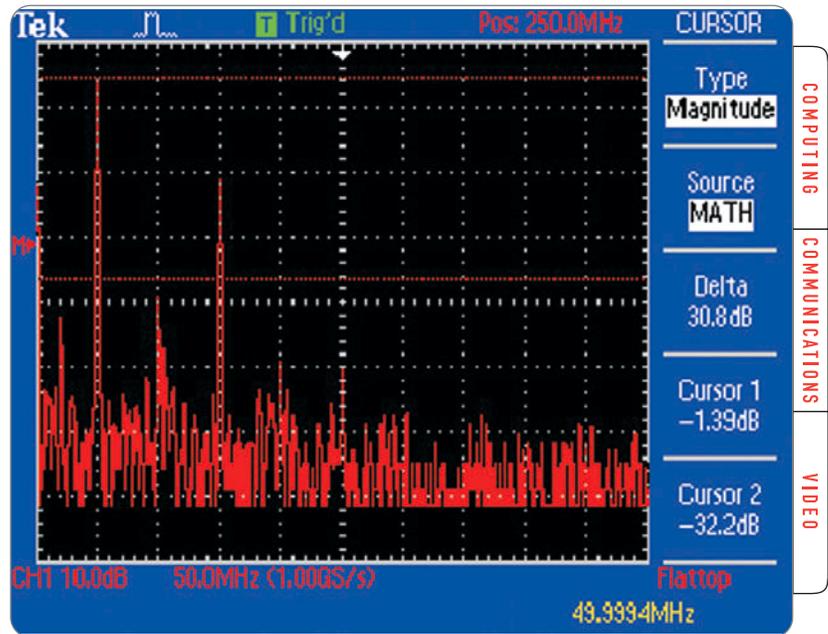


Spectral Analysis And Time-Domain Measurements Join Forces To Solve Troubleshooting Problems



► TDS2000 Series Oscilloscopes Deliver Practical Spectral Analysis to Solve Challenging Design Issues

Engineers and technicians are under constant pressure to solve design problems quickly, and an oscilloscope is usually part of the solution. These oscilloscope users are always looking for tools that can give them a different perspective on either the symptoms or the causes of their design problems, leading them more quickly toward the result they want—a proven, finished product.

The latest generation of affordable oscilloscopes such as the Tektronix TDS2000 Series offers built-in Fast Fourier Transform (FFT) spectral analysis features as standard equipment. With this new capability, users gain a powerful, integrated tool that provides a new perspective for troubleshooting and verification work. In this application note we will discuss FFT basics and illustrate their value in solving everyday measurement problems.

Two Perspectives On The Same Signal

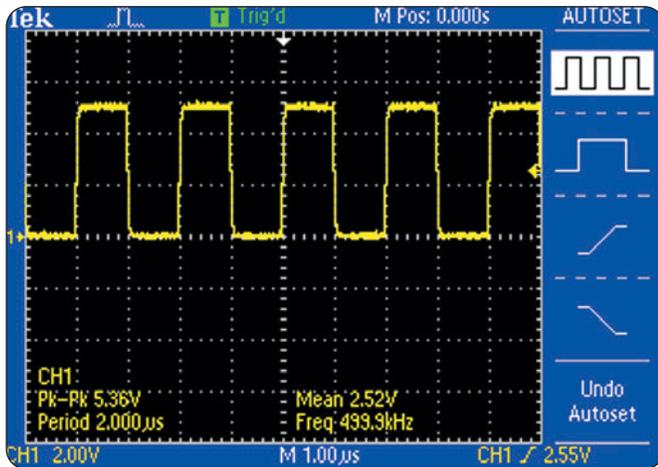
The behavior of electronic signals can be viewed in both time and frequency domains. Each view provides unique details about the events that make up the signal. The time-domain view is the most basic oscilloscope measurement: the signal's changing amplitude

(mapped on the vertical axis) is plotted over the horizontal axis, time. Sine waves, pulses, even uncorrelated noise—all are time-domain views. During troubleshooting, this perspective tells you whether the signal is present, and whether its waveform conforms to the basic amplitude and frequency characteristics your circuit should be producing.

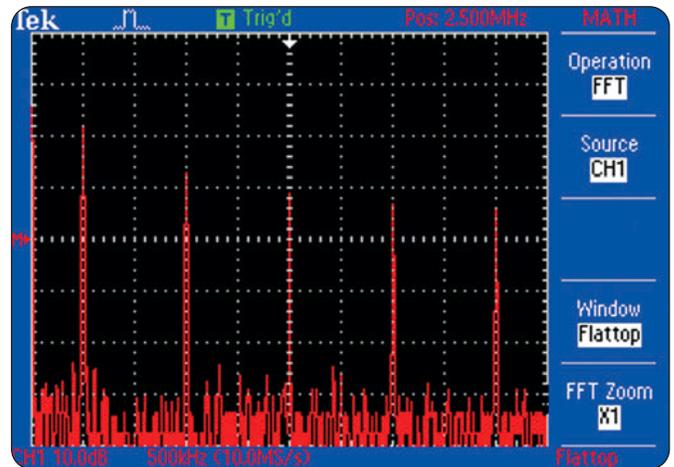
The FFT produces a frequency-domain measurement, known as a spectral view. Using the same signal input as the time-domain view, the FFT reassigns the two axes. The vertical axis now displays amplitude (sometimes known as magnitude, or, if phase information is included, phase) while the horizontal axis displays frequency. The resulting spectral view reveals events and trends unseen in the time domain. The FFT can speed your troubleshooting by making certain types of signal errors very obvious to the eye.

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► **Figure 1.** Time-domain view of a square wave signal



► **Figure 2.** Frequency-domain view of the square wave

Spectral or Spectrum Analysis?

Figures 1 and 2 depict the two contrasting views of a square wave signal.

The FFT's spectral analysis produces an output similar to that of a true spectrum analyzer. However the two technologies differ in some important ways. The spectrum analyzer uses analog mixing and filtering to classify the signal's components into a continuous frequency plot. Because of its analog, non-real-time methodology (it sweeps through the band of interest rather than capturing the signal), the spectrum analyzer does not track a varying signal as well as an FFT.

FFT-based spectral analysis is produced by post-processing stored samples. When properly set up, this approach provides excellent frequency resolution even though its digitally-calculated bins are not as seamless as those of a spectrum analyzer. Because it works on "snapshots" of stored data, the FFT can better track a varying signal.

Some FFT Basics

While a detailed explanation of FFT theory is beyond the scope of this document, it is important to understand the basic concept involved.

Fourier Transform spectral analysis is based on the theory that all complex waves are made up of sine waves combined in various amplitudes, phases and frequencies. For example, a pure square wave is a series of sines, one at each odd harmonic frequency. Therefore a 1 MHz square wave contains sine components at 1 MHz, 3 MHz, 5 MHz, and so on, in successively decreasing amplitudes. All symmetrical waveforms (like triangle waves) exhibit the same harmonic distribution with different amplitudes. Non-symmetrical waveforms (such as rectangular pulses with a skewed duty cycle) also include even harmonics. Such a pulse would exhibit components at 1 MHz, 2 MHz, 3 MHz, 4 MHz, 5 MHz, and so on.

The FFT transforms the sampled signal in the time domain to represent it as a series of spectral peaks in the frequency domain as shown previously in Figure 2. In the TDS2000 Series FFT, each of these peaks denotes the magnitude (expressed in decibels, dB) of the sine wave representing a specific frequency. The usual constraints of resolution and bandwidth apply, but within those tolerances the oscilloscope display reveals the spectrum of frequencies contained in the signal.

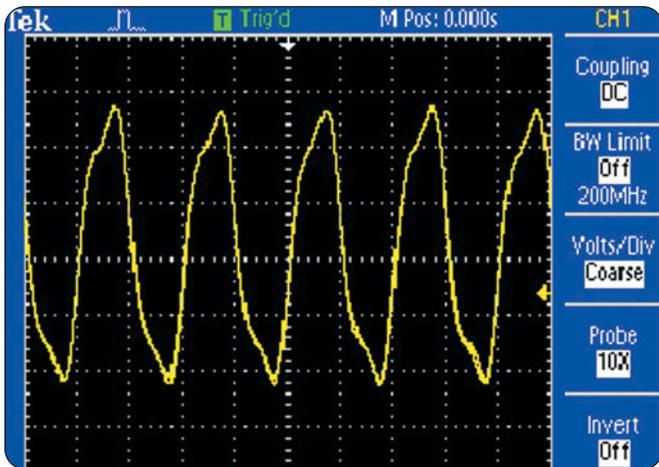
What FFT Can Do For You

Why is this information so useful? Imagine that the square wave FFT image in Figure 2 showed an unexpected peak magnitude on, say, the fifth harmonic. This might point to an irregularity, or aberration, in the waveform (a nearly-indistinguishable overshoot on the rising edge, for instance) or it might indicate crosstalk from signals on adjacent circuit traces. Even though you may not know what is causing the aberrant peak, the spectral view has quickly revealed a problem that might be overlooked in the time-domain view.

The cost-effective Tektronix TDS2000 Series oscilloscopes bring practical spectral analysis to the service tech, the production engineer, and the field maintenance team. The TDS2000 Series makes it easy to examine a waveform and quickly switch to the FFT view for a different perspective.

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► **Figure 3.** Time-domain view of 50 MHz clock signal, showing varying amounts of distortion on peaks. This implies that the signal is being modulated by a lower-frequency source.

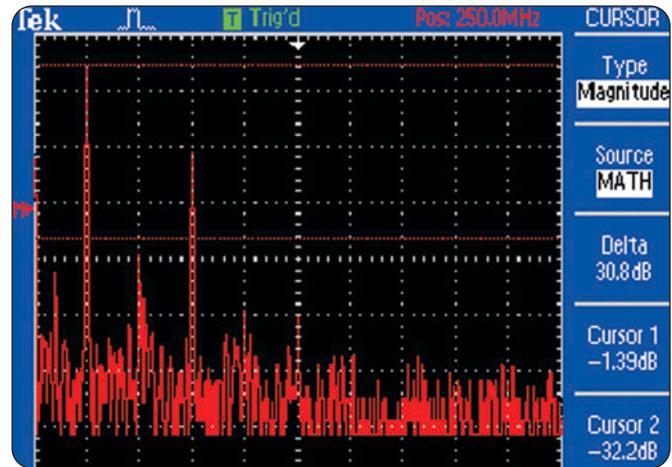
The TDS2000 Series' spectral analysis features support a wealth of applications:

- Electronic troubleshooting: general circuit debugging—detect oscillations and crosstalk; locate noise and crosstalk sources; characterize noise, distortion and frequency response; detect unwanted modulations
- Automotive: suspension and frame design—determine mechanical resonances and stresses
- Aviation: design of wings and control surfaces—locate and correct stress points; reduce vibration; identify mechanical noise sources
- Vibration analysis: design and proof-testing of mechanical systems—detect and eliminate resonances; verify theoretical models; confirm measurements made with other tools
- Environmental: noise reduction—characterize noise levels and frequencies in hospitals, factories, and other work environments; minimize noise due to fans and HVAC systems
- Physiological: health research—measure cardiopulmonary and neurological signal characteristics
- Electronic design: power supply design—measure harmonics and nonlinearities on power supply outputs; detect and quantify oscillations; characterize distortion and harmonics in DC-to-DC converters

FFT Application Examples

Electronic Troubleshooting

FFT analysis is a powerful adjunct to conventional time-domain measurements with an oscilloscope. Simply by switching to the FFT mode and viewing the signal, it is often possible to detect behaviors that are almost invisible in the time-domain waveform.



► **Figure 4.** Frequency-domain view of the 50 MHz clock. A peak at 20 MHz reveals the source of the modulation.

A signal may contain frequency components that are masked in the time-domain view by the signal's normal content. An FFT view can reveal this at a glance.

The FFT is an ally in the search for noise and oscillation-related problems in all types of circuits. Even in this age of software design tools and modeled prototypes, the first hardware prototype of a new design often presents many unexpected results. One of the most common problems is unintentional coupling of signals from one circuit trace to another, "modulating" the signals on the affected line. This crosstalk is a problem today and will become an even greater challenge as operational frequencies continue to increase in the future.

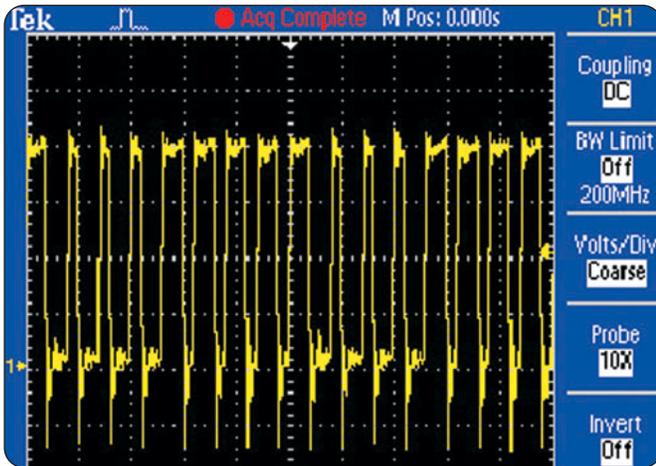
To illustrate the situation, consider the time-domain waveform in Figure 3. This is a 50 MHz clock signal from a processor board. In a perfect world, the waveform would be a symmetrical wave, but modern digital circuits are fairly forgiving and the signal shown here is sufficient to clock the device reliably under normal circumstances.

Knowing this, it would be easy to overlook the small differences in the peaks of each waveform cycle. But the slightly irregular wave shape implies that something is modulating the main clock signal at a subharmonic frequency. What is the frequency, and what is the extent of its presence in the clock signal?

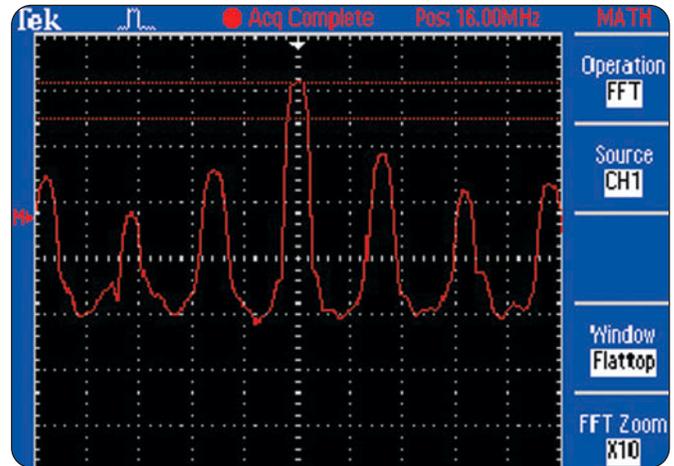
Switching the oscilloscope to FFT mode provides immediate answers to these questions. Figure 4 shows the FFT view of the same 50 MHz clock waveform shown in Figure 3.

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► **Figure 5.** A 16 MHz signal that is being phase-modulated by a 2 MHz frequency.



► **Figure 6.** The FFT plot of the 16 MHz signal. Note sidebands on 2 MHz spacing due to the modulating 2 MHz signal.

The frequency range of the FFT display is set to 500 MHz, which means that each horizontal division equates to 50 MHz. The left side of the graticule is 0 MHz. The tallest peak, on the first vertical division line, represents the fundamental frequency of the clock signal. On the next two vertical lines, we see the second (100 MHz) and third (150 MHz) harmonics, respectively. These appear in normal proportions, as do the remaining higher-order harmonics. But something is going on between 0 MHz and the 50 MHz fundamental. There is a peak at about 20 MHz that is almost as large as the second harmonic. The presence of this subharmonic peak confirms that an unwanted 20 MHz signal is indeed modulating the clock. With one keystroke, the FFT has verified that there is crosstalk, and has pinpointed the offending frequency. For the troubleshooter, this is the clue that expedites the search for the modulating signal and the means by which it is coupling into the clock line.

Characterizing Phase Modulation

In the previous example we looked at the effects of unintentional modulation caused by crosstalk. In some cases, modulation is used intentionally. Phase modulation, for example, can be used to vary specific pulse widths within a stream of binary information. The phase changes represent binary information—ones and zeroes.

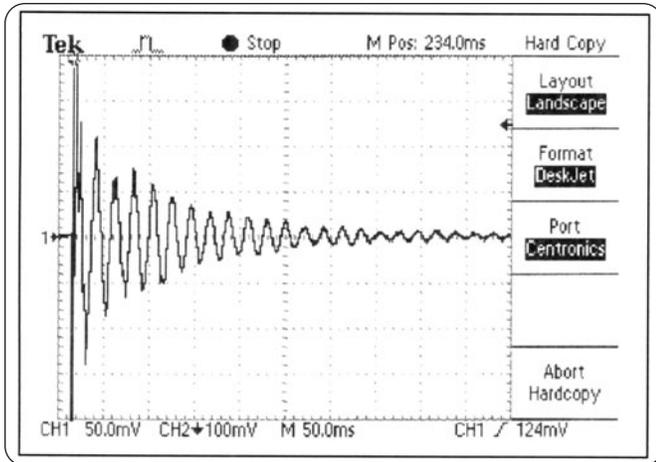
The pulse train in Figure 5 is a 16 MHz clock signal that has been modulated by a 2 MHz square wave. Note that the result is a pattern that repeats in groups of eight pulses—as you might expect from the arithmetic ratio of the two interacting signals. Here, the ratio of "narrow" to "wide" pulses is the modulation variable—the way in which up to eight states can be represented. In Figure 5, the ratio is 5:3; that is, five wide to three narrow.

Viewing the phase-modulated signal in the frequency domain (using the FFT), the effects of the modulation are clearly visible. In Figure 6 ("zoomed in" by a factor of ten for clarity), the frequency on the center line is the fundamental, 16 MHz. The dividing characteristic of the 2 MHz modulating frequency shows up as a series of sidebands at 2 MHz intervals. By examining the relative amplitudes of the sidebands, it is possible to identify which of the divide ratios is in effect. Knowing this, you can easily determine which of the 8 possible states is represented.

Although this information can also be distinguished in the time-domain view, the FFT approach simplifies and speeds interpretation. If the signal is noisy, for example, it may be difficult to identify the pattern of the data in a time-domain view. This problem becomes even more challenging when the difference between "wide" and "narrow" pulses becomes smaller. But the FFT is inherently able to distinguish between the modulation and the noise, even when there are fairly small variations in phase.

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► **Figure 7.** The time-domain view of the resonant frequency of the roof bow beam.

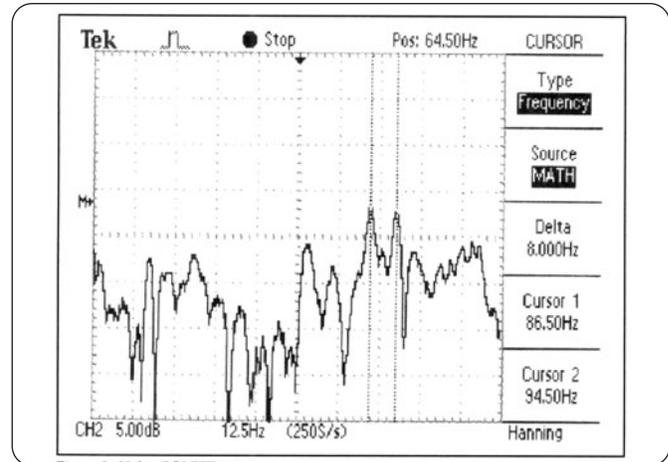
Analyzing Mechanical Resonances and Vibration

In the design of automotive equipment, a component's mechanical resonances can have a big impact on the comfort and safety of the vehicle's passengers, as well as the reliability of the component itself.

This makes it necessary to predict the fatigue life of various structural elements within the automobile. A case in point is the car's roof bow (a support beam above the front seats) which is increasingly being used to support optional equipment such as DVD viewers and associated mounting fixtures. The roof bow's "natural" (resonant) frequency is important to know, as are the effects on the beam of the acceleration and deflection in the vehicle's chassis as a whole.

The basic resonant frequency of the roof bow can be determined with accelerometers and an impact hammer, a specialized tool that sends a trigger signal to an oscilloscope when the hammer face hits a target surface. It can also provide information about the amount of force applied and whether or not any "deadening" of the blow occurred due to resilient surfaces. The oscilloscope captures the response from the sensors and displays either the time-domain waveform or its spectral equivalent.

The time domain waveform resulting from the hammer strike appears in Figure 7. This is a classic damped oscillation waveform with a natural resonant frequency of 47.4 Hz, a figure determined by using the oscilloscope's automated frequency measurement feature. Note that Figure 7 is not an FFT plot.



► **Figure 8.** FFT plot of the vibrations occurring on the roof beam during simulated vehicle movement.

The next step is to measure the vibrations that might occur in real-world driving conditions, that is, continuous shocks and stresses at unpredictable frequency and intensity. One proven method is to build a simple excitation source—such as an intentionally unbalanced rotating weight—and place it a strategic point in the car. With sensors attached at the roof bow, the resulting TDS2000 Series FFT plot is shown in Figure 8. In this example the critical resonant peaks occur in the range from 85 Hz to about 95 Hz. Here, a cursor measurement pinpoints the frequencies of the two peaks.

When the data was compiled, the study proved that there was a consistent relationship between the natural frequency of the roof bow, and the acceleration that could be expected at the point of interest when the chassis itself experienced an acceleration. Findings such as those in Figure 8 are valuable to the designer developing mechanical components. The FFT plot narrows down the field of variables, and provides reliable preliminary results that engineers can use to confirm modeled parameters and stresses. It is of course essential to verify these initial measurements with subsequent tests using a laboratory-quality signal analyzer and Finite Element Analysis tools.

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Some Caveats About Aliasing

The FFT capability built into Tektronix TDS2000 Series oscilloscopes is meant to be a convenient and easy-to-use tool that supplements the normal time-domain capabilities. It works on sampled data to provide fast answers about the spectral content of a signal.

The Nyquist sampling theorem, on which all sampling devices (including DSOs like the TDS2000 Series) are based, states that the highest frequency that any system can reproduce is less than but not equal to 1/2 its current sample rate setting. Thus a 100 megasample-per-second rate can acquire and allow reproduction of a 50 MHz sine wave signal.

Note that the Nyquist theorem stipulates a sine wave input signal. As explained earlier, non-sinusoidal waveforms contain higher harmonic frequencies. In an FFT, a phenomenon known as aliasing can cause these higher-frequency signal components to be incorrectly displayed within the frequency band of interest. If the acquired signal contains harmonics that exceed the sample rate, aliasing will occur even though the fundamental is within the Nyquist frequency specification.

A dedicated spectrum analyzer, since it does not sample the data, does not suffer from aliasing. Thanks to its filtering and sweep ranges, it can focus on a small portion of the bandwidth that is open to it.

With models offering up to 200 MHz bandwidth, the TDS2000 Series oscilloscopes can meet a wide range of FFT analysis needs without aliasing. To avoid aliasing under many circumstances when performing spectral analysis with a TDS2000 Series instrument, simply adjust the sample rate such that a stable display of at least one cycle of the waveform is visible in the time-domain view.

Contact Tektronix:

ASEAN / Australasia / Pakistan (65) 6356 3900

Austria +43 2236 8092 262

Belgium +32 (2) 715 89 70

Brazil & South America 55 (11) 3741-8360

Canada 1 (800) 661-5625

Central Europe & Greece +43 2236 8092 301

Denmark +45 44 850 700

Finland +358 (9) 4783 400

France & North Africa +33 (0) 1 69 86 80 34

Germany +49 (221) 94 77 400

Hong Kong (852) 2585-6688

India (91) 80-2275577

Italy +39 (02) 25086 1

Japan 81 (3) 3448-3010

Mexico, Central America & Caribbean 52 (55) 56666-333

The Netherlands +31 (0) 23 569 5555

Norway +47 22 07 07 00

People's Republic of China 86 (10) 6235 1230

Poland +48 (0) 22 521 53 40

Republic of Korea 82 (2) 528-5299

Russia, CIS & The Baltics +358 (9) 4783 400

South Africa +27 11 254 8360

Spain +34 (91) 372 6055

Sweden +46 8 477 6503/4

Taiwan 886 (2) 2722-9622

United Kingdom & Eire +44 (0) 1344 392400

USA 1 (800) 426-2200

USA (Export Sales) 1 (503) 627-1916

For other areas contact Tektronix, Inc. at: 1 (503) 627-7111

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