

Noise Reduction Design in Printed Circuit Boards

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ABSTRACT

To reduce the amount of high-frequency noise generated in automotive electronics, we have compiled circuit board design techniques that are based on the physical properties of high-frequency signals into a set of circuit board design guidelines.

These guidelines were created according to a fundamental approach toward noise reduction, which dictates that high-frequency noise generated as a result of electronic circuit operation must not be allowed to propagate widely through the printed circuit board, and noise radiation sources that resonate with the noise frequency and act as antennas must not be created.

To check the noise reduction effect of the circuit board design guidelines, we used them to redesign the printed circuit board of an information-processing electronic control unit that normally has a large number of FM bandwidth noise suppression parts mounted therein. Using this test ECU, we examined the noise reduction effect resulting from using the redesigned printed circuit board.

As a result, we were able to confirm that an information-processing electronic control unit using the printed circuit board that was designed in accordance with the design guidelines exhibited a noise reduction effect of up to approximately 10 dB μ V/m in the high-frequency bandwidths at and above the FM bandwidth.

1. Foreword

Modern automobiles are equipped with a variety of electronics, and these electronics fulfill a variety of functions. Meanwhile, as greater performance is demanded of automotive electronics, digital circuit operations are becoming faster. As a result, it is becoming important to take measures to suppress the high-frequency noise generated by automotive electronics. There are cases in which developers must struggle to find ways to deal with noise issues that become apparent in the later stages of development. Because trying to deal with an issue after it becomes apparent is time consuming and labor intensive, it would be preferable to take measures to deal with noise in the initial stages of design. One way to do this is to design printed circuit boards in accordance with design guidelines whose noise reduction effects have been verified⁽¹⁾.

We focused on the physical properties of high-frequency signals in printed circuit boards and compiled design principles for reducing high-frequency noise into a set of circuit board design guidelines.

If electromagnetic noise leakage from automotive electronics interferes with an automobile's FM radio, the noise will create audible static and reduce the marketability of the automobile. That is why for the sake of marketability, it is necessary to strictly suppress the electromagnetic noise leaked by automotive electronics in the FM bandwidth (76 MHz to 108 MHz). Thus, automotive electronics designers are keenly

interested in whether circuit board design guidelines are effective for FM bandwidth noise reduction.

For this reason, we examined whether circuit board design guidelines are effective for FM bandwidth noise reduction.

We used the circuit board design guidelines to redesign the printed circuit board of an information-processing electronic control unit (ECU) that normally has a large number of FM bandwidth noise suppression parts mounted therein. Using this test ECU, we examined the noise reduction effect resulting from using the redesigned printed circuit board. The details of the above process are reported below.

2. The Physical Properties of High-Frequency Signals in Printed Circuit Boards

All conductors have inductance. The effects of this inductance can be ignored for low-frequency signals but cannot be ignored for high-frequency signals. Therefore, when thinking of how to reduce high-frequency noise, it is necessary to take into consideration the fact that all the conductor circuit patterns that form circuits on printed circuit boards have inductance. Figure 1 shows the ground plane formed on a printed circuit board, the integrated circuits (IC1 and IC2) mounted thereon, and the circuit pattern that corresponds to the signal transmission path from IC1 to IC2. However, it is assumed that the ground plane is isolated from the positive power supplies of IC1 and IC2, the signal terminals, and the circuit pattern.

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When a signal is transmitted along the circuit pattern from IC1 to IC2, the feedback current of the signal travels through the ground plane from IC2 to IC1. If the signal is a low-frequency signal, most of the current flows across the shortest distance between the integrated circuits, which is indicated by the purple line. This is because the dominant factor of the impedance of a low-frequency signal is the DC resistance component of the ground plane.

On the other hand, if IC1 is a digital circuit that operates at a high speed and the high-frequency noise generated by the high-speed operation travels through the circuit pattern, most of the feedback current will flow along the path indicated by the blue line in the figure that follows the circuit pattern. This is because the dominant factor of the impedance of a high-frequency signal is the inductance component of the ground plane.

Figure 2 shows how the mutual inductance M between the two inductances L_o and L_r of a two-line signal

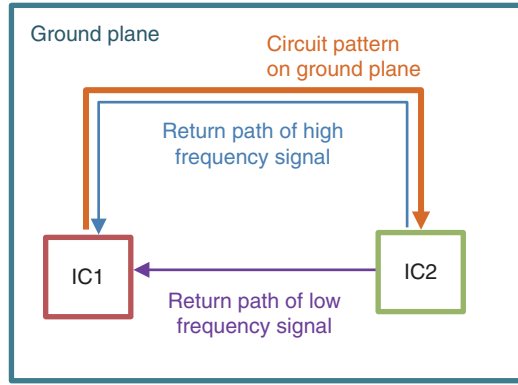


Fig. 1 Return path of signal on printed circuit board

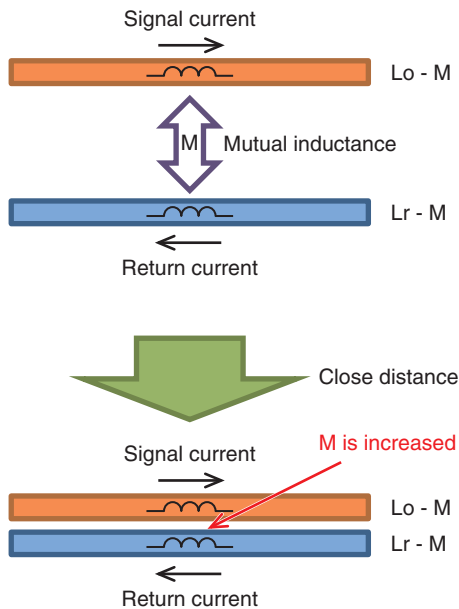


Fig. 2 Inductance of printed circuit with high frequency signal

transmission path increases as the lines get closer. As a result, the inductance on the return path becomes smaller along with $L_r - M$, and the impedance to the high-frequency signal decreases.

In the same manner, the high-frequency impedance in the ground plane is lower closer to the signal line, so most of the high-frequency noise feedback current flows along a path in the ground plane that follows the signal line.

3. Circuit Board Design Guidelines

The circuit board design guidelines that we developed are based on the following objectives: reducing the return-path impedance of high-frequency noise on the basis of the physical properties of high-frequency signals, suppressing common mode current, and preventing the shapes of printed circuit board patterns from leading to antenna formation.

3.1. Conduction Modes and Radiated Noise Strength

A conduction mode is the way that a signal is transmitted. There are two conduction modes: differential mode and common mode. The amount of the noise radiated by a conductor varies depending on the conduction mode of the high-frequency noise traveling through the conductor.

3.1.1. Differential mode radiation

In differential mode, the signal pattern is the forward path, the ground pattern is the return path, and the current orientations in the forward path and return path are reversed (Fig. 3).

The disturbance field strength E_d [V/m] caused by differential mode current I_d can be approximated using Eq. (1).

$$E_d = 1.316 \times 10^{-14} \times \frac{I_d \times f^2 \times S}{d} \quad (1)$$

I_d : Differential mode current [A]

f : Signal frequency [Hz]

S : Area of loop formed by forward path and return path [m^2]

d : Distance to noise measurement point [m]

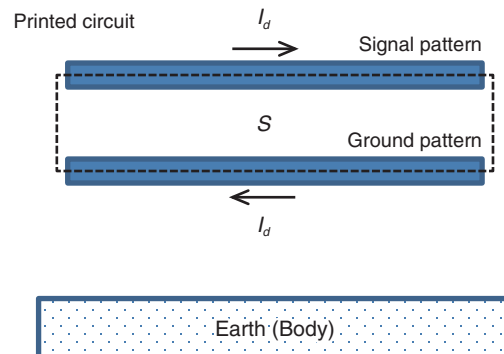


Fig. 3 Simple model of differential mode current

The strength of the disturbance field generated by the differential mode current under the conditions listed below is as follows.

$$\begin{aligned} I_d &= 1 \text{ mA} \\ f &= 100 \text{ MHz} \\ S &= 0.3 \text{ cm}^2 \\ d &= 10 \text{ m} \end{aligned}$$

$$E_d = 0.3948 \text{ } \mu\text{V/m}$$

3.1.2. Common mode radiation

In common mode, the current orientations in the forward path and return path are the same (Fig. 4).

The disturbance field strength E_c [V/m] caused by common mode current I_c can be approximated using Eq. (2).

$$E_c = 1.257 \times 10^{-6} \times \frac{I_c \times f \times l}{d} \quad (2)$$

$$\begin{aligned} I_c &: \text{Common mode current [A]} \\ f &: \text{Signal frequency [Hz]} \\ l &: \text{Wiring length [m]} \\ d &: \text{Distance to noise measurement point [m]} \end{aligned}$$

The strength of the disturbance field generated by the common mode current under the conditions listed below is as follows.

$$\begin{aligned} I_c &= 1 \text{ mA} \\ f &= 100 \text{ MHz} \\ l &= 10 \text{ cm} \\ d &= 10 \text{ m} \end{aligned}$$

$$E_c = 1257 \text{ } \mu\text{V/m}$$

In this example, when the intensity of the noise current is the same, the disturbance field strength of the noise radiation generated by the common mode current is approximately 3000 times greater than that of the noise radiation generated by the differential mode current.

Thus, suppressing the generation of common mode current is an important part of noise reduction.

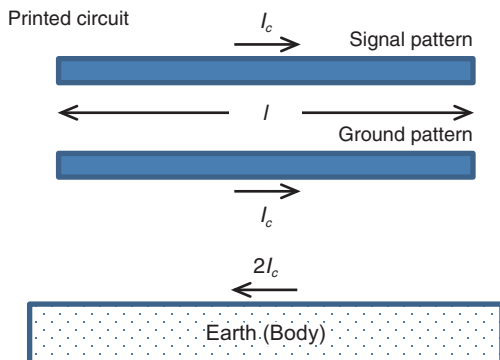


Fig. 4 Simple model of common mode current

Table 1 Conductive pattern length for each frequency

Signal frequency [MHz]	Conductive pattern length [cm]					
	$\lambda/4$	$3\lambda/4$	$5\lambda/4$	$\lambda/2$	$3\lambda/2$	$5\lambda/2$
25	136.8	410.5	684.2	273.7	821.0	1368.4
50	68.4	205.3	342.1	136.8	410.5	684.2
100	34.2	102.6	171.0	68.4	205.3	342.1
200	17.1	51.3	85.5	34.2	102.6	171.0
500	6.8	20.5	34.2	13.7	41.1	68.4
1000	3.4	10.3	17.1	6.8	20.5	34.2

3.2. Antennas Formed by Printed Circuit Board Patterns

When a pattern of a length that resonates with a certain frequency (wavelength) is formed, that pattern may function as an efficient antenna and generate strong noise radiation.

Equation (3) shows how the wavelength on the circuit board corresponds to the frequency.

$$\lambda = \frac{C}{f \times \sqrt{\mu \times \epsilon_r}} \quad (3)$$

$$\begin{aligned} \lambda &: \text{Wavelength [m]} \\ C &: \text{Speed of light [m/s]} \\ f &: \text{Signal frequency [Hz]} \\ \mu &: \text{Relative permeability [-]} \\ \epsilon_r &: \text{Dielectric constant [-]} \end{aligned}$$

Here, on a glass epoxy printed board whose dielectric constant ϵ_r is 4.8, Table 1 shows examples of pattern lengths that produce efficient antennas for different noise frequencies.

As is evident from the table, even on a relatively small printed board, it is highly likely that patterns will be formed that can become antennas for high-frequency noise.

Also, patterns whose lengths are close to those listed in Table 1 can also serve as radiation sources, albeit less efficient ones. Thus, for all bandwidths, including the FM bandwidth, it is necessary to be careful to avoid unintentionally forming patterns that can act as antennas.

3.3. Printed Circuit Board Design Guidelines

On the basis of the two points discussed in sections 3.1. and 3.2., we came up with design principles for suppressing common mode current and preventing circuit board patterns from becoming antennas.

Section 3.3.1. explains the principle for suppressing common mode current on a printed circuit board. Section 3.3.2. provides an example of a guideline that has been determined on the basis of this principle.

3.3.1. Suppressing common mode current

In Fig. 5, IC1 and IC2 are integrated circuits that have

been mounted on a printed circuit board. An electrical signal is transmitted from IC1 to IC2 through a wiring pattern on the printed circuit board. Z_o is the forward path wiring impedance to the electrical signal. Z_r is the return path wiring impedance. Z_c is the earth (vehicle body, etc.) impedance. I_d is the differential mode current, and I_c is the common mode current. As shown in Fig. 5, when the sizes of the forward path current ($I_d + I_c$) and return path current ($I_d - I_c$) are different, a common mode current equivalent to the difference ($2I_c$) is generated.

This means that making Z_r as small as possible makes I_d larger and thus makes I_c smaller.

The circuit board design guidelines provide concrete design principles for decreasing the return-path impedance Z_r to the circuit board with high-frequency signals in the FM bandwidth and above.

3.3.2. Guideline example

In a circuit pattern such as that shown in Fig. 6 in which there is a slit in the ground plane directly beneath the signal line, the high-frequency feedback current tries to proceed along the signal line but is separated and diverted by the slit. As a result, the return path impedance increases, and

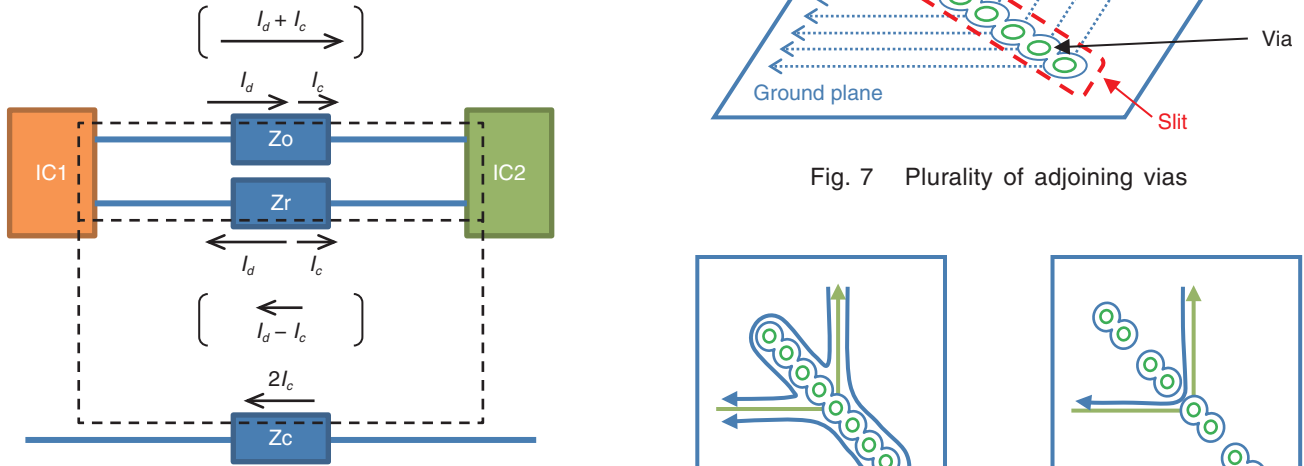


Fig. 5 Common mode current on printed circuit board

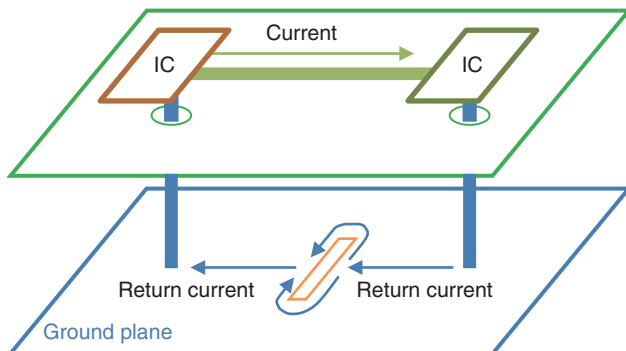


Fig. 6 Effect of slit in ground plane

this results in the generation of common mode current. Also, because the slit makes the electromagnetic field discontinuous, the electromagnetic field widens, and the slit may become a noise radiation source. This is the same phenomenon that occurs in a slot antenna.

Figure 7 provides a concrete example of a wiring design in which this type of large slit may be formed on a printed circuit board from a plurality of adjoining vias.

Because of this phenomenon, the design guidelines stipulate that when there is a plurality of adjoining vias, intervals should be provided between the vias in the manner shown in Fig. 8 so that a return path for the feedback current can be secured.

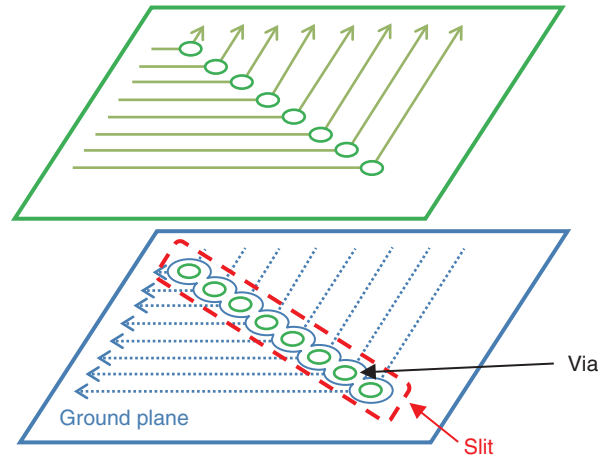


Fig. 7 Plurality of adjoining vias

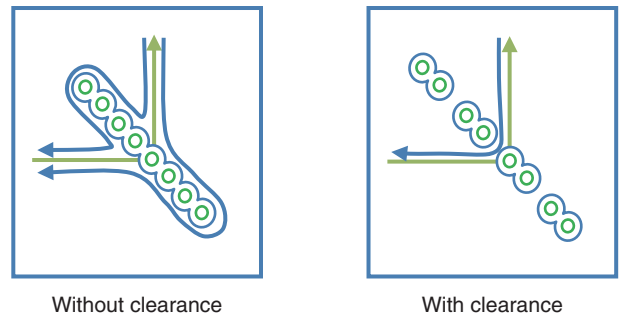


Fig. 8 Secure return path

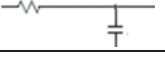
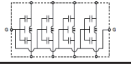
4. Printed Circuit Board for Testing

4.1. Circuit Configuration of the Circuit Board Used in the Noise Comparison Test

To examine whether the circuit board design guidelines are effective for reducing noise, we created the test ECU described below.

We created a test ECU whose circuit board was redesigned according to the circuit board design guidelines

Table 2 Removed noise suppression parts

Type	Equivalent circuit	Quantity
Three-terminal filter		4
Capacitor		4
CR		2
Ferrite bead		6
Ferrite bead array		13
Three-terminal filter array		5

from a conventional ECU, which would normally use a variety of noise suppression parts to reduce FM bandwidth noise. Neither the original ECU nor that with the redesigned circuit board had noise suppression parts mounted thereon. We chose not to use noise suppression parts so that we could compare the noise resulting from the different circuit board designs.

Figure 9 shows the ECU circuit configuration. The circuit comprised a microprocessing unit (MPU), gate array, random access memory (RAM), and power source. The circuit was connected to a wire harness via a connector. The printed circuit board had high-speed signal wiring that included signal buses that could easily serve as noise propagation paths. Also, the circuit board was housed in an aluminum chassis.

4.2. Noise Suppression Parts

Table 2 shows the noise suppression parts that we removed for the purpose of examining the noise reduction effect resulting only from differences in printed circuit board design.

We performed a test to determine whether the test ECU with a printed circuit board that was redesigned according to the circuit board design guidelines (ECU2) exhibited a noise reduction effect compared to the original ECU (ECU1).

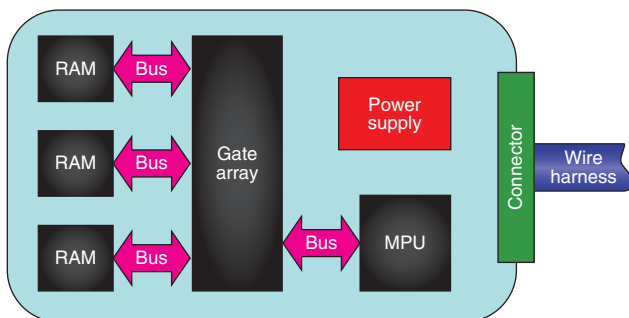


Fig. 9 ECU circuit configuration

5. Results of Noise Reduction Effect Examination

We measured the noise of ECU1 and ECU2 in a 3 m method anechoic chamber that conforms to the CISPR 25 ALSE standard⁽²⁾. The noise measurement results for each ECU are shown in Figs. 10 and 11.

Comparing ECU1 and ECU2, we can see that ECU2 exhibits a noise reduction effect starting from approximately 70 MHz. We were able to confirm that the FM bandwidth noise in Fig. 11 is up to approximately 10 dB μ V/m lower than that in Fig. 10. It is also clear that a noise reduction

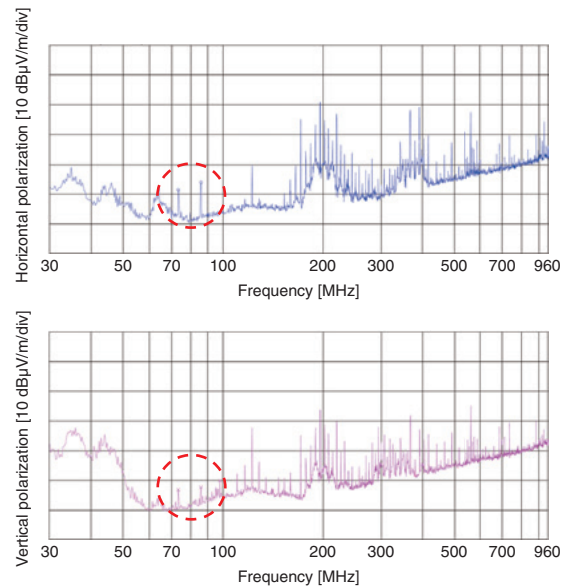


Fig. 10 Noise measurement result (ECU1)

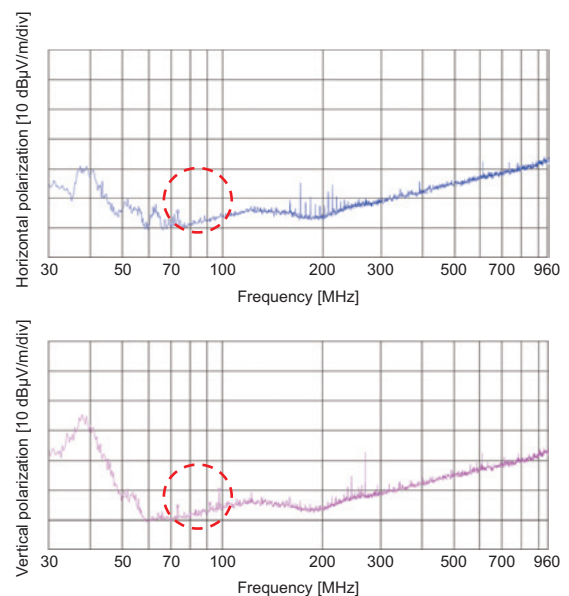


Fig. 11 Noise measurement result (ECU2)

effect is exhibited in bandwidths above the FM bandwidth.

The above results verify that circuit board design techniques that follow the circuit board design guidelines are effective for reducing high-frequency noise in the FM bandwidth and above.

6. Design Process

Appropriately following the circuit board design guidelines requires a significant amount of time for checking and other work. As a result, the necessary design time when the circuit board design guidelines are used is approximately 1.5 times greater than when they are not used. However, we believe that using the guidelines is beneficial from a broader perspective because doing so reduces the number of circuit board revisions and test circuit boards that need to be created in later stages to address noise issues through trial and error.

7. Conclusion

We compiled design principles for printed circuit board design that can be expected to exhibit high-frequency noise reduction effects into a set of circuit board design guidelines.

We were able to confirm that an ECU using a printed circuit board designed according to the circuit board design guidelines exhibited a noise reduction effect of up to 10 dB μ V/m in the FM bandwidth.

There was also a noise reduction effect in high-frequency bandwidths above the FM bandwidth, and we were able to confirm that designing circuit boards in accordance with the circuit board design guidelines is an effective way of dealing with the high-frequency noise that accompanies the high processing speed of ECU circuits.

Circuit board design following the design guidelines is a front-loading design method in which noise countermeasures normally taken in later stages are addressed at the circuit board design stage. The goal of this design is to spend time in the design stage and thereby reduce the time and effort required for countermeasures in later stages. As a result, it is important to understand that the design period will be extended and to create a system for effectively applying the design guidelines.

References

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