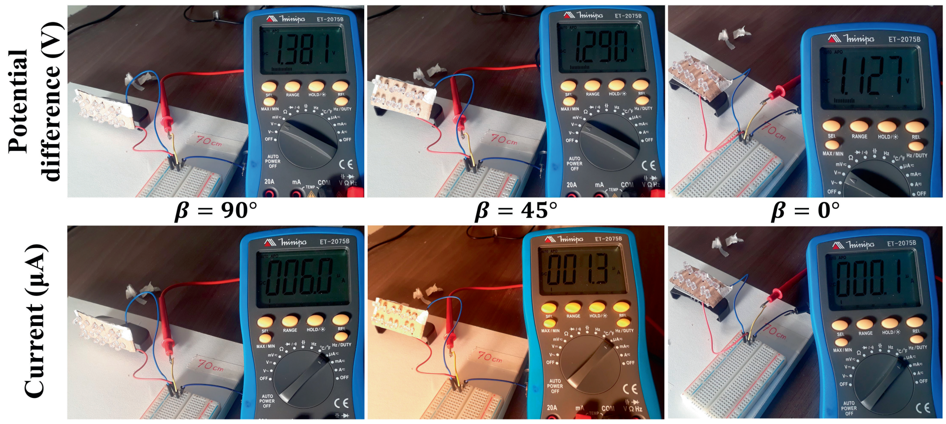

Figure 9: Inclination angle β dependence on potential difference across and on current through the "solar cell" (LED set), considering $\theta_Z = 90°$.

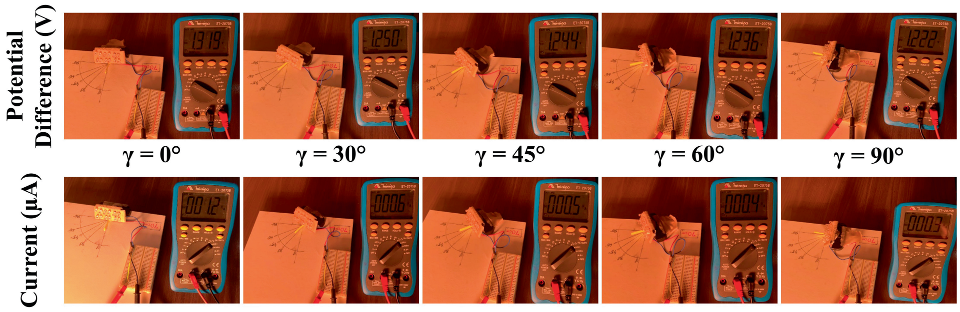

Figure 10: Azimuthal angle γ dependence on the potential difference across and current through the "solar cell" (LED set), considering $\theta_Z = 90°$.

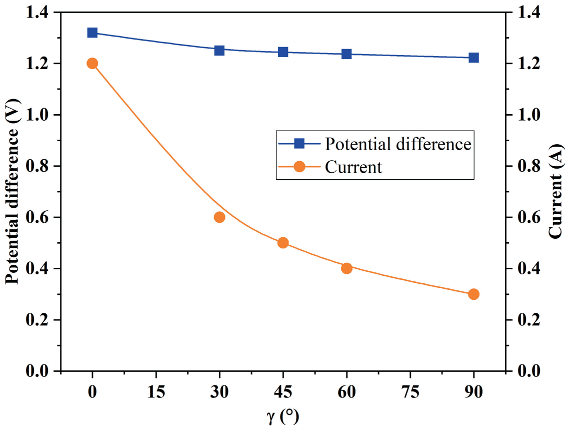

Figure 11: Surface azimuth angle γ dependence on the potential difference across (blue squares) and current through (orange circles) the "solar cell" (LED set). In both cases, the experimental results are eye-guided by full line.

owing to the different angular positions of the roofs or surfaces according to the geographic north.

As is shown in Figure 10, when varying the azimuthal angle (γ) of the "solar cell", taking into account the angles 0°, 30°, 45°, 60° and 90°, the multimeter shows a slight variation in potential difference but reveals a considerable variation in current. Figure 11 shows the angle's dependence on the "solar cell" potential difference and current for comparison.

This experiment simulates the variation (γ) that occurs in a solar panel's energy transformation owing to the roof's different positions about the northern geographic direction of the roofs to which the panel is installed.

2.3. *I-V* and *P-V* curves of the "solar cell" experiment

The I-V curve can evaluate the performance of a photovoltaic panel, the correlation between current and potential difference, and the P-V curve, the correlation between electric power and potential difference. These curves show essential points such as short-circuit current and maximum potential difference in the terminals of the photovoltaic panels. Moreover, a diode is characterised by a curve I-V when directly polarised.

To carry out this experiment, we keep the distance between the light source and the LED set. Two variable resistors are wired in series to the LED set. The electrical circuit diagram of the assembly is shown in Figure 7, indicating the voltmeter and ammeter connections.

The electrical quantity performance of an LED set as a "solar cell" can be shown by the current through *versus* potential difference across the "solar cell" curve (I-V curve) and electric power *versus* potential difference (P-V curve). We illustrated those curves in Figure 12.

From Figure 12(a), we can see that the short-circuit current $I_{sc} = 2.3\,\text{mA}$, detected for resistance load

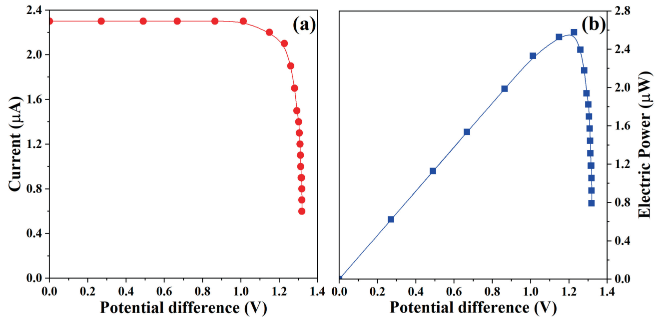

Figure 12: Characteristics of the "solar cell" (LED set): **(a)** current *versus* potential difference curve (*I-V* curve), and **(b)** Electric power *versus* potential difference curve (*P-V* curve). In both cases, the experimental results are eye-guided by full line.

$R_L = 0$ (turning off both variable resistor knob) and from Figure 12(b), the open-circuit potential difference $V_{oc} = 1.3\,\text{V}$, for $R \to \infty$ (turning totally on both variable resistor knob).

The I-V and P-V curves found for the "solar cell" shown in Figure 12 match the trend of the curves compared to manufactured photovoltaic solar panels.

2.4. How translucent paper affects energy transformation in a "solar cell" experiment

This experiment was done by placing a translucent paper screen between the light source and the "solar cell" to simulate a cloudy day. The comparison of I-V curves with "sunny" and "cloudy" days is plotted in Figure 13.

As shown in Figure 13, the generation of electrical current decreased when the translucent screen blocked some of the light from the source to the "solar cell". Therefore, energy transformation also decreases under these conditions.

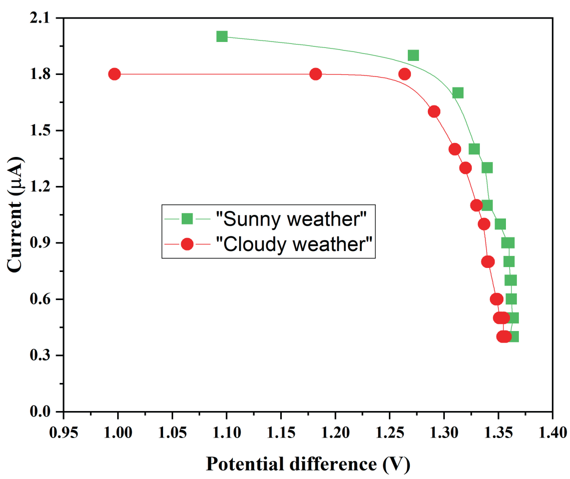

Figure 13: *I-V* curves generated from the variation of resistances in the rheostats, considering the system with a screen between the light source and "solar cell" (red circles) and without a screen (green squares). In both cases, the experimental results are eye-guided by full line.

This experiment simulates what happens to energy generation in a solar panel when the weather is cloudy, blocking part of the passage of sunlight to the panel. In this situation, as demonstrated in experience, the energy transformation by the panel decreases.

3. Discussion and Conclusion

The discussion of climate problems caused by fossils and the possibility of replacing them with clean and renewable energy sources must be conducted by society.

In this sense, the school plays a vital role in taking this debate into the classroom to make students aware of the impacts of burning fossils and the possibility of replacing them with cleaner sources.

Therefore, in this work, we provide suggestions on the topic of photovoltaic solar energy, clean and renewable energy sources with the potential to transform energy without harming nature. In this sense, photovoltaic solar energy is a topic that can be worked on in courses with specific disciplines linked to it and in physics courses, which cover various aspects of photovoltaic technology.

Through a simple experiment with a "solar cell" built with LED, it is possible to show the generation of electricity in a solar panel from sunlight and the behaviour of electrical quantities in commercial photovoltaic modules. Furthermore, it works on energy quantisation, photoelectric effects, and semiconductor physics.

The experiment proposed by the authors has been tested, and the results show that it is a viable option to simulate the performance of a commercial solar cell and its electrical characteristics through the use of the I-V and P-V curves. The use of this simulation in teaching photovoltaic technology and modern physics concepts is a great alternative, as it accurately replicates the physics and characteristics of commercial solar modules when exposed to sunlight. Furthermore, it brings new ideas that can be incorporated into physics courses at various levels of learning.

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