Fundamentals webinar series

# OSCILLOSCOPE FUNDAMENTALS

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Make ideas real

# CONTENT

- **Oscilloscope Basic Operation**

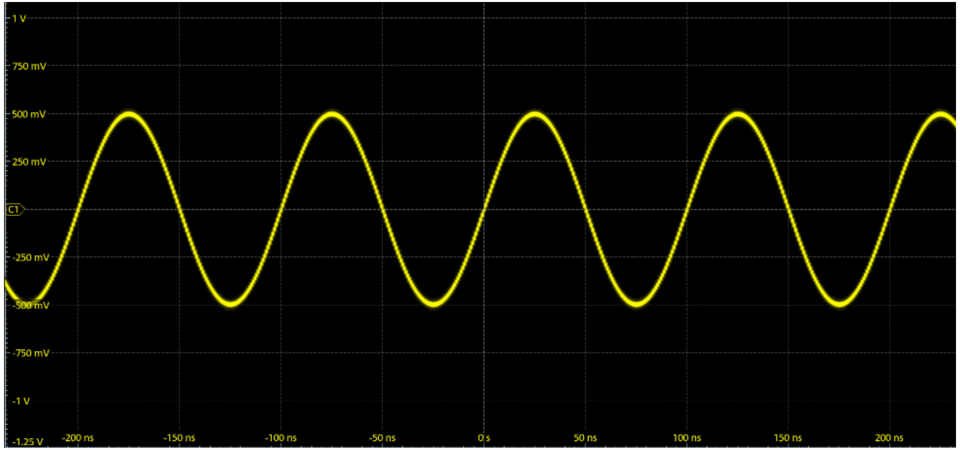
- **Oscilloscope Key Specifications**
  - **Bandwidth**
  - **Acquisition rate and blind time**
  - **Memory**
  - **Trigger**

# OSCILLOSCOPE BASIC OPERATION

# What is an oscilloscope?

- Primarily used to measure and display voltage vs. time

- Many additional functions:
  - Automatic measurements
  - Serial bus analysis
  - Mixed signal analysis
  - Frequency domain analysis



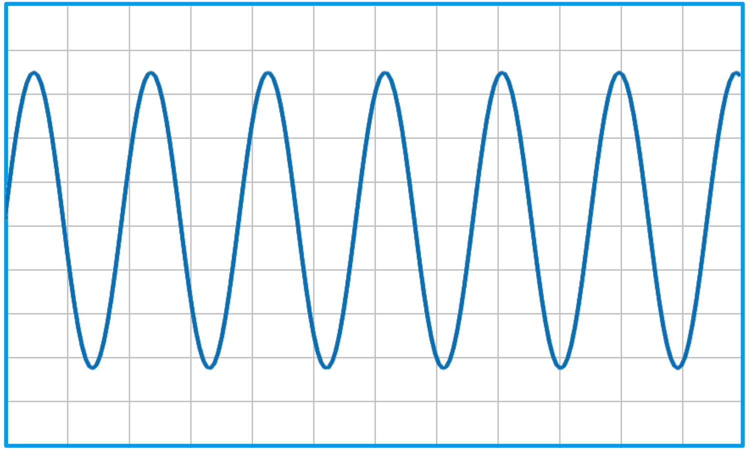
# Basic oscilloscope operation

Basic oscilloscope operation involves four “systems”:

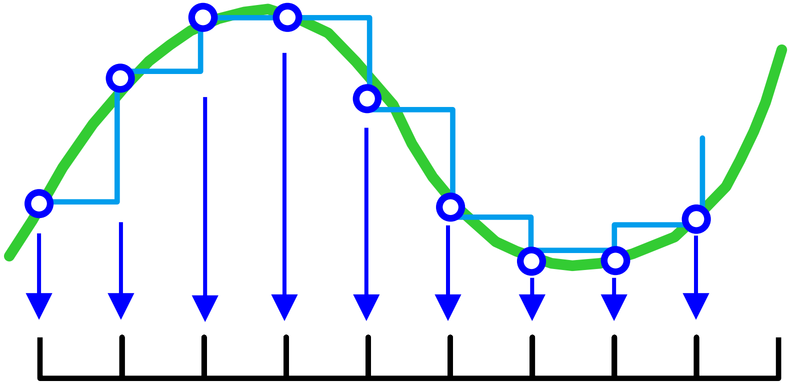
► **Vertical system**
  – Scales and positions the waveform vertically

► **Horizontal system**

# About the horizontal system



Waveform display

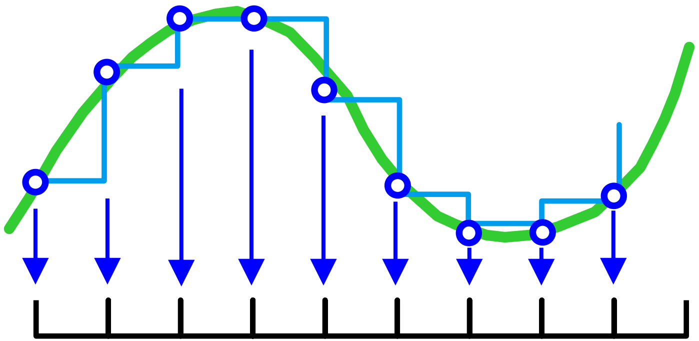


Sample rate

# About sampling

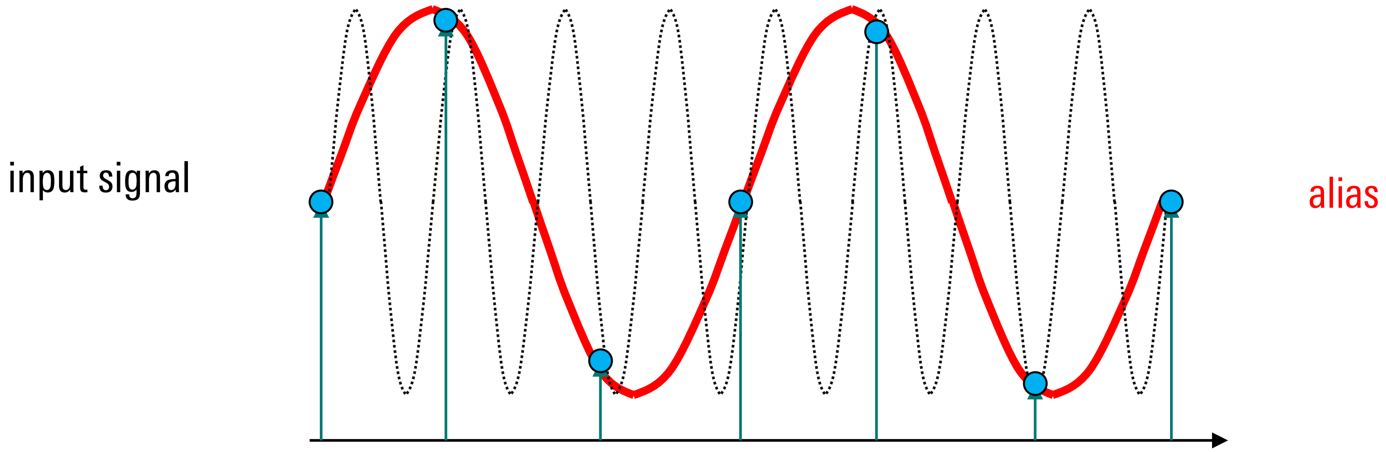
- The horizontal system digitizes the input signal at a given sample rate (samples/second)

- The higher the sample rate:
  - The greater the resolution / detail of the displayed waveform
  - The greater the probability of catching infrequent events
  - The greater the storage requirements (larger memory depth)



# Sample rate recommendations

- Nyquist rule: sample at twice the signal's highest frequency to avoid aliasing
- In most cases, it's safe to let the scope choose the sample rate



# DEMO: EFFECTS OF INSUFFICIENT SAMPLE RATE

# Basic oscilloscope operation

Basic oscilloscope operation involves four “systems”:

- ► **Vertical system**
  - – Scales and positions the waveform vertically
- ► **Horizontal system**
  - – Scales and positions the waveform horizontally
  - – Determines the sampling rate
- ► **Trigger system**
  - – Starts acquisition for single-shot / repetitive waveforms
- ► **Display system**
  - – Provides tools for analyzing / measuring results

# DEMO: DISPLAY SYSTEM

# AGENDA

► **Oscillloscope Basic Operation**

► **Oscilloscope Key Specifications**

- **Bandwidth**
- **Acquisition and blind time**
- **Memory**
- **Trigger**

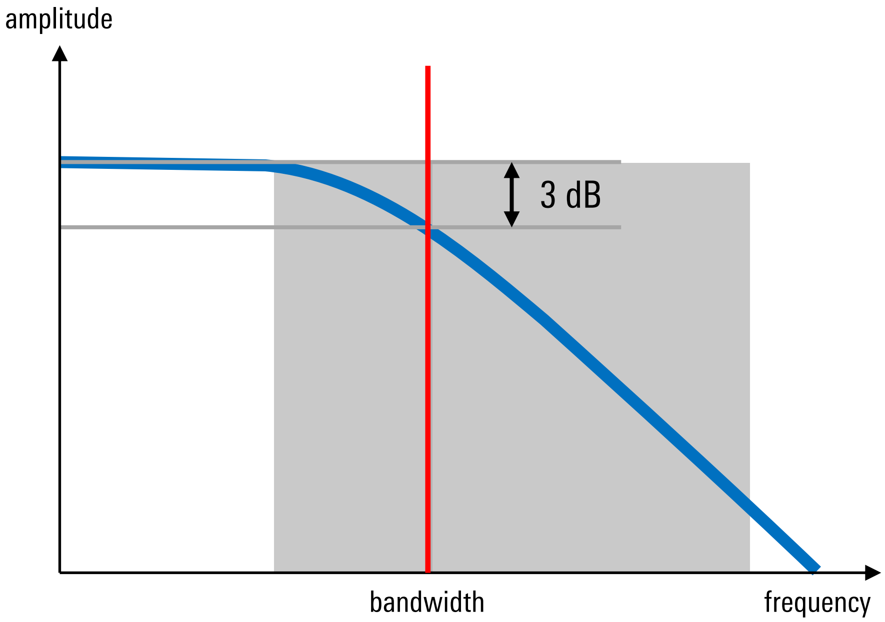
# BANDWIDTH

# Defining "Bandwidth"

- Frequency at which the **measured** amplitude of a sinusoidal input signal is attenuated by 3dB (~29.3%)

$$-3\ dB = 20\log_{10}\frac{V_{out}}{V_{in}}$$

- Fundamental oscilloscope specification
  - Specified in units of Hz
  - Typically ~100 MHz to GHz



# How much scope bandwidth is needed? (analog signals)

- Required scope bandwidth depends on test signals frequency components

- For “analog” applications (no steep edges, no sharp transitions)
  - Bandwidth = **3x** the highest sine wave frequency is sufficient

- 3x rule usually also applies for low speed serial decodes (UART, SPI, I2C, etc.)

# How much scope bandwidth is needed? (digital signals)

- “Digital” = a square or rectangular shape
  - Typically (very) high speed / steep edges
  - Extremely common in modern applications

- Digital “square” wave is composed of odd sine wave harmonics
  - According to signal theory, a rectangular (digital) signal can be expressed as an infinite sum of sinusoidal signals

$$f(t) = \frac{4h}{\pi}\left(\sin(\omega t) + \frac{1}{3}\sin(3\omega t) + \frac{1}{5}\sin(5\omega t) + \cdots\right) = \frac{4h}{\pi}\sum_{n=1}^{\infty}\frac{\sin\{(2n-1)\omega t\}}{2n-1}$$

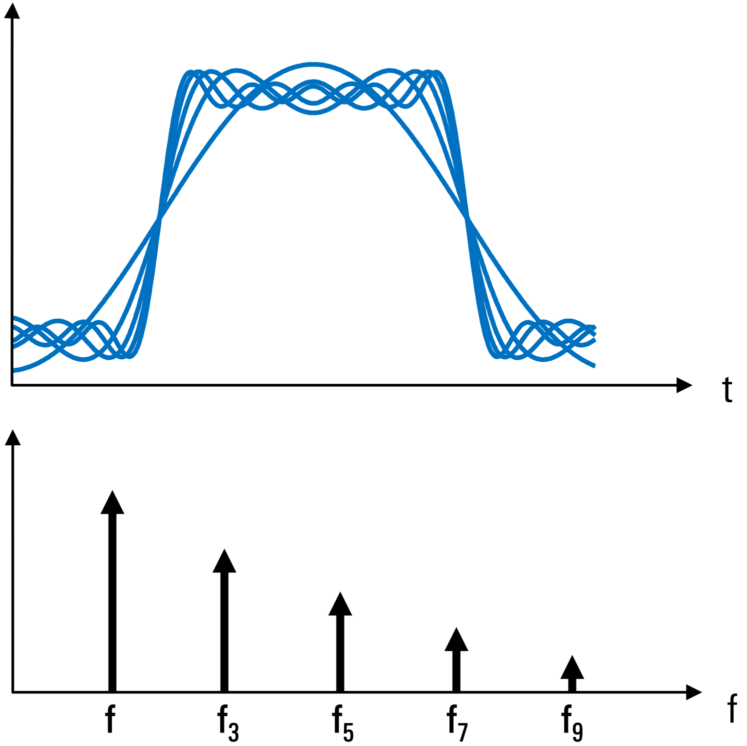
# How much scope bandwidth is needed? (digital signals)

- ► More harmonics measured
- → steeper edges of the waveform

- ► For digital applications, rule of thumb: measure 3rd and 5th harmonics

**Rule of thumb:**
$BW_{Scope}$ = 3-5x $f_{clk}$ of Test Signal

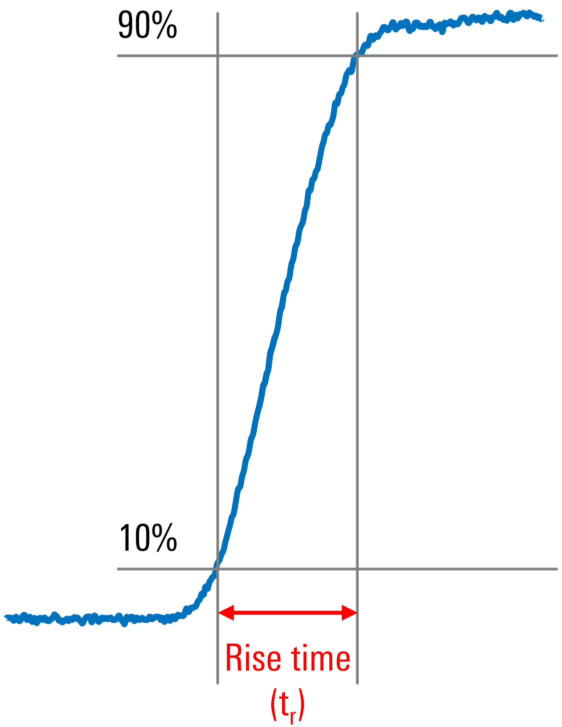
- ► Higher order harmonics are also important for signals with very fast rise times
- ► In some scopes, the amplitude of higher order harmonics may be below the noise floor



# DEMO: CONSEQUENCES OF INSUFFICIENT BANDWIDTH

# Using rise time to determine required bandwidth

- For digital signals, rise time ($t_r$) is another way to calculate required BW
- Rise time is a function of higher frequency signal components (harmonics)
- Higher bandwidth is needed to accurately measure faster rise times (sharper edges)



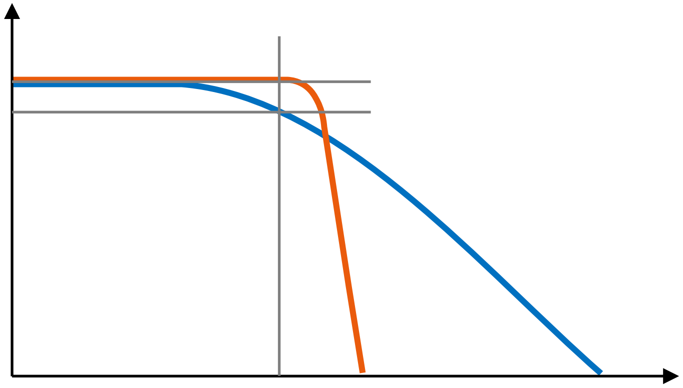
# Calculating bandwidth from rise time

- Bandwidth can be calculated by multiplying the reciprocal of rise time ($t_r$) by a scaling factor

$$BW = \frac{factor}{t_r}$$

**Rule of thumb:**

$$BW = \frac{0.5}{t_r}$$



$$BW_{Gaussian} = \frac{0.35}{t_r}$$

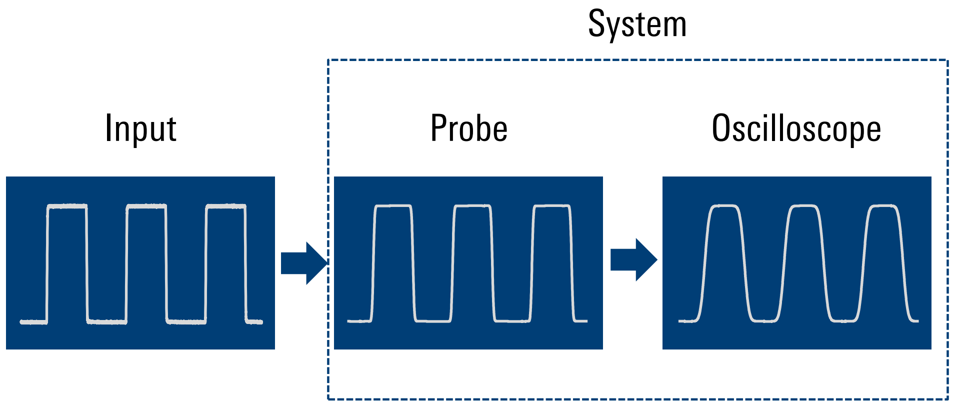
$$BW_{flat} = \frac{0.4x}{t_r}$$

# System bandwidth

- A measurement system consists of
  - Oscilloscope
  - Probes (cables / fixtures)

- Each has its own bandwidth

- The **system bandwidth** is a function of these two bandwidths

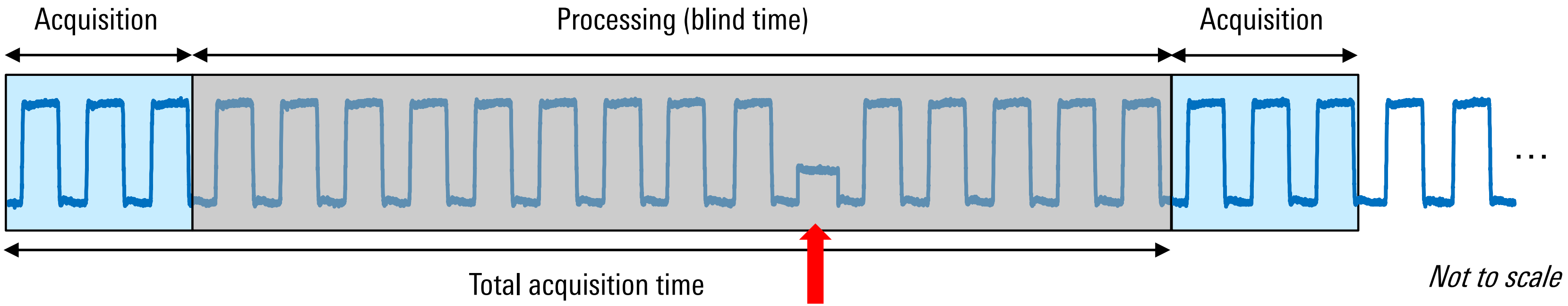



$$BW_{system} = \frac{1}{\sqrt{\left(\frac{1}{BW_{probe}}\right)^2 + \left(\frac{1}{BW_{scope}}\right)^2}}$$

# ACQUISITION RATE AND BLIND TIME

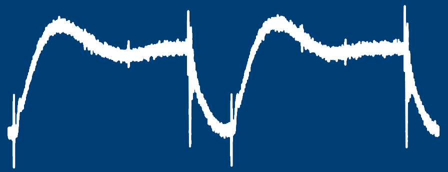
# About acquisition rate and blind time

- **Acquisition rate**: also called “update rate,” “capture rate,” etc.
  - How quickly can the oscilloscope can trigger, process, and display sequential waveforms
  - Specified in units of **waveforms per second** (higher is better)
- **Blind time**
  - the period of time during which the scope is not acquiring new samples and therefore blind to any waveform data.
- Blind time can be very high (> 99%) in some oscilloscopes

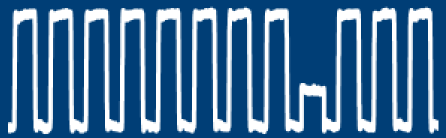


# How a higher acquisition rate reduces test time?

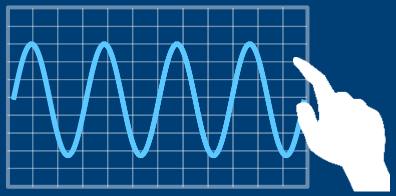
### Signal visibility



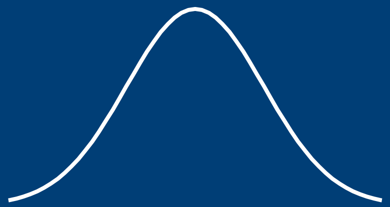
### Capturing rare events



### Usability / responsiveness



### Statistical confidence



# DEMO: IMPROVED SIGNAL VISIBILITY DEMO

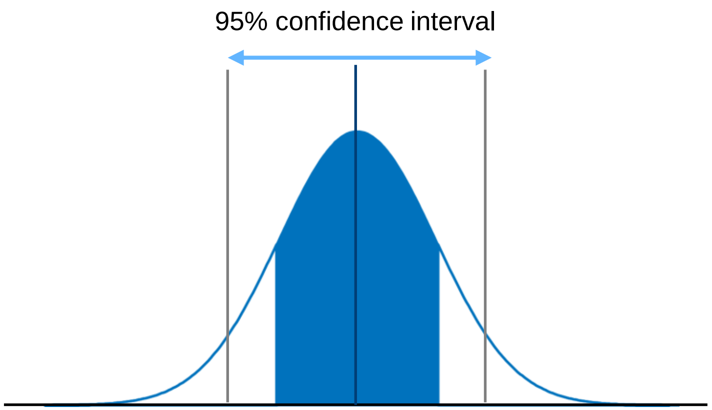
# DEMO: CAPTURING RARE EVENTS

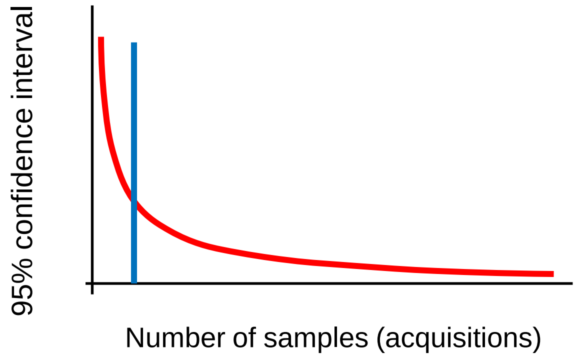
# Usability / responsiveness

- ▶ Waveform processing takes priority over user interface
  - →Scope only updates display and/or responds to user input at the end of each acquisition
- ▶ Faster acquisition make a scope more responsive
- ▶ Improves overall user experience
  - – Decreases user frustration and probability of user error
  - – Decreases overall test time

# Higher statistical confidence

- ► Scopes are often used to generate statistical data
  - – Each acquisition is a “sample” of the input signal
- ► With increasing acquisition count:
  - – Greater confidence that the measured statistics are closer to the actual values
- ► Higher acquisition rates provide more “samples” (waveforms) per unit time
  - – Can greatly reduce test time needed to obtain the desired statistical confidence



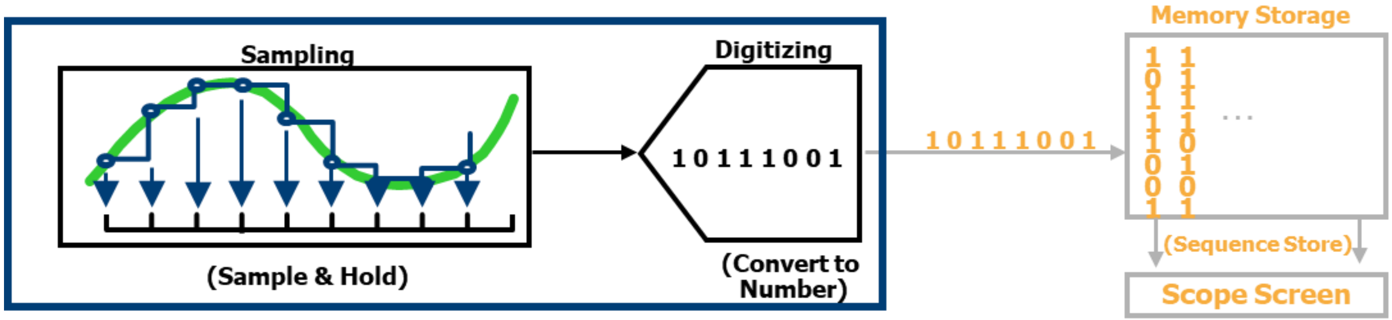
# CONTENT

- ► **Oscilloscope Basic Operation**

- ► **Oscilloscope Key Specifications**
  - – **Bandwidth**
  - – **Acquisition rate and blind time**
  - – **Memory**
  - – **Trigger**

# ACQUISITION MEMORY

# Record length




$$Sample\ Rate\ x\ Acquisition\ Time = Record\ Length$$

$f_{sample}\ x\ t_{meas} = n_{samples}$ with $t_{meas} = [Time\ scale]\ x\ [\#\ of\ Divisions]$

e.g. Sample Rate = 10 GSa/s: $10\,\frac{GSa}{s} \times 100\,\frac{ns}{div} \times 10\text{ div} = 10\text{ kSa}$

$$10\,\frac{GSa}{s} \times 100\,\frac{\mu s}{div} \times 10\text{ div} = 10\text{ MSa}$$

# Value of deep memory

- Capture longer time

$$Time\ captured = \frac{Memory}{(Sample\ rate)}$$

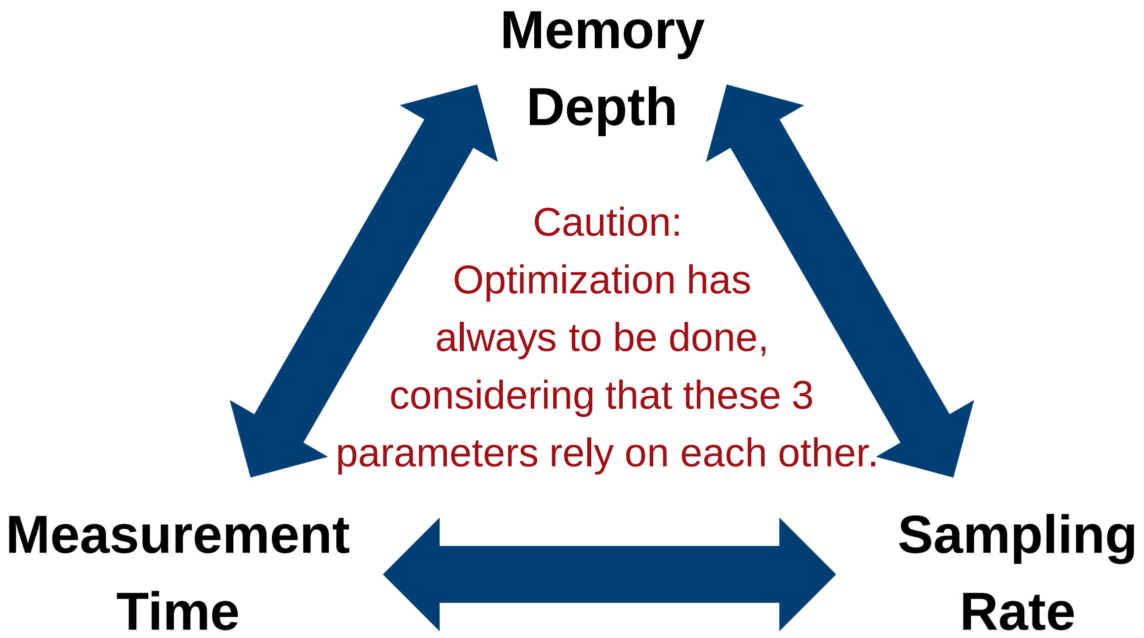
  - Also allows you to zoom in on the signal without losing detail

- Retain Needed Sample Rate When More Time is captured

$$(Sample\ rate) = \frac{(Time\ captured)}{Memory}$$

  - More reliable measurement

# Important parameters of oscilloscopes



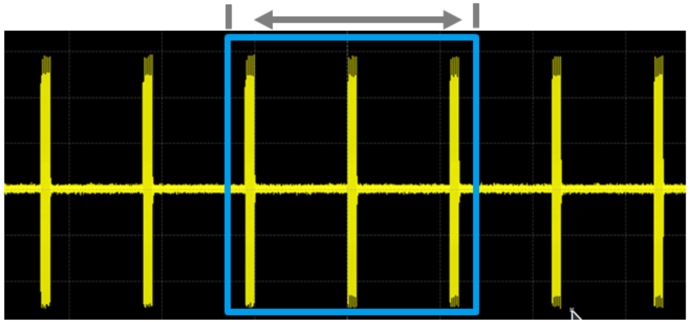
# DEMO: DEEP MEMORY

# Segmented memory

- ► Segmented memory mode: a standard oscilloscope function
- ► Acquistion memory of an oscilloscope is sliced into a certain number of segments.
- ► Each segment stores one acquistion of defined length.

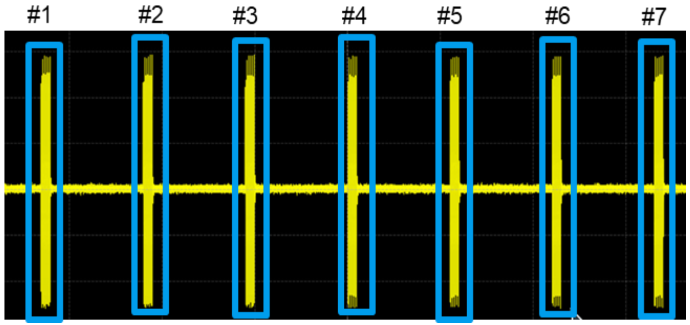
Tradition single-shot Acquisition

Total Acquisition time = memory depth / sample rate



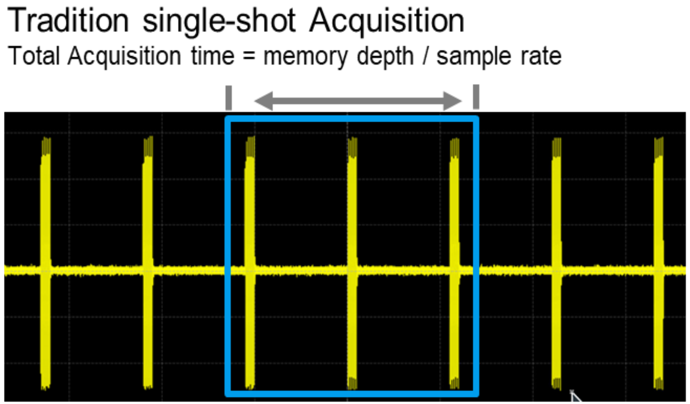
Segmented Memory Acquisition

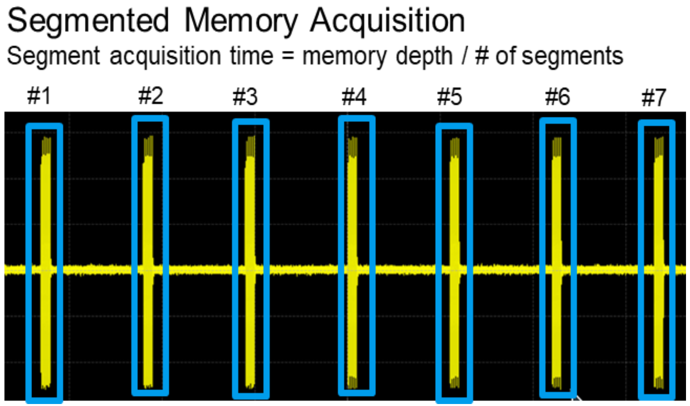
Segment acquisition time = memory depth / # of segments



# Segmented memory

- ► More efficient memory utilization for applications where a single shot acquisition is sufficient
- ► With deep memory:
  - – More segments
  - – More sample rate
  - – More time with each segment



# Trade-offs of Using More memory

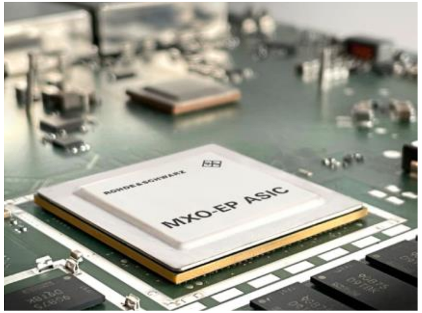
► As more memory memory is utilized, the oscilloscope's processing requirement increases

→ Overall scope operation slows down

→ Lower update rate

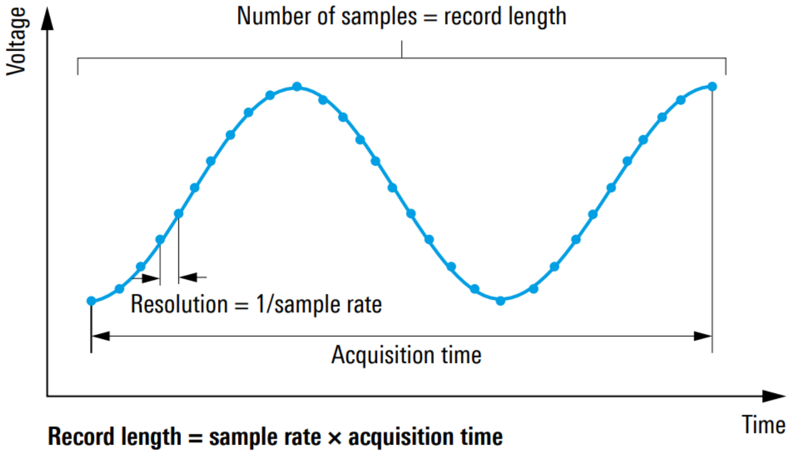
→ Dead time between acquisitions increases

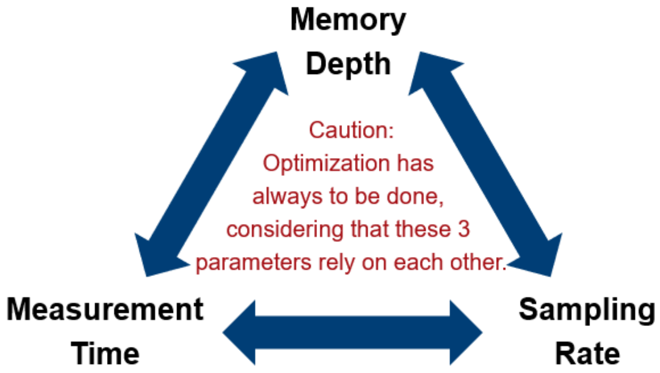
► A high performance (ASIC performance) can help to ensure that the scope stays responsive even with deep memory



# Summary: Acquisition Memory

- Deep memory offers insurance for both current and future application test and debug needs
- Greater flexibility…
  - …in capturing for longer periods of time
  - …retaining higher sample rates with slower time bases

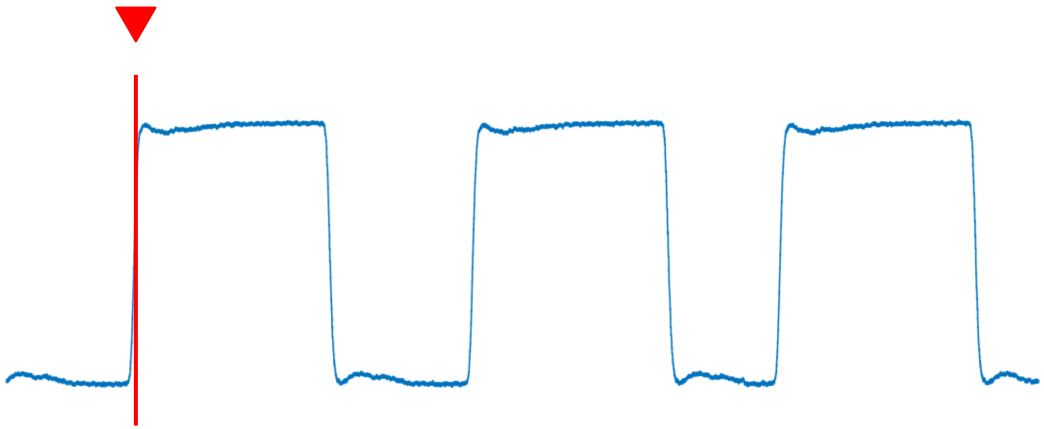


# TRIGGER

# About triggering

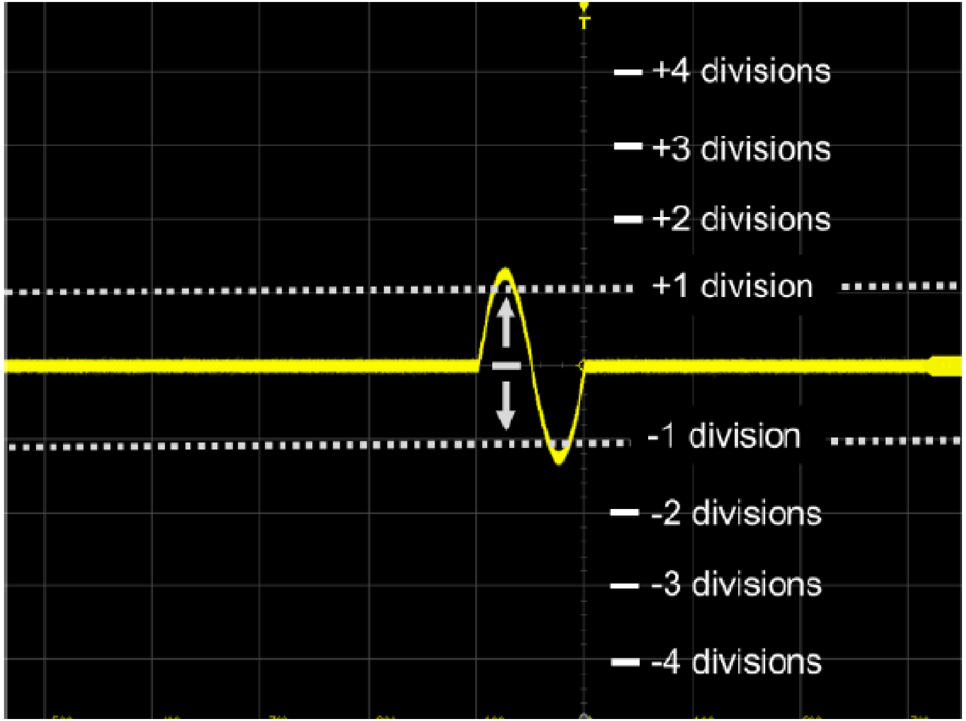
- Digital storage oscilloscopes digitize input signals and convert them into sample values
- This acquisition process is normally started when a **trigger** event occurs
- Most often used to stabilize a repeating waveform on the screen
  - Acquisition restarts with each trigger
- Also used for:
  - Single shot captures
  - Segmented memory



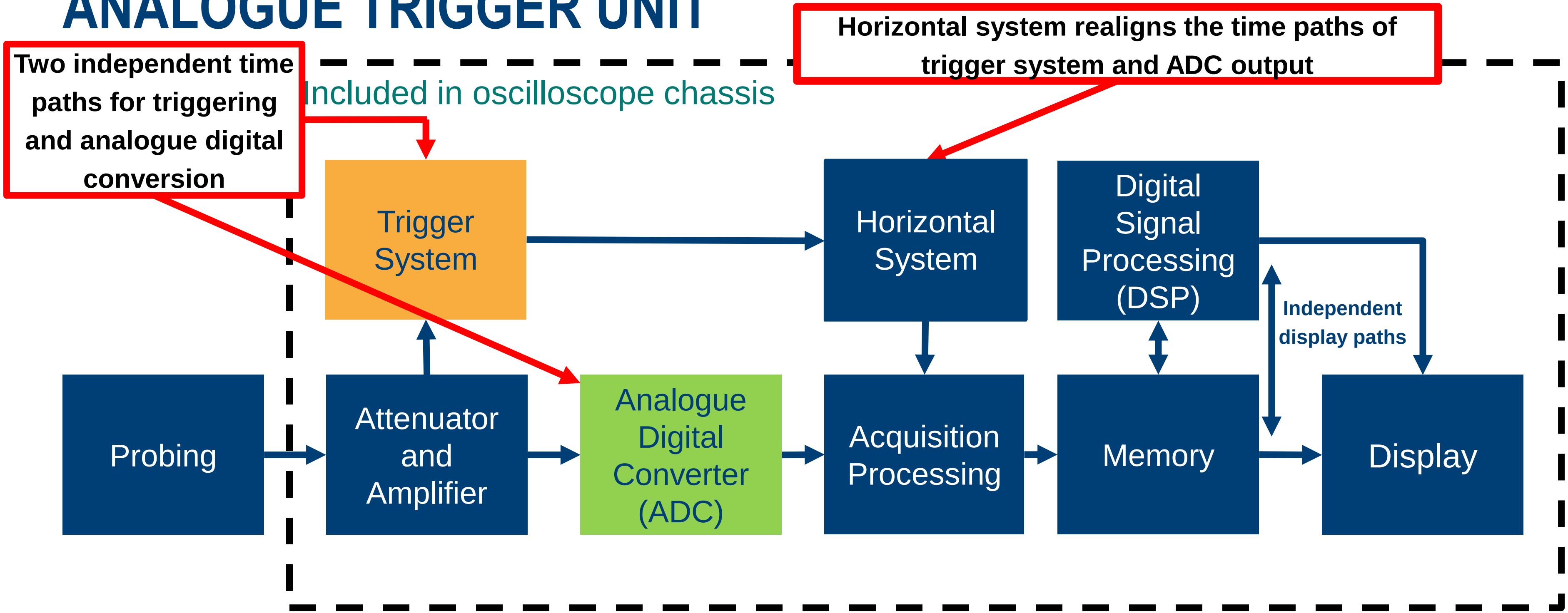
# About Trigger Sensitivity

- The required amplitude of a signal (measured in vertical divisions) for the oscilloscope to ensure the signal will be detected as a trigger event.

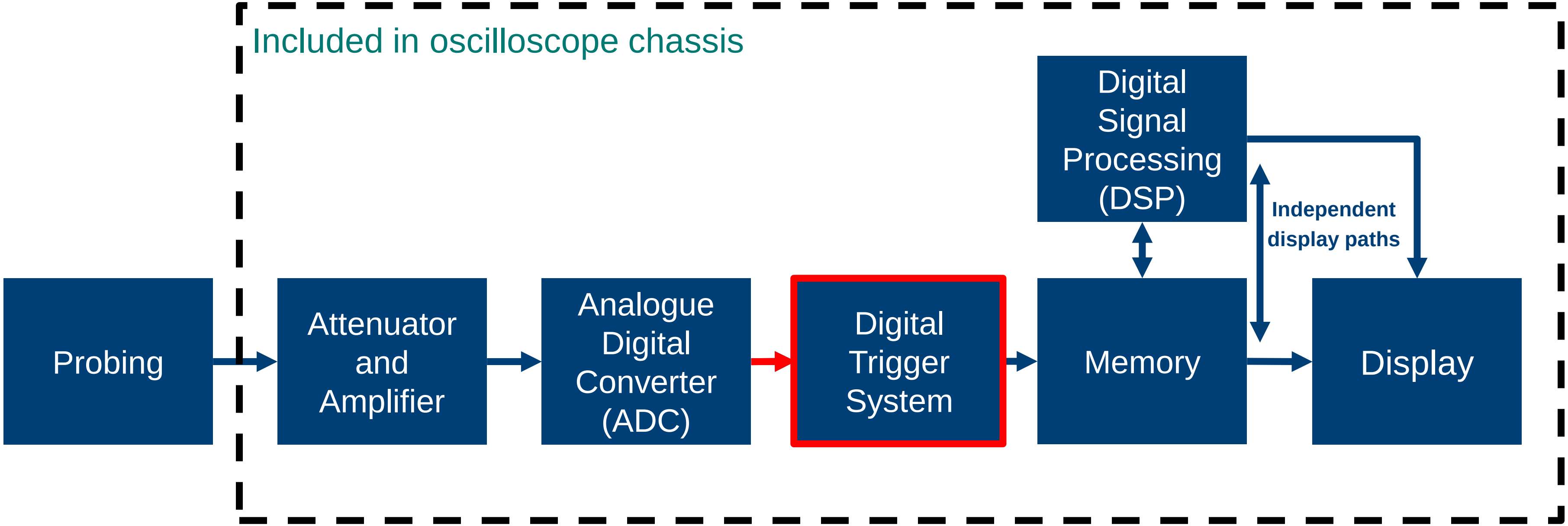
- 2 types of trigger systems:
  - **Analogue** trigger system,
  Typically requiring 1-2 divisions for a trigger event
  - **Digital** trigger system,
  Sensitivity of 0.1 divisions or even less



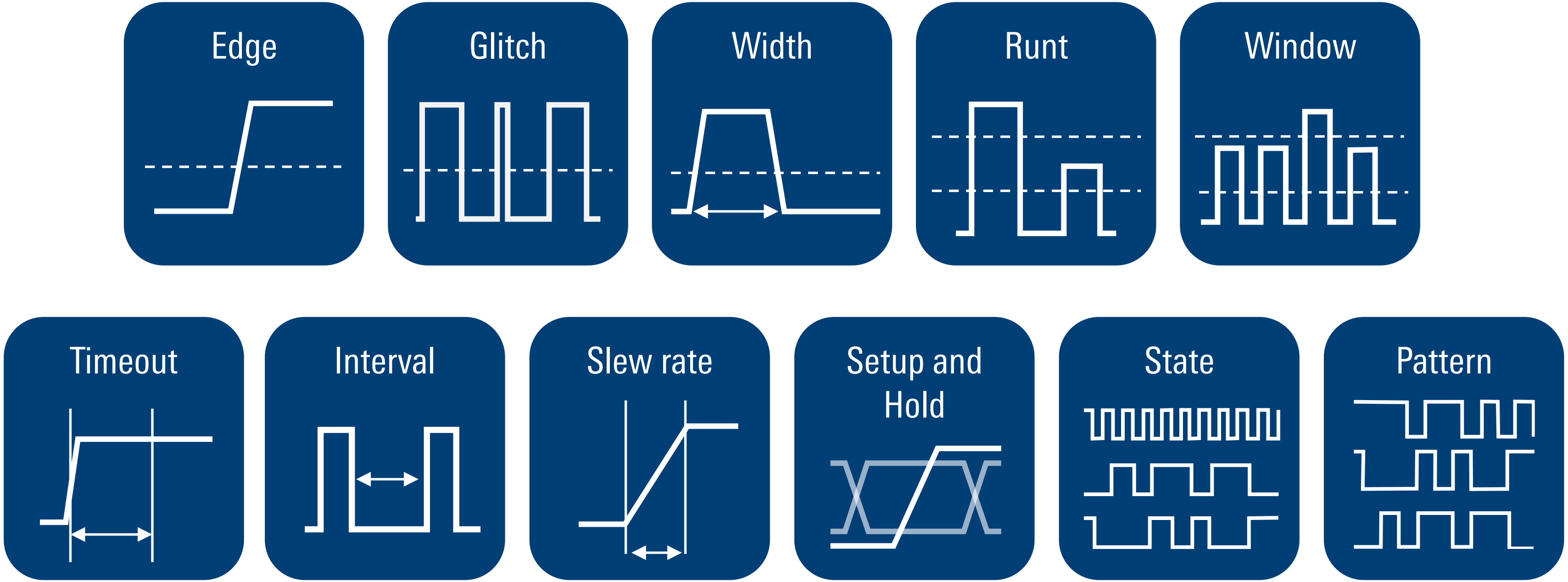
# DIGITAL OSCILLOSCOPE ANALOGUE TRIGGER UNIT



# DIGITAL OSCILLOSCOPE
# DIGITAL TRIGGER UNIT



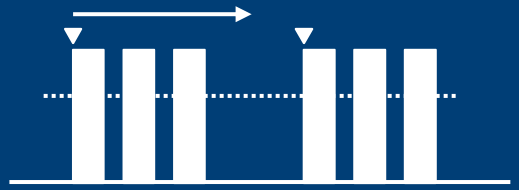
# Trigger types



# DEMO OF TRIGGER TYPES

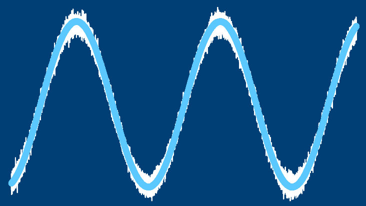
# Additional trigger parameters

Hold off



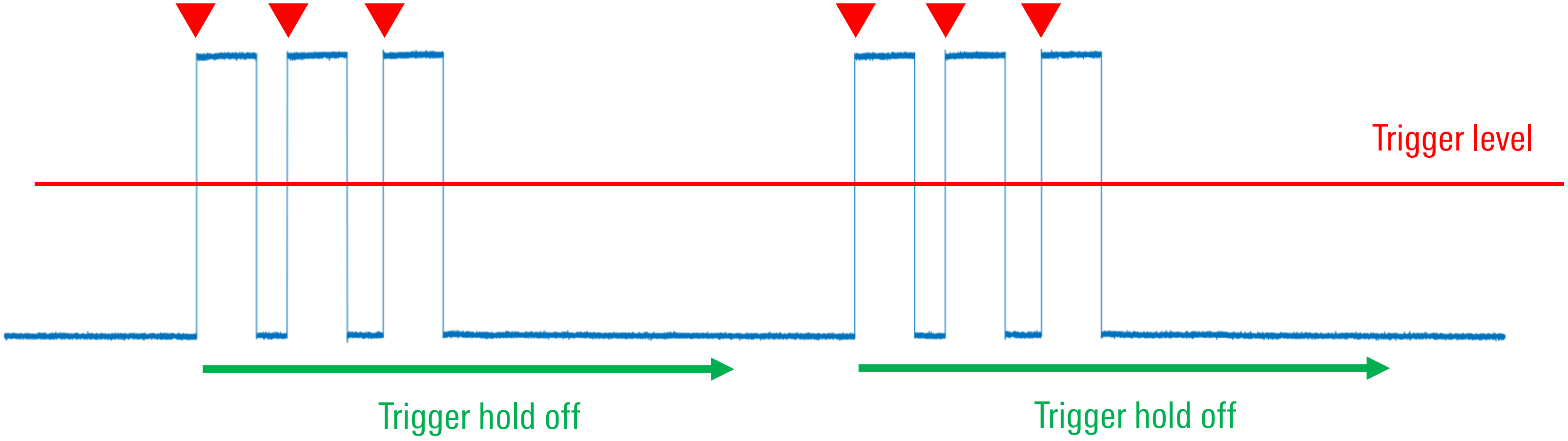
Hysteresis

Filtering



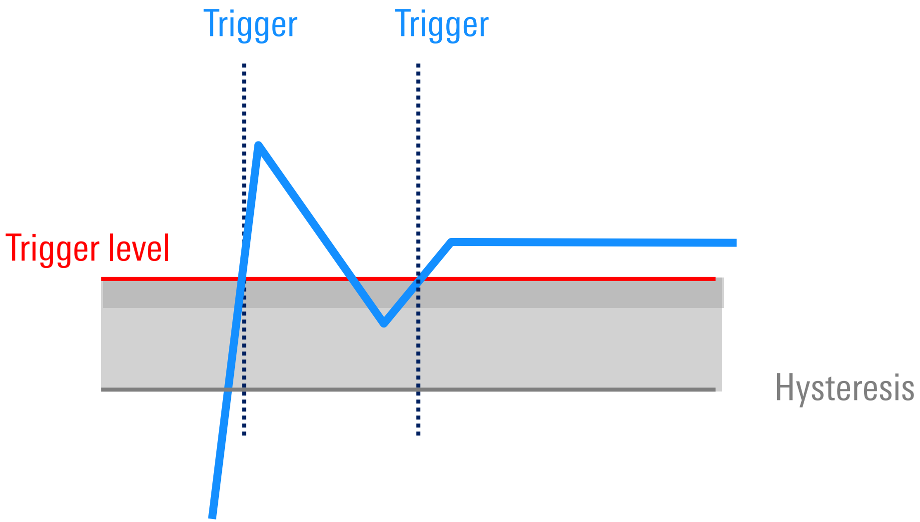
# Trigger holdoff

- Determines conditions that must occur **before** next trigger event will be recognized
- Primarily used to trigger on waveforms with multiple trigger locations in a single “cycle”
- Most often defined as a minimum time between trigger events
  - Other criteria can be used (e.g. number of trigger events to skip)



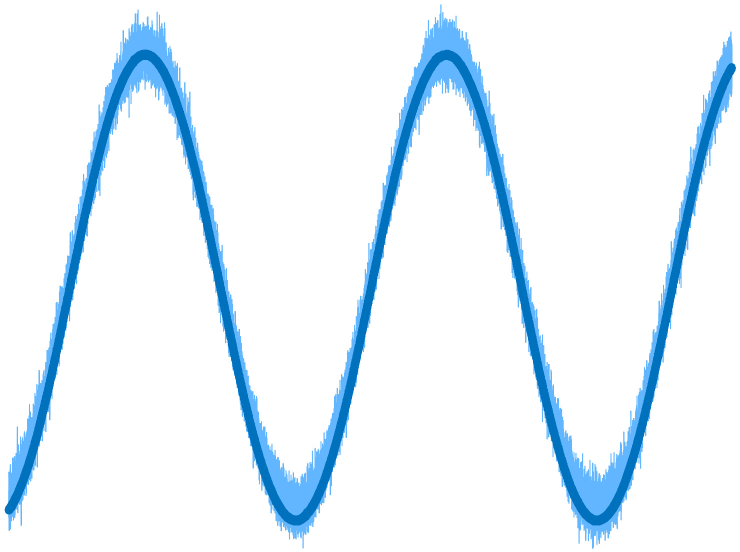
# Trigger hysteresis

- ▶ Available for many trigger types
- ▶ Reduces false triggering on noisy signals
  - – More stable trigger
- ▶ Can be represented as a region or box
  - – Defined by trigger and hysteresis levels
- ▶ Signal must “cross the whole box” to be considered a valid trigger event
- ▶ Width of the hysteresis region can be set automatically or configured as an absolute or relative range



# Trigger filtering

- The trigger signal can also be filtered to reduce unwanted triggering
- Two types of trigger signal filters:
  - Low-pass (RF reject)
  - High-pass (LF reject)
- RF rejection filter typically has a configurable bandwidth / cut-off frequency
  - Can be adjusted to remove high-frequency noise on a signal
- This filtering is only performed on the trigger signal, not on the acquired waveform



# Oscilloscope Trigger: Summary

- Triggering is a fundamental oscilloscope system
  - Defines the start of an acquisition
- Many different trigger types available on an Oscilloscope
  - Common: edge, width, timeout, etc.
  - Less common: setup and hold, patterns, etc.
- External trigger sources can also be used
- Configuring triggers usually involves:
  - Defining amplitude thresholds
  - Defining time thresholds
- Additional trigger parameters include holdoff, hysteresis, and filtering

# Oscilloscope summary (cheat sheet)

- 4 Fundamental systems:
  - **Vertical**, use it all (ADC resolution)
  - **Horizontal**, “Timebase” (Memory/Record length)
  - **Trigger**, Stabilizing the waveform
  - **Display**, gives the tools for analysis

- **Sample** rate
  - **Nyquist Theorem**,
  2x highest frequency = correct sampling (avoid aliasing)

- **Bandwidth** (BW), 3dB cut-off frequency
  Rules of thumb:
  - **Sinusoids**, up to or greater than defined BW
  - **Digital signals**, 2 methods:
    - 3x – 5x the highest frequency
    - ~0.5/Rise time = BW
  - **System bandwidth** = A function of both Probe and Oscilloscope

- **Waveform acquisition rate**, the speed the Oscilloscope can trigger, process and display an acquisition

- **Blind time**, time missed between each acquisition
  - Function of Acquisition rate, Faster = Less blind time
  - High statistical confidence in measurements

- **Acquisition memory**, amount of data points defined in 1 acquisition
  - Sample rate x Timebase = Record length
  - Segmented memory used to focus on desired waveforms separated by areas of no interest

- **Trigger** parameters:
  - **Digital** High sensitivity, **Analogue** ~1-2 divisions
  - Types: Edge, Glitch, Runt, Window etc…
  - Parameters: Hold-off, Hysteresis, Filtering
  (Use parameters and types to optimise your Acquisitions stability)

# THANK YOU

Find out more

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