How Do You Build an OCT A-scan System?

VCSEL Swept Sources are poised to fuel the third generation of OCT systems and enable large market penetration for various application in medical and industrial segments. The CALIPER platform from OCTLIGHT is a VCSEL Swept Source addressing this new generation of OCT. This application note describes how to use the CALIPER for fast OCT imaging systems.

Figure 1 shows an eye examination at an ophthalmologist.
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Introduction

Optical Coherence Tomography (OCT) is a technology for non-invasive cross-sectional optical imaging of tissue [1]. Tomography is the cross-sectional imaging that slices the sample into sections.

OCT is widely adopted within eye care where it is the gold standard for in vivo imaging of the retina [2]. The eye specialist can perform non-invasive optical biopsies using the OCT technique. Figure 2 shows a schematic of an OCT system where light from the wavelength sweeping laser is split into a reference and sample arm and the interference of the reflected signals at the beam splitter is then detected by a photodetector. The OCT technique allows the doctor to see a cross-section of the retina of the eye where the sharp vision is formed.

Are you wondering how to get started with your OCT A-scan system? Then read this application note, where we describe the system, main concepts, and details from the optical characteristics to the signal processing. When that is in place you are ready for the next step regarding how to add the light beam scanner and scanning optics specific to your application.
How to set up the VCSEL Swept Source

In the following section we will describe how you characterize the VCSEL Swept Source.

The Caliper VCSEL Swept Source

The Caliper VCSEL Swept Source, seen in Figure 3, is the ideal wavelength sweeping laser for Swept Source OCT (SS-OCT). With its small and compact form factor, flexible and fast sweeping-rate and being based on reliable VCSEL technology, this is the scalable technology of choice within cost efficient and niche to mass market 3D sensing applications.

The Caliper laser platform is built in full-body aluminum enclosure, ready for integration in products or in a R&D setup. The laser has the interface for integrated with data acquisition and laser safe system: power, interlock, USB communication, sweep trigger output and laser optical fiber output.

The laser is enabled through the software interface, and once started, the laser sweeps the desired bandwidth and at the desired frequency, synchronously with the output trigger signal for data acquisition synchronization.

Power Spectrum

The optical power spectrum shows the averaged output power with the wavelength sweep. This confirms the wavelength sweeping operation. Connect an optical spectrum analyser (OSA) or a narrow band (ca. 100nm) spectrometer at about 1060nm. Make sure to use FC/APC to connect to the VCSEL Swept Source and FC/PC to connect to the OSA.
The example spectrum Figure 5 is flat and has a peak on each side. The peak at each end of the spectrum is due to the sinusoidal motion of the MEMS, which reduced the wavelength sweep rate at each end of the wavelength sweeping range where the MEMS is turning.

The intensity outside of the sweeping range seen in Figure 5 is the amplified spontaneous emission (ASE) of the semiconductor optical amplifier (SOA) used to amplify the optical output power to the desired value. The ASE is a DC part of the OCT signal and is filtered by the balanced detector in the system. The noise floor of the laser is around -40dB below signal intensity.

The wavelength sweep bandwidth is 40 nm, which defines the axial resolution calculated using this formula:

$$\delta_z = \frac{4 \ln (2) }{n \Delta k} = \frac{2 \ln (2) \lambda_0^2}{n \Delta \lambda} \approx 12 \mu m \text{ in air, or } 9 \mu m \text{ in tissue (refractive index } \sim 1.4)$$

with the following parameters

- $\lambda_0$: Central wavelength of laser = 1060nm
- $\Delta \lambda$: Sweeping Bandwidth of laser = 40nm
- $\Delta k$: Sweeping Bandwidth of laser in k
- $\delta_z$: Resolution along optical axis
- $n$: Refractive index of material
A-scan Trigger

Each wavelength sweep of the VCSEL Swept Source generates a depth scan referred to as A-scan. Lateral scanning in the x-y planes generates line and volume scans, referred to as B-scan and C-scan respectively. To synchronize the VCSEL wavelength sweep with the digitizer the VCSEL Swept Source provides a A-scan trigger signal output. It produces an rising edge for each sweep cycle. This can be recorded with an oscilloscope, an example of which is seen in Figure 6 with a trigger frequency of 757.9kHz. The A-scan trigger indicates both upward and downward wavelength sweep on rising and falling edge, hence the A-scan rate of the OCT system will be twice 1515.8kHz.

![Oscilloscope Trace](image)

*Figure 6 shows the oscilloscope trace of the A-scan trigger.*
How to build the A-scan setup

The first step in building an OCT system is to build the OCT interferometer with reference arm/delay line and a sample arm with a single reflection, referred to as A-scan. The next step is then to insert a beam scanner and scan lens, also called OCT scanner, to scan the probe beam and reconstruct the image. The beam scanner is application depend, why this document focus on how to do a A-scan setup.

An optical block diagram of a OCT system is seen in Figure 7. An example list of components is seen in the Appendix on page 34.

Figure 7 Diagram of an Optical Coherence Tomography system using fiber couplers in a Michelson interferometer configuration.
In the following key design consideration of the Optical Coherence Tomography system will be described.

Choosing the optical reference path

OCT is a differential measurement method and thus it is crucial that the optical reference path $L_S$ and sample path $L_R$ are equally long. The variables in the following equations refer to the fibre lengths (remember to account for the refractive index). The variables are shown in the optical block diagram Figure 7 in blue writing.

$$L_S = n(3C_1 + X + C_2) + 2S$$
$$L_R = n(C_1 + 2M + 2A + C_2) + \frac{\Delta R}{2}$$
$$X = -2C_1 + 2M + 2A + \frac{\Delta R}{2n} - \frac{2S}{n}$$

For the system described above with a sample arm distance of 25cm and a M of 1.5m, the custom made fiber must have a length of 72cm.

$$X = -2 \cdot 1m + 2 \cdot 0.5m + 2 \cdot 1m + \frac{0.175m}{2 \cdot 1.5} - 2 \frac{0.25m}{1.5} = 0.725m$$

Choosing the right Balanced Photodetector

The choice of balanced photodetector depends on the wavelength sweep rate and the desired measurement range:

$$BW = 2z_{max} \cdot n \cdot \frac{f_{sweep} \Delta \lambda}{F_d \lambda_0^2}$$

- $\lambda_0$ VCSEL Swept Source center wavelength = 1060nm
- $\Delta \lambda$ VCSEL Swept Source wavelength bandwidth = 40nm
- $f_{sweep}$ VCSEL Swept Source wavelength sweep rate
- $z_{max}$ Measurement range
- BW Balanced Photodetector bandwidth
- $n$ Refractive index of sample material
- $F_d$ Factor of duty cycle (data acquisition time during a wavelength sweep)

For a system with a sweep frequency of 1.7MHz, a duty cycle of 1 and a measurement range of 7mm in air, this would result in a BW of 850MHz.
Choosing the right Digitizer

The Sampling rate of the digitizer must be at least twice the bandwidth BW. If there is a high order analog anti-aliasing filter built into the digitizer this will suffice. If it there is no such filter, your sampling frequency probably needs to be a decade higher than the BW of the detector.

\[ f_s = 2 \times BW \quad OR \quad f_s = 10 \times BW \]

\( f_s \) Sweeping Frequency of laser
\( BW \) Bandwidth of balanced detector

For the above balanced detector, this means a sampling frequency of at least 1.7GSPS (remember to consider antialiasing).

Testing the System

In the following section the optical spectrum is characterized throughout the OCT system to show how each component alter the original optical spectrum of the VCSEL Swept Source.

Power spectrum at system input

Figure 9 shows the optical spectrum measured using the setup in Figure 8. For reference, the laser output was calibrated to enter the sample system with 100uW of power. To do so an additional attenuator was used. This does not influence the spectrum.

Measurement setup:
Power spectrum at system sample arm

Figure 11 shows the optical spectrum measured at the point seen in the setup of Figure 10.

Measurement setup:

![Measurement setup diagram](image)

*Figure 10 shows the setup with a swept source, 80/20 coupler, and OSA.*

Spectrum:

![Spectrum graph](image)

*Figure 11 shows the spectrum at system sample arm with an additional attenuator.*
Power spectrum at balanced detector

Figure 13 shows the optical spectrum measured at the negative and positive input of the balanced photodetector using the setup seen in Figure 12.

Measurement setup:

![Diagram of the measurement setup](image)

Figure 12 shows a schematic measurement setup.

Spectrum:

![Spectrum graphs](image)

Figure 13 shows the spectrum at a) negatively and b) positively balanced detector.
Acquisition of A-scan OCT signal
Figure 15 shows the Fourier Domain (FD) signal measured at the balanced photodetector seen in Figure 14 and the A-scan acquired by a digitizer card (a delay setting can be used to compensate signal delay). The optical path delay (OPD) for this measurement between the single reflector and delay line was 2 mm.

Setup:

Result:

Figure 14 shows a schematic measurement setup.

Figure 15 shows the frequency domain signal (blue) and the trigger signal (black).
Further information and support
Following the above tutorial, you have acquired your first OCT A-scan signal with the Caliper VCSEL Swept Source.

In order to generate OCT images, you need to insert a beam scanner in the sample arm and implement digital signal processing to compute the Spatial Domain (SD) signal for visualization. We cover how you can do the signal processing in Appendix A: OCT signal post-processing on page 14. Before doing the signal processing you need to do calibration of the OCT system as described in Appendix B: OCT system calibration on page 26 which is describe the remapping used to linearize the FD signal before Fourier Transform, how to measure the axial spacing unit to get the SD signal and how to measure the OCT Sensitivity.

We hope you have found this application note on how to build a OCT A-scan setup useful. For additional questions, quote on the VCSEL Swept Source or support in your application you can contact us at sales@octlight.com or +45 53862737.

References
Appendix A: OCT signal post-processing

In this section on OCT signal post-processing the numerical procedure to take the raw signal Fourier Domain (FD) from the digitizer to the Spatial Domain (SD) signal is presented. Figure 16 shows the full a-scan processing chain.

Figure 16 shows the post-processing steps from digitizer to visualization.

Those steps are explained one by one in this section.

Fourier domain signal

First the balanced detected interferogram needs to be digitized by an acquisition hardware. Usually this is a digitizer PCI card including an anti-aliasing filter. The sample data in Figure 17 is from a single reflecting surface.

Figure 17 shows the FD-signal for a single reflecting surface.
Background signal removal

In a calibration measurement one can record measurements while blocking the sample arm, reference arm and both arms. Using this, one measures reference arm, sample arm and dark background light. Subtracting these from the signal will minimize most of the DC part of the signal. It can also reduce auto-correlations. Figure 18 shows the FD Signal after the removal of the background signal which centers the FD signal.

![Figure 18](image)

*Figure 18 shows the FD-signal for a single reflecting surface when the background is removed.*

Removal of DC offset

After the background removal a DC filter gets rid of any DC parts that are still in the signal. This is particularly important as some of the post-processing algorithms are not designed to deal with big DC offsets in the signal. Especially the remapping algorithms can have very different performance. Figure 19 shows the FD signal after DC filtering and it is now centered around zero.
Figure 19 shows the FD-signal for a single reflecting surface after adding a DC-filter.

**Windowing**

The windowing process step reduces side-lopes in the SD-signal by reducing the impact of the edges of the sweep where the relative intensity noise (RIN) is usually higher than at the middle part. Further it shapes the power spectrum of the sweep in a Gaussian form. This also contributes to a Gaussian form of the peak in the SD-signal. Figure 20 shows the FD signal after Hann windowing which is now closer to the ideal Gaussian-shaped coherence function of a Gaussian-shaped light source.
Figure 20 shows the FD-signal for a single reflecting surface after windowing.

Inverse Fourier transform

The inverse Fourier transformation converts the frequencies of the FD-signal to the peaks of the SD-signal. Those peaks correspond to the optical path differences of all the reflections of the sample arm. The frequencies of those peaks depend linearly on this path difference. Therefore, one can calibrate them to represent distances. Figure 21 shows the FD signal after the inverse Fast Fourier transform with a single peak and its mirror.

Figure 21 shows the FD signal for a single reflecting surface after a inverse fast Fourier transform (IFFT).
Fourier shift

In OCT by convention, one usually shifts the FFT so the DC part of the signal is in the middle and the highest frequency is at the edges. Figure 22 shows the FD signal after the iFFT shift.

![Typical FD-Signal]

Figure 22 shows a FD signal of a single reflecting surface after a IFFT shift.

OCT magnitude

After the Fourier transformation the signal is complex. For the display of the OCT signal the absolute value is calculated. The phase is neglected in most case. Figure 23 shows the absolute value of the FD signal.
Figure 23 shows the FD signal for a single reflecting surface after taking the absolute value.

OCT logarithmic scale

As intensity differences of reflections may vary in order of magnitudes one usually converts the signal to a logarithmic scale. Figure 24 shows the FD signal on a logarithmic scale. The balanced detector bandwidth of 1.2GHz is seen by the drop in signal amplitude from -70 to -100 dB. On the right side is a zoomed version of the same measurement that displays the frequencies of the FD-signal. As the laser is sweeping sinusoidal it is expected to be a broad peak like that. To create a sharp PSF, a remapping of the signal is necessary. This is one of the two processing steps missing in the processing chain above. To perform a remap, the system must be calibrated. More to that can be found in the calibration section of the document.
Figure 24 shows the FD signal in dB. This makes it apparent that there is a bandwidth limitation at 1.2GHz which is due to the photodetector.

Remapping
When doing OCT, it is important that the samples are measured equally spaced in relation to the wavenumber (k). This means there is only one frequency in the FD-signal for a single reflective surface. Often this is not the case because the sweeping laser does not sweep linearly in k. Then the measured signal has a frequency chirp. Figure 25 shows the FD signal of a single reflective surface where a frequency chirp is present. Notice, in this case the frequency is slower at the edge and faster in the middle of the A-scan.

Figure 25 shows the FD signal for a single reflective surface without sample equally spaced in relation to wavenumber.
Remapping resamples the measured points using a calibration vector to compensate for this. The resulting FD signal is seen in Figure 26. Now, there is no frequency chirp anymore.

**Figure 26 shows the FD signal for a single reflective surface with sample equally spaced in relation to wavenumber.**

Figure 27 shows the FD signal after iFFT of Figure 25 without remapping.

**Figure 27 shows the FD signal for a single reflecting surface without remapping.**

Figure 28 shows the FD signal after iFFT of Figure 26 with remapping. The peaks become narrow.

**Figure 28 shows the FD signal after iFFT of Figure 26 with remapping. The peaks become narrow.**
Figure 28 shows the FD signal for a single reflective surface with remapping (equally spaced in relation to wavenumber).

This shows that remapping is one of the critical steps in the OCT processing chain and the quality of the calibration vector is crucial for its performance. Remapping is described in Appendix B: OCT system calibration on page 26.

Note: Instead of remapping there is also the possibility of sampling the data direct linearly in k. This requires a so-called k-clock and a digitizer capable of measuring according to an external trigger signal. The third option is to have the laser sweeping linear in k (check out Caliper-FLEX for this option).

Dispersion compensation

If there is a lot of dispersion in the system, there is the possibility to compensate for it because dispersion just adds a complex phase to the signal which we can adjust mathematically. For low dispersion system this is not necessary. Figure 29 shows the FD-signal after compensation for dispersion in the OCT system.
Figure 29 shows the FD-signal after compensating for the dispersion in the system.

Dispersion compensation is done by multiplying a complex phase to the windowed FD signal. This is basically a Taylor approximation of the dispersion with a fourth order polynomial. With that is possible to sharpen one peak at the expense of the other. The resulting FD signal is seen in Figure 31.
Figure 30 shows the FD-signal after compensating for the dispersion among the other steps in the diagram above.

Comparing Figure 31 and Figure 28 it can be seen that the FD signal is more narrow. If the coefficients are precisely chosen, then this improvement will apply to all frequencies.

Figure 31 shows a close-up of the FD-signal after compensating for the dispersion.
Figure 32 shows the FD-signal after compensating for the dispersion in the sample.
Appendix B: OCT system calibration

For the OCT post-processing, it is especially important that the sweep is linear in k-space where k is the wave number. For a stable VCSEL Swept Source such as the Caliper-HERO the k-linearization can be done using a remapping procedure.

Remap

Remapping can be applied after acquiring the OCT signal. It is a mathematically an interpolation or resampling of the OCT A-scan signal such that the OCT vector is linear in k and not time (as it will typically be from sampling the digitizer at a fixed sampling clock). The difference between the k-linear and timewise linear points are shown in Figure 33. To do the interpolation there are multiple algorithms from low computational demands like linear interpolation, to very high computational demands like a cubic spline interpolation. The results of the interpolation get better with more complex algorithms.

To create such a remap vector an OCT signal of a single reflection is required. With the aid of the Hilbert transformation this is converted to an analytical signal. From there the phase can be extracted. When unwrapped it is the remap vector. Therefore the remap vector basically contains the phase information of the analytical signal $X_a$:

$$X_a = H(t) + j \cdot \mathcal{H}[X(t)]$$

To illustrate this without diving into complex math the idea behind it is shown graphically in the Figure 34. The starting point is a real signal (a), where positive and negative frequencies are symmetric. With the help of Hilbert it is transformed to a pure imaginary signal (b). Multiplying it with the imaginary number j rotates it by 90° (c). If a and c are now added the result is d which is the analytical signal.
Another way to look at this is by taking the frequency spectrum of a real signal and deletes all the negative frequencies. Thus, resulting in the following equation for the analytical signal:

\[ X_a = \mathcal{F}^{-1}[F(X(t)) \cdot 2\varepsilon(f)] \]

Where

\[ \varepsilon(f) = \begin{cases} 0 & \text{if } f < 0 \\ 1 & \text{if } f \geq 0 \end{cases} \]

Therefore, the phase of a FD-signal is:

\[ \varphi_{X_a} = \angle X_a \]

The creation of a remap vector for an OCT system needs a calibration method that acquires one sweep with a system that has exactly one reflecting surface and therefore single OPD. For such a system the interference signal is described by the equation below. There are two terms contributing to the phase of this sweep. One is caused by nonlinearities of the laser, the other by dispersion.

\[ I_D = S(k)\left[2r_Sr_R \cos\left(2k\Delta z + \Delta \varphi_{\text{Disp}}(k)\right)\right] \]

By subtracting the phases of two different OPDs we extract the dispersion free phase information.

\[ \varphi_{\text{remap}} = \varphi_{X_{a1}} - \varphi_{X_{a2}} = \left(2k\Delta z_1 + \Delta \varphi_{\text{Disp}}(k)\right) - \left(2k\Delta z_2 + \Delta \varphi_{\text{Disp}}(k)\right) \]
\[ = 2k\Delta(z_1 - z_2) \]

This is only true if the dispersion remains unchanged between the two OCT A-scan signals, which is true when calibrating with a mirror at two different OPDs in air. Once this remap vector is found it can be used repeatedly to do the necessary resampling of the measurements as depicted in Figure 35. The only condition for this to work is that the nonlinearity in \( k \) does not change in time.

![Figure 35 Conversion from a not remapped signal to remapped signal.](image-url)
2-point calibration

From a practical point of view this means two calibration measurements are needed for calibrating the nonlinear k-sweeping of a swept source laser. As a rule of thumb those calibration measurements should be at on third and two thirds of the target measurement range. So, if the target measurement range is 10mm, then the calibration measurements should be at 3.3mm and 6.6mm. The sample must create only one clean single reflection. Thus, either a mirror or a glass surface is appropriate. But consider the thickness of the glass as it has a back side. Therefore, the glass thickness must be bigger than the measurement range or it has a wedged back side which does not reflect.

When applying the above calculations to those two calibration measurements results in the remap vector. Now the last remaining step is to scale the remapped vector so it translates the number of input samples to the new number of output samples. This is done by dividing the total phase and multiplying the desired number of output sample.

\[ \text{Scaling factor} := \frac{N_{\text{desired}}}{\phi_{\text{max}}} \]
The axial sampling unit (ASU) is the distance between two measurement points. Thus, it can be calculated with the measurement range and number of recorded points during a measurement which is shown in Figure 37. They are both dependent on the sweeping range in k.

Hence:

\[
\text{asu} = \frac{2z_{\text{max}}}{f_s T_{\text{Sweep}}} = \frac{z_{\text{max}}}{N_{\text{Sweep}}} = \frac{\pi}{\Delta k}
\]

This means the ASU is another unit to describe the axial resolution of a system if the system does not use zero-padding. It can be measured with a precise calibration target which is explained on the next page.
Target sample

To calibrate the ASU of an OCT system one needs a special target with two reflecting surfaces at a highly precise distance and a good remap vector or other method for k-linearization. The two reflecting surfaces produce one peak each. The ratio of the physical distance of the two surfaces and the distance in number of sample points give the ASU. For example, two reflecting surfaces exactly 1mm apart produce two peaks with 1000 measurement points in between results in an ASU of 1mm/1000px = 1um/px.

The accuracy of the spacing between the two reflecting surfaces is therefore crucial as it directly translates to the accuracy of the calibrated OCT system. One way to reach a high accuracy is with the test target shown in Figure 38. The spacer ring here is very precisely machined. The reflecting surfaces are the two glass rods on each side of the spacer ring.

![Figure 38 Example of ASU calibration target.](image)

Measuring the OCT Sensitivity

An OCT system can measure very weak signals. That is because the measured reflected signal from the sample arm is optically amplified by the reference arm. The dynamic range of a detector is limited though to the number of bits of the digitizer. This limits the dynamic range of the OCT system to about 72dB for 12bit digitizers and 60dB for 10bits. The faster the detector the smaller is the number of bits. Therefore an OCT system cannot be characterized by the SNR. The SNR measurement would only return the digitizers dynamic range. So the sensitivity is defined as the ratio between the maximal signal power and the minimal detectable signal power $R_{s,min}$.

$$\Sigma = \frac{1}{R_{s,min}} = \frac{SNR_{max}}{R_{s,min}}$$

To measure this the sample arm signal has to be dampened to the point where the dynamic range does not limit the SNR measurement anymore and the optical system needs to be optimized for a maximized signal.

This is achieved by inserting tilted neutral density filter into the sample arm as seen in Figure 39.
In general, the SNR can be calculated as follows:

$$SNR_{dB} = 10 \log \left( \frac{I_D^2}{\sigma_N^2} \right) = 20 \log \left( \frac{I_D}{\sigma_N} \right)$$

Here $I_D$ is the detector signal and $\sigma_N$ is the noise as shown in Figure 40. Applied to a SD-signal this means:

$$SNR_{dB} = 20 \cdot \log_{10} \left( \frac{P}{\text{RMSNoise}} \right)$$

Figure 39 shows the sample arm with a tilted neutral density filter.

Figure 40 The graph shows the SD signal with the sample peak value $P$, the noise root means square (RMSNoise) and noise standard deviation ($\sigma_{Noise}$) with the zero term in the center.

To get to the sensitivity, the inserted losses need to be considered as well. The are the ND filter $V_{filter}$ and reflective of the sample $V_{Sample}$.
To get the sensitivity everything needs to be added up. The filters need to be accounted for twice, as the light travels forth and back.

\[ V_{Filter_{dB}} = -10 \cdot \log_{10}(T_{ND1} \cdot T_{ND2}) \]
\[ V_{Sample_{dB}} = -10 \cdot \log_{10}(R_{Sample}) \]

\[ \text{Sensitivity}_{dB} = \text{SNR}_{dB} + 2 \cdot V_{Filter_{dB}} + V_{Sample_{dB}} \]
### Appendix C: Example of item list for OCT setup

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</tr>
<tr>
<td>Delay line</td>
<td>Gooch &amp; Housego OCT Variable Optical Delay Line</td>
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<tr>
<td>Sample arm</td>
<td>Application dependent</td>
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<td>Polarization Controller</td>
<td>Thorlabs FPC020</td>
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<td>Attenuator</td>
<td>Thorlabs VOA1064-APC</td>
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<td>Balanced Detector</td>
<td>Thorlabs PDB481C-AC</td>
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<td>Digitizer Card</td>
<td>Aquiris SA240P</td>
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<tr>
<td>Computer</td>
<td>Computer with GPU: Nvidia GeForce1080Ti or higher required for processing.</td>
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