Introduction

The MR16 Development Kit demonstrates a dimmable MR16 LED bulb driver module. The board uses an ES version of the Atmel® ATtiny24A to decode dimming information from leading/trailing edge dimmer and uses it to change LED brightness accordingly. The ATtiny24A incorporates a two-stage topology consisting of a boost converter followed by a constant current buck converter to power the LEDs. The board is designed to induce halogen lamp electronic transformers to fire and operate reliably at 10W.

The board is designed to work from the following power sources:

- 10 to 15VDC input capable of producing 15W or more
- 11 to 12VAC 50/60Hz magnetic transformer capable of producing 15W or more
- 11 to 12VAC, 20kHz to 100kHz electronic transformer with 50/60Hz envelope, capable of producing 13W or more

Features

- Compatible with 12VAC electronic transformers from leading suppliers *)
- Compatible with leading and trailing edge dimmers from leading suppliers *)
- Supports DC, magnetic transformer and electronic transformer inputs
- 10% to 100% dimming performance
- Up to 80% efficiency
- Preconfigured to generate 10W output for four LEDs
- Scalable power rating and LED configuration

Figure 1. MR16 Development Kit.

*) Compatibility varies for ETs and dimmers and needs to be verified.
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1. **Kit Contents**

- MR16 main development and evaluation board
- LED load board with heat-sink attached (+ LEDs are in series on the load board)
- LED load board connection wires
- The following items are required but not included in the kit
  - A compatible power source – maybe 12VDC, 12V magnetic transformer or 12V electronic transformer (recommendation: Hatch RS12-80MGN)
  - Leading or trailing edge dimmer (recommendation: Lutron Diva DVELV-300P)

**Figure 1-1. Input and Output Connectors.**

Note: The ATtiny24A functions as the LED driver IC and comes pre-coded with firmware to perform the power control, dimming control, and housekeeping functions. The firmware is available upon request by signing a royalty-free licensing agreement.
2. **Connecting and Operating the MR16 Evaluation Board**

   a) Attach wires between output connector X2 on the main board to connector J1 on the LED load board.
      1. Ensure the heat-sink is attached to the back of the LED load board.
      2. If the heat-sink has fallen off in shipping, reattach it to the back of the LED load board by apply gentle and even pressure.

   b) Connect the input connector X1 to your power source. The board is designed to work from any of the following power sources:
      1. 10 to 15VDC input capable of producing 15W or more.
      2. 11 to 12VAC 50/60Hz magnetic transformer capable of producing 15W or more.
      3. 11 to 12VAC 40kHz electronic transformer with 50/60Hz envelope, capable of producing 15W or more.

   c) To dim the MR16 bulb, connect an AC dimmer compatible to your chosen transformer prior to the transformer shown in Figure 2-1.

   Refer to the electronic transformer manufacturer’s datasheet for the dimmer compatibility. Specific dimmer and transformer combinations might require higher load. For such combinations more than one lamp will be needed for stable operation.

   **Figure 2-1. Connection Diagram.**
3. **Block Diagram**

*Figure 3-1. Circuit Block Diagram.*

![Figure 3-1](image)

*Note: Dimmer must be compatible with Electronic Transformer (Refer to datasheet of the Dimmer and Electronic Transformer)*

Figure 3-1 shows the block diagram of the scheme used in the implementation of the MR16 lamp. The input voltage is processed by the boost converter. A digital block inside the Atmel ATtiny24A implements the PI controller transfer function and adjusts the conditions in the circuit such that the desired boost bus voltage is achieved.

A constant off-time floating buck topology is used. The floating buck is advantageous in cases where the load (the LEDs) does not have to be grounded, because it uses a low-side MOSFET, which is easy to drive. Constant off-time control allows for accurate control of the LED current and is simple to implement. The average LED and inductor currents are equal.
4. Schematic

Figure 4-1. Schematic.
5. **Design Equations**

5.1 **Buck Stage**

The MR16 evaluation boards consist of boost converter followed by a constant current floating buck power stage as shown in Figure 4-1. It is a constant off-time floating buck topology. The output bus voltage of the boost section acts as input to the buck converter to regulate the LED string current. The buck is operated in the peak-current control mode with buck inductor current in continuous conduction mode. There is an internal delay inside the controller in detecting the buck inductor peak-current and it restricts the minimum on time $T_{onMIN}$ of the MOSFET Q2 to 2µs. With the MOSFET off time having a fixed value of $T_{off}$, it follows that the maximum switching frequency for the buck converter is,

$$f_{buckMAX} = \frac{1}{T_{onMIN} + T_{off}} = 200 \text{ kHz}$$

Note: Constant off-time operation of the buck converter is particularly attractive for LED drivers because the ripple current, and hence the average LED current, is insensitive to the changes in the buck stage input voltage, as long as the LED voltage is relatively constant. The switching frequency adjusts to keep the ripple and average current constant as the input voltage varies.

Figure 5-1. **Buck Stage Plots.**

Continuous conduction operation is assured when the peak-to-peak ripple current in the inductor, $\Delta i_L$, is less than twice the average LED current, i.e.,

$$\Delta i_L \leq 2 I_{AVE}$$

where $I_{AVE}$ is the average LED string current.

Assuming the valley buck inductor current = $I_v$ then the average LED string current or average buck inductor current $I_{AVE}$ can be written as:

$$I_{AVE} = \frac{I_{PEAK} + I_v}{2}$$

If the fraction of average buck inductor current allowed as ripple in the buck inductor is $\beta$ (a design parameter). Then $\Delta i_L = \beta I_{AVE}$
Calculations are needed to accurately determine the value of sense resistor for the buck MOSFET. Propagation delays in the current sense comparator and in the control block, results in higher peak buck inductor current. This makes the LED current higher than desired, necessitating an increase in the sense resistor value. If the total propagation delay $t_{delay}$ from the instant that the inputs of the comparator become equal to when the MOSFET switches-off, is known, and assuming that the input offset voltage of the comparator is negligible in comparison with the comparator’s reference voltage, the correct sense resistor value can be computed as follows:

The total peak-to-peak ripple current $\Delta i_L$ in the inductor is set by the duty ratio $D = \frac{V_{LED}}{V_{BUS}}$.

$$\Delta i_L = \Delta i_{L,\text{ideal}} + \Delta i_{L,\text{delay}} = \frac{(V_{BUS} - V_{LED})D}{L_2 f_{buck}}$$

From Figure 5-2 two equations can be written to express the starting current $I_s$.

$$I_s = I_{REF} = \frac{(V_{BUS} - V_{LED})}{L_2} \left( \frac{D}{f_{buck}} - t_{delay} \right) = \frac{V_{REF}}{R_{11}} \left( \frac{V_{BUS} - V_{LED}}{L_2} \left( \frac{D}{f_{buck}} - t_{delay} \right) \right)$$

and,

$$I_s = I_{AVE} = \frac{(V_{BUS} - V_{LED})}{L_2} \left( \frac{D}{2f_{buck}} \right)$$

where $I_{AVE}$ is the desired LED average current.

Equating these two expressions gives:

$$R_{11} = \frac{V_{REF}}{I_{AVE} + \frac{(V_{BUS} - V_{LED})}{L_2} \left( \frac{D}{2f_{buck}} - t_{delay} \right)}$$

This equation is accurate if the input to the system is DC and the bus voltage is ripple-free. In the case of ac-input the ripple current in the inductor is dependent on the bus ripple voltage. For the AC input, $R_{11}$ will need to be increased slightly and it can be achieved empirically.

Now we need to have a second design equation to decide the inductance of the buck inductor. Equation for the MOSFET in off-state can be written as:

$$V_{LED} = L \frac{\Delta i_L}{T_{off}}$$

$$L_2 = \frac{V_{LED}T_{off}}{\Delta i_L} = \frac{V_{LED}T_{off}}{\beta I_{AVE}}$$
Finally, two buck-stage design equations can be summarized as listed below.

\[
R_{11} = \frac{V_{REF}}{I_{AVE}} + \left( \frac{V_{BUS} - V_{LED}}{L_2} \right) \frac{D}{2T_{buck} - t_{delay}}
\]

\[
L_2 = \frac{V_{LED}T_{off}}{\beta I_{AVE}}, \text{ Where } T_{off} = 3\mu s.
\]

Buck inductor saturation current should be more than twice the peak inductor current \(I_{peak}\) flowing through the inductor in order to avoid any un-intentional core saturation because of the current overshoots or overtemperature.

### 5.1.2 Buck Sense Resistor Reference Voltage

The reference voltage is compared to that across sense resistor \(R_{11}\) to determine when to turn off the buck FET \(Q2\). If this voltage is too low, it becomes comparable to the input offset voltage of the comparator and current sensing accuracy suffers. If it is too high, there is excessive dissipation in the sense resistor \(R_{11}\), and the voltage across this resistor subtracts from the gate drive voltage of \(Q2\). The reference voltage corresponding to peak current should be set between 200 and 500mV. The reference voltage is generated by the dimming decoding circuit in the controller. A PWM signal with amplitude of 5V and a duty ratio proportional to the dimming level required is output at pin 5 of the controller. When no dimming is required the output is steady at \(V_{CC} = 5V\) and the peak reference voltage is given by,

\[
(V_{buckFB})_{PEAK} = \frac{R_{19}}{R_{17} + R_{19}} \times 5V = (I_{buck})_{PEAK} \times R_{11} = 200mV \text{ to } 500mV
\]

### 5.2 Boost Stage

#### 5.2.1 Value of \(V_{BUS}\) and \(C_{BUS}\)

Let us consider switching frequency of the buck converter is \(f_{buck} = 150kHz\).

Hence,

\[
T_{ON} + T_{OFF} = \frac{1000}{f_{buck}}, \text{ where } T_{ON} \text{ and } T_{OFF} \text{ are in } \mu s \text{ and the value of } T_{OFF} \text{ is } 3\mu s.
\]

Therefore, the value of \(T_{ON}\) is given by the following equation.

\[
T_{ON} = \left( \frac{1000}{f_{buck}} - T_{OFF} \right) \mu s
\]

In addition, the buck MOSFET on-time duration equation can be written as,

\[
V_{BUS} - V_{LED} = L_2 \frac{I_{PEAK} - I_{V}}{T_{ON}}
\]

Hence,

\[
V_{BUS} = V_{LED} + L_2 \frac{\beta I_{AVE}}{T_{ON}}
\]

Potential divider resistors need to be sized correctly in order to achieve the desired boost stage bus voltage. A digital PI controller implements the feedback transfer function, adjusting the conditions in the circuit such that the output voltage of the gain stage sits at a voltage equal to the digital reference number for the ADC, nominally 2.56V. Values of the potential divider resistors \(R_4\) and \(R_9\) for the bus voltage can be selected using following equation.

\[
V_{bus} \times \frac{R_9}{R_4 + R_9} = 2.56V
\]
The bus voltage has slightly different average values for DC and for AC operation. During AC operation the bus voltage has a significant ripple across it and is sampled once in each line half cycle. Its DC value will depend on what point it is sampled at in the ripple cycle. The difference in the averaged values is of little consequence because the buck converter corrects for it and gives the right LED current.

Because of the limited space in MR16 application, the largest through-hole boost converter electrolytic capacitor package that will fit in this fashion in the MR16 form factor is 10mm diameter by 12mm long (or 0.4in diameter by 0.5in long). The bus voltage capacitor should be as large as possible, because this minimizes the capacitor’s physical size. The largest capacitor value in this size should be used.

For example, in four LED, 10W design, the best design becomes one where \( V_{BUS} = 24V \) for \( V_{LED} = 14V \) (for four LEDs). Then for \( P_{LED} = 10W \) the best capacitor value is \( C_{BUS} = 220\mu F, 35V \). The input current is shaped to have a constant value during all times while the input voltage is being applied to the circuit. For the current shape the peak-to-peak ripple voltage with a non-dimmed magnetic transformer is 5V. If the circuit were power factor corrected then the ripple-voltage would be 8V. In both cases the ripple voltage is inversely proportional to the bus capacitance for a fixed bus voltage. The bus voltage should not be lowered below about 20V even if less than four LEDs are powered. Otherwise, the bus capacitor can become too large or the ripple will be too large, unless the attendant problems are acceptable. If more than four LEDs are used a good rule of thumb is to make the bus voltage approximately 1.5 to 2 times greater than the LED voltage. If the power level is lowered below 10W, these cautions can be relaxed, since the relative ripple voltage in the bus capacitor is less.

### 5.2.2 Boost Inductor

The boost inductor value is determined by the need to fit in the MR16 form factor, and to ensure boost continuous conduction (CCM) operation. The largest practical inductor value is 10mm x 10mm. For reasons related to the need to ensure proper firing of electronic transformers under all dimming conditions, the worst operating condition for the inductor is going to be observed with 12VDC input. If the boost current can be kept continuous with the DC input, it will be continuous with the AC input as well. The switching frequency of the boost converter was picked to be 350kHz so that the design could fit in the space available. Then it becomes easy to pick a minimum inductor value to ensure CCM operation.

The minimum inductor value \( L_{BST,MIN} \) which will give critical conduction operation, where the peak inductor current is twice the average input current. Ignoring power losses, the peak inductor current \( \Delta i_{L,BST} \) in critical conduction is,

\[
\Delta i_{L,BST} = 2I_{IN} = 2 \frac{P_{LED}}{V_{IN}}
\]

The duty ratio of the boost converter is,

\[
D_{BST} = 1 - \frac{V_{IN}}{V_{BUS}}
\]

Hence the minimum inductor value is,

\[
L_{BST,MIN} = \frac{V_{IN}D_{BST}}{\Delta i_{L,BST}f_{BST}}
\]

A good operating point is with ripple current equal to input current, that is, with half the ripple current obtained with critical conduction. This gives adequate operating margin.

### 5.2.3 Damping and Noise Rejection Network

Capacitor \( C_9 \) and resistor \( R_9 \) constitute a damping and noise reduction network. The capacitor is required to provide energy storage at the switching frequency (20kHz – 100kHz) of the electronic transformer. Without it the input voltage to the boost is a high frequency square wave with a line frequency sinusoidal envelope and is extremely noisy. The resistor is added to damp the tendency of some electronic transformers to oscillate waywardly with the input of the M16. The damper is extremely effective.
5.2.4 Boost Current-Sense Resistor

The boost sense resistor $R_2$ is picked to ensure continuous conduction operation, but also to minimize power dissipation. It is determined by the maximum peak input current and power dissipation desired. Referring to the schematic, the maximum reference (or current limit) voltage to which the peak current in $R_2$ is compared, is given by,

$$V_{I,\text{lim}} = \frac{V_{CC} R_{10}}{R_8}$$

Where $V_{CC} = 5V$ is the supply voltage of the controller.

The sense resistor is given by dividing this voltage by the maximum peak current at current limit.

5.2.5 Boost Switching Frequency

In theory the boost converter’s switching frequency is supposed to be determined by the inductor, sense resistor and the components in the circuit around the comparator $U_4$. However, the comparator used for $U_4$ is a generic one, and has a long response time in the 1µs range. This reaction time significantly lowers the switching frequency. Including the effects of comparator response time and with respect to the components on the schematic, the peak-to-peak ripple current in the input inductor is given by,

$$\Delta i_L = \frac{V_{CC} R_{12}}{R_2 (R_7 + R_{12})} \left(1 + \frac{R_{10}}{R_8}\right) + \frac{V_{IN}}{L_1} t_{\text{r,on/off}} + \frac{(V_{BUS} - V_{IN})}{L_1} t_{\text{r,off,on}}$$

where $t_{\text{r,on/off}}$ and $t_{\text{r,off,on}}$ are respectively the comparator response times when MOSFET $Q1$ is turning off and turning on, and are usually about the same and $V_{CC} = 5V$ is the supply voltage to the comparator.

Therefore, the switching frequency is given by,

$$f_{\text{bus}} = \frac{1}{L_1 \Delta i_L} \left(\frac{V_{IN}}{V_{BUS}}\right) (V_{BUS} - V_{IN})$$

The switching frequency for a DC input voltage of 12V and a bus voltage of 24V is about 350kHz, which allows the circuit to fit in the MR16 form factor at a good efficiency. The switching frequency will vary with the line for the AC input.

Note: Negative (or cathode pin) of the LED string is floating and not connected to the ground of the driver. Therefore, make sure that the scope is isolated before taking voltage measurement of the LED string. Otherwise, use a differential voltage probe to measure the LED string voltage.

5.2.6 Low conduction angle dimming behavior

If the circuit is dimmed to an input voltage conduction angle of about 10-20 degrees or less, the LEDs can flicker to a significant degree for the following reason. At such low angles the LED current is dominated by its ripple component, because the dc part has become very small.

In this development kit a circuit has been implemented to turn off the buck converter at the lowest dimming angles, but to leave the LEDs on. This scheme, which we are using and is illustrated by the components $Q5$ and $R3$ in Figure 5-3, can be implemented by connecting a resistor from the cathode terminal of the bottom LED to ground through a MOSFET controlled by the MCU. Then, when the buck converter goes off, a constant current determined by the difference between the boost voltage and the LED voltage flows in the resistor and LEDs, shown in the equation below. If the resistor is chosen so that the current in it matches the minimum buck switching current the apparent flash is eliminated. In this scheme is that the power required for loading the electronic transformer and maintaining the proper shape of the input voltage is mostly dissipated in the LEDs. Hence, the resistor can be the same size as the others in the circuit. In the prototype the resistor has a value of about 50Ω and only 50mW power is dissipated in it, allowing it to have a 0603 footprint.
Figure 5-3. Preload circuit for low conduction angle dimming.

Equation:

\[ I_{LED} = \frac{V_{BUS} - V_{LED}}{R3} \]

There are other ways of reading low conduction angle flicker. User can modify the circuit and code if necessary.
6. Performance Characterization for Four LEDs 10W Solution

An MR16 prototype board designed to produce 10W was characterized for various input sources. The load was four series-connected LEDs running at a current of 730mA and a voltage of about 13.5V.

6.1 DC INPUT

Table 6-1. Efficiency with DC Input.

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Figure 6-1. Start-up Waveforms: Ch1=input voltage; Ch2=boost input (inductor) current at 1.33A/div.; Ch3=buck_FET current at 1A/div.; Ch4=boost output voltage.

Figure 6-1 illustrates that the system starts up gracefully without significant or dangerous voltage or current overshoots.

Figure 6-2. Switching Waveforms: Ch1=boost FET gate drive voltage; Ch2=boost input (indicator) current at 1.33A/div.; Ch3=buck FET current at 1A/div.; Ch4=buck FET gate drive voltage.
Figure 6-3. Switching Waveforms: Ch1=boost FET drain voltage; Ch2=boost inductor current at 1.33A/div.; Ch3=buck FET current at 1A/div.; Ch4=buck FET drain voltage.

Figure 6-2 and Figure 6-3 show that the switching waveforms are clean and have the expected shapes and values.

Figure 6-4. Boost Converter Load Transient Response: Ch1=output voltage; Load current step=300mA to 350mA. Buck LED driver unloaded.

Figure 6-4 illustrates that the digital PI controller in the boost converter confers excellent stability to the feedback loop.
Figure 6-5. Boost Converter Waveforms: Ch1=sensed input voltage at microcontroller pin; Ch2=sensed boost output voltage at microcontroller pin; Ch3=output of microcontroller PWM for boost at pin 7; Ch4=low pass filtered microcontroller PWM across C16.

Figure 6-5 shows the output of the PWM controller and low-pass filtered analog output.

6.2 AC INPUT

Figure 6-6. Start-up Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.
Figure 6-7. Detail of Start-Up Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.

Figure 6-8. Finer Detail of Start-Up Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.

These figures illustrate that even with an AC input voltage, the circuit again starts up gracefully and safely without voltage or current overshoots.
Figure 6-9. Switching Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div.; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.

Ideally the buck current should be insensitive to the boost output voltage ripple. In practice, because of finite propagation delays in the LED current comparison comparator, the peak current tends to follow the peak boost voltage somewhat. If this dependency is unacceptable, a faster current comparator can be used.

Figure 6-10. Boost Converter Load Transient Response: Ch4=boost output voltage. Boost output current step 300mA to 350mA with LEDs disconnected.

Figure 6-10 shows that the load transient response of the boost converter remains excellent with an ac input voltage.
7. **HATCH RS12-60M ELECTRONIC TRANSFORMER INPUT WITH LUTRON DIVA DVELV-300P DIMMER**

7.1 **Non-dimmed Waveforms**

Figure 7-1. Undimmed Start-up Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.

This graph again shows excellent system start-up characteristics. Immediately their input voltage is applied, an inrush current control resistor is connected in the input path to limit the current. This resistor is bypassed just before the circuit begins to switch.

The input inductor current shows a large inrush current spike. This spike is limited by design to a maximum value of the peak input voltage (always 17V or less) divided by the inrush current resistor (presently set at 2.5Ω), or to less than 6.8A in all cases.

Figure 7-2. Detail of Undimmed Start-up Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.
Figure 7-3. Finer Detail of Undimmed Start-up Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.

This graph shows that even with the very dirty input voltage from a high frequency AC electronic transformer, the LED current is still well-regulated. The disturbances in the inductor current (blue) waveforms are not real, but are oscilloscope artifacts, as one zooms into the waveform, as Figure 7-5 shows.

Figure 7-4. Undimmed Switching Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div.; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.

This graph shows that even with the very dirty input voltage from a high frequency AC electronic transformer, the LED current is still well-regulated. The disturbances in the inductor current (blue) waveforms are not real, but are oscilloscope artifacts, as one zooms into the waveform, as Figure 7-5 shows.
7.2 50% Dimmed Waveforms

Figure 7-6. Start-up Waveforms With 50% Dimming: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.
Figure 7-7. Detail of Start-up Waveforms With 50% Dimming: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.

Figure 7-8. Finer Detail of Start-up Waveforms With 50% Dimming: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.
7.3 Fully Dimmed Waveforms

Figure 7-10. Fully Dimmed Start-up Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div.; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.
Figure 7-11. Fully Dimmed Switching Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.

Figure 7-12. Detail of Fully Dimmed Switching Waveforms: Ch1=rectified input voltage; Ch2=boost input (inductor) current at 1.33A/div; Ch3=buck FET current at 1A/div.; Ch4=boost output voltage.
# Bill of Material

Bill of Material for Four LEDs and 10W Design

## Table 8-1. Bill of Material.

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Dimmable MR16 Development Kit [USER GUIDE AND DESIGN GUIDELINE]
9. Revision History

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