# ECE 546
# Lecture - 24
# Jitter Analysis

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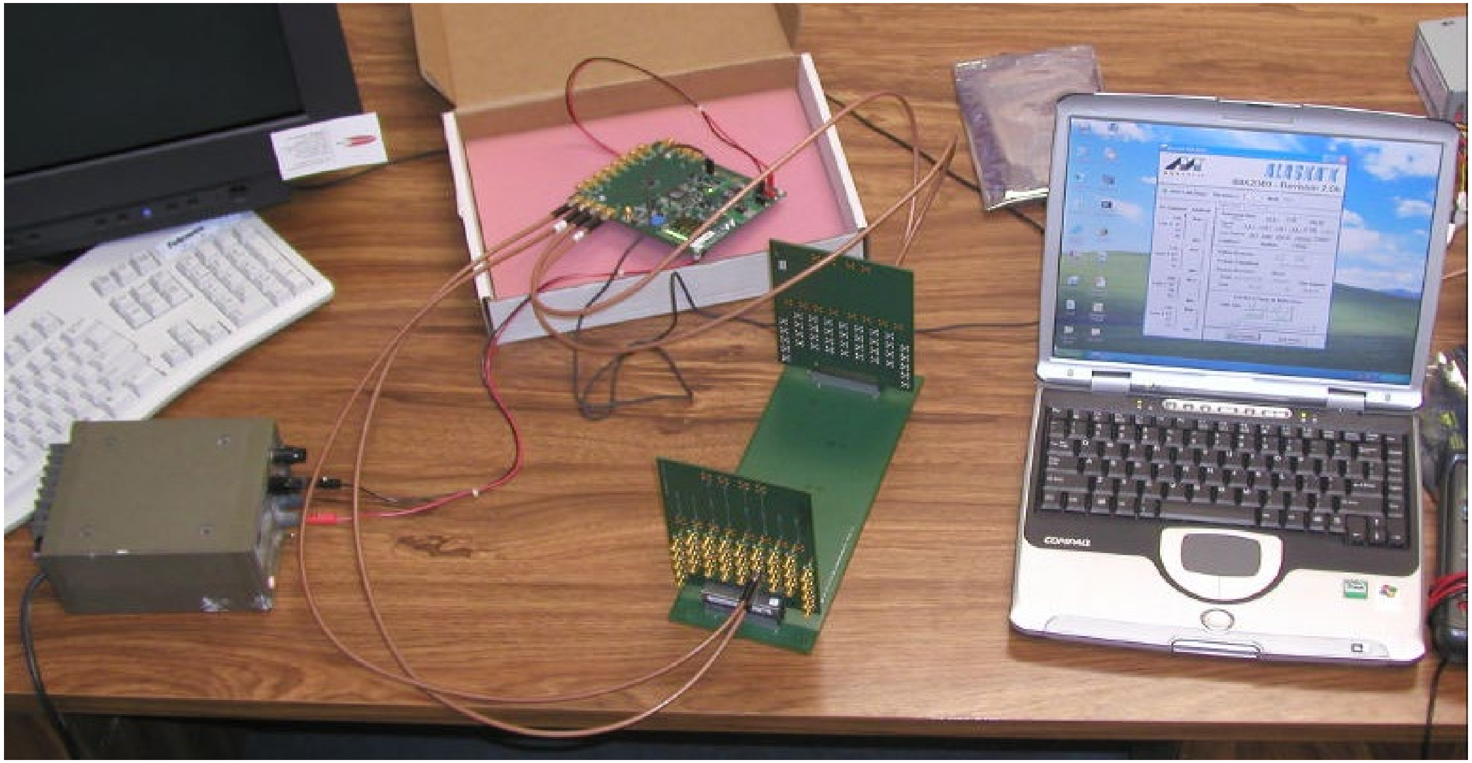
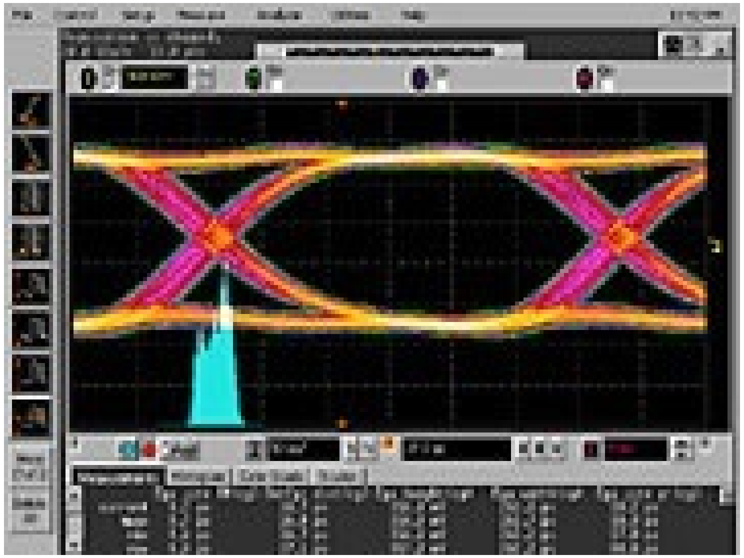
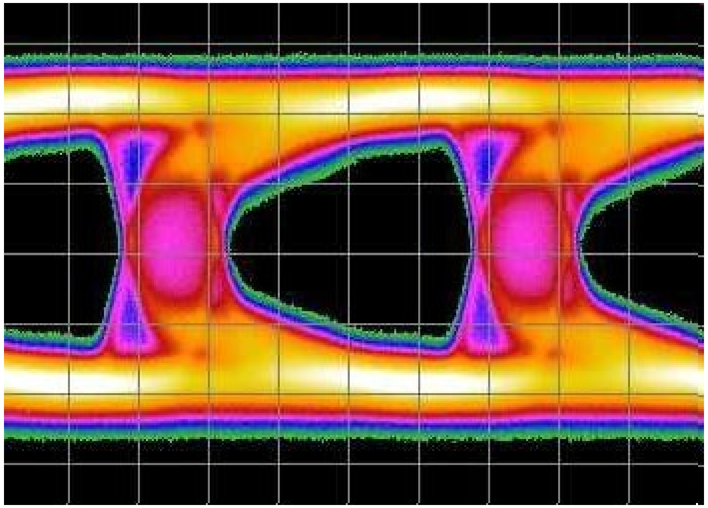
# Measuring Jitter



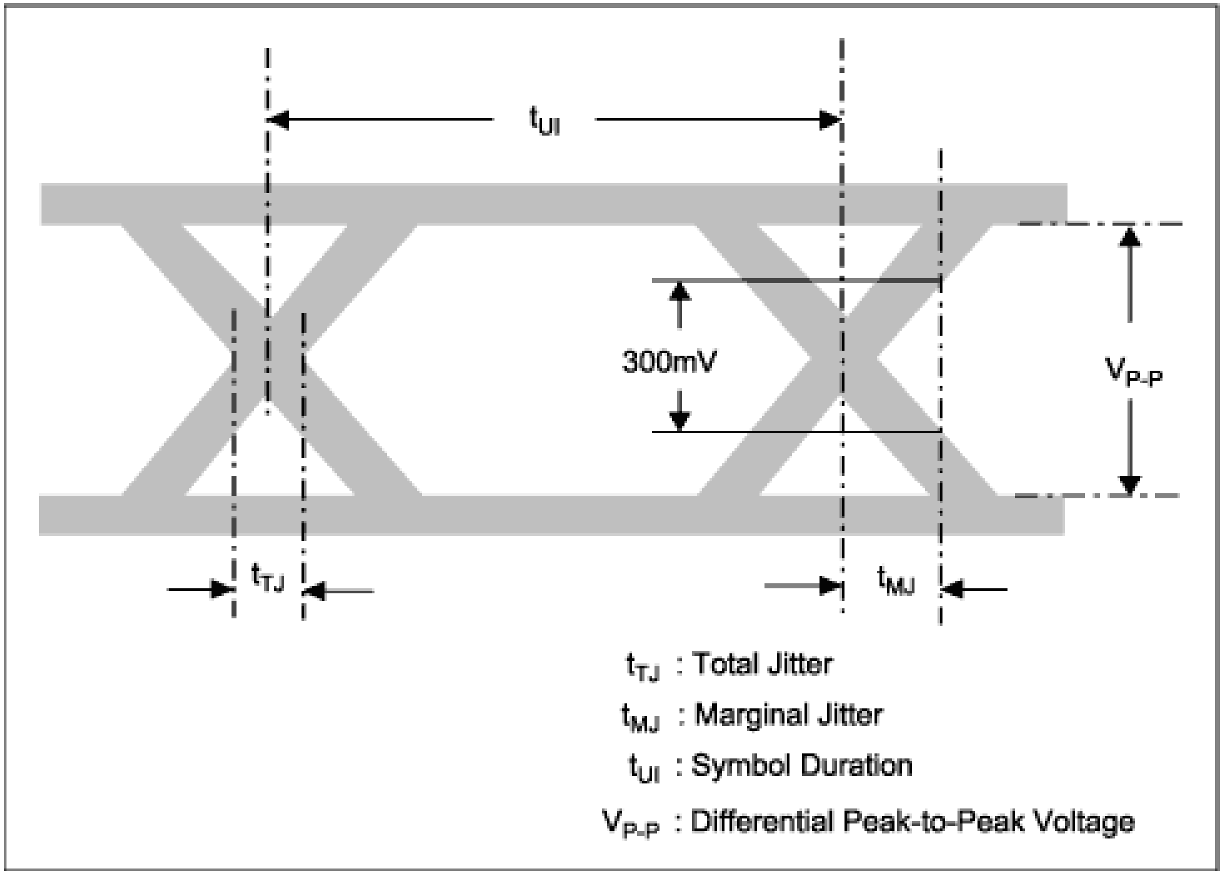
# Eye Diagrams

• Eye diagrams are a time domain display of digital data triggered on a particular cycle of the clock. Each period is repeated and superimposed. Each possible bit sequence should be generated so that a complete eye diagram can be made



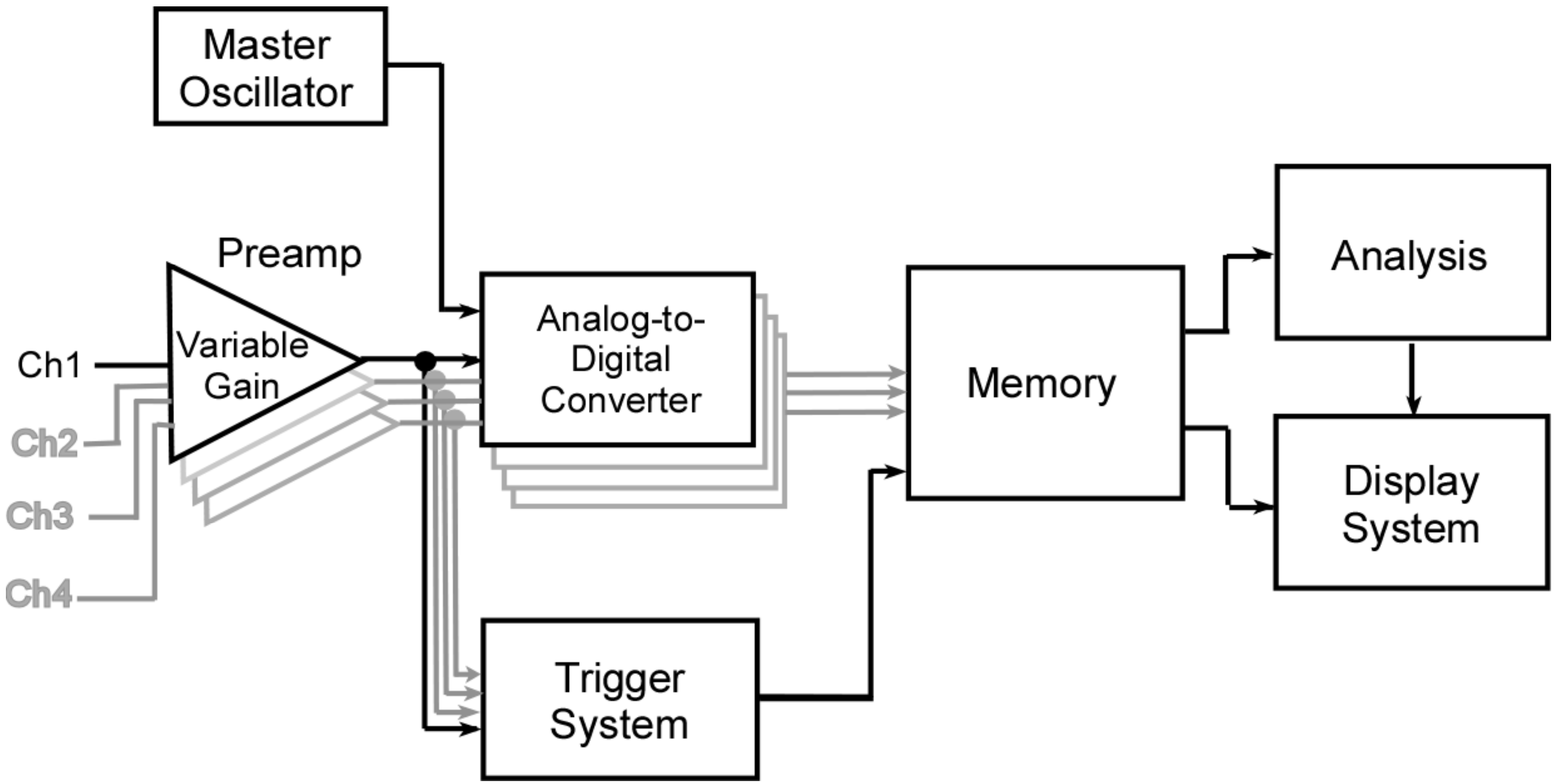


# Eye Diagram



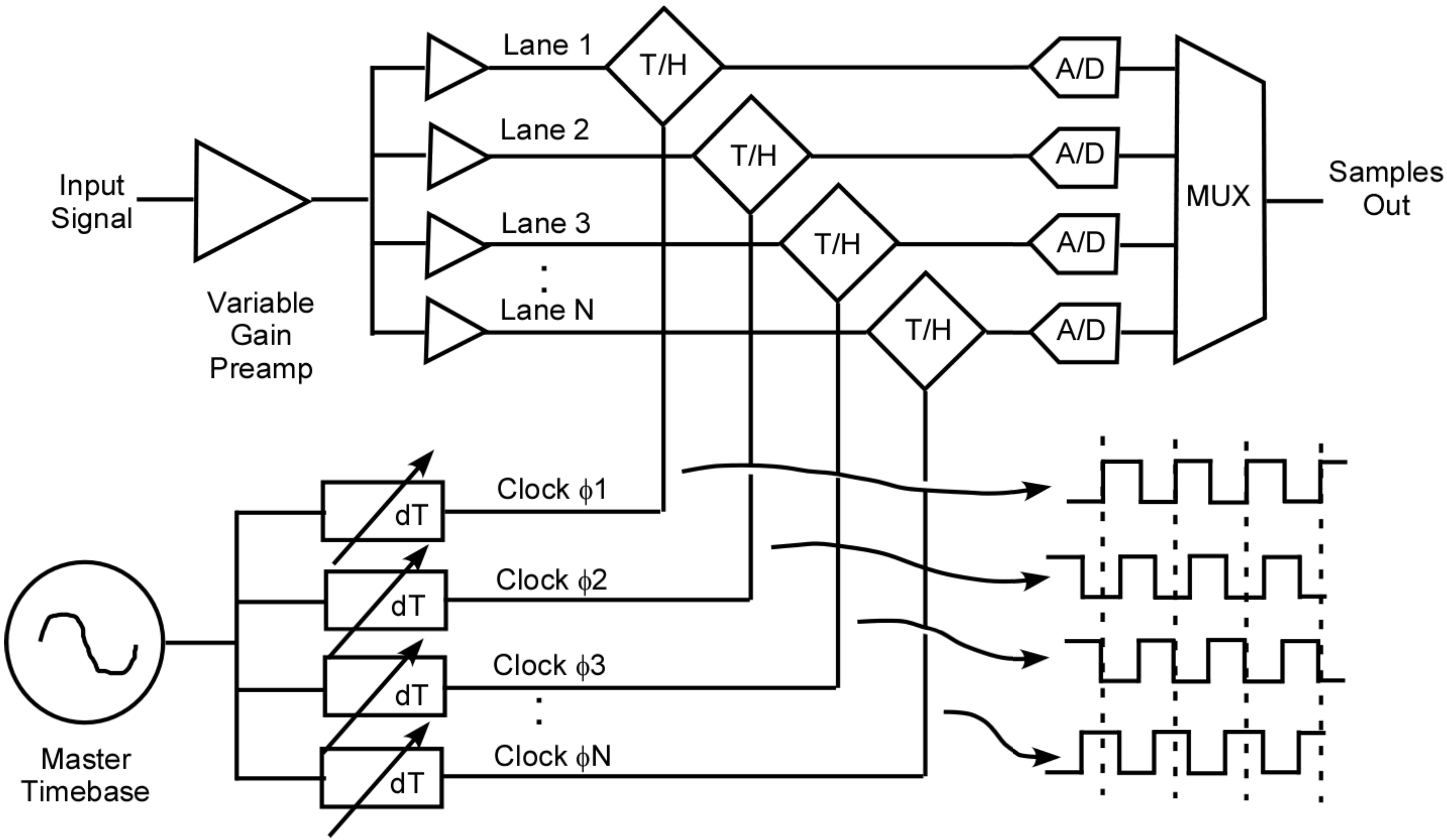
$t_{UI}$
300mV
$V_{P-P}$
$t_{TJ}$
$t_{MJ}$
$t_{TJ}$ : Total Jitter
$t_{MJ}$ : Marginal Jitter
$t_{UI}$ : Symbol Duration
$V_{P-P}$ : Differential Peak-to-Peak Voltage

# High-Speed Oscilloscope




**8-bit flash ADCs provide 256 discrete levels along vertical axis**

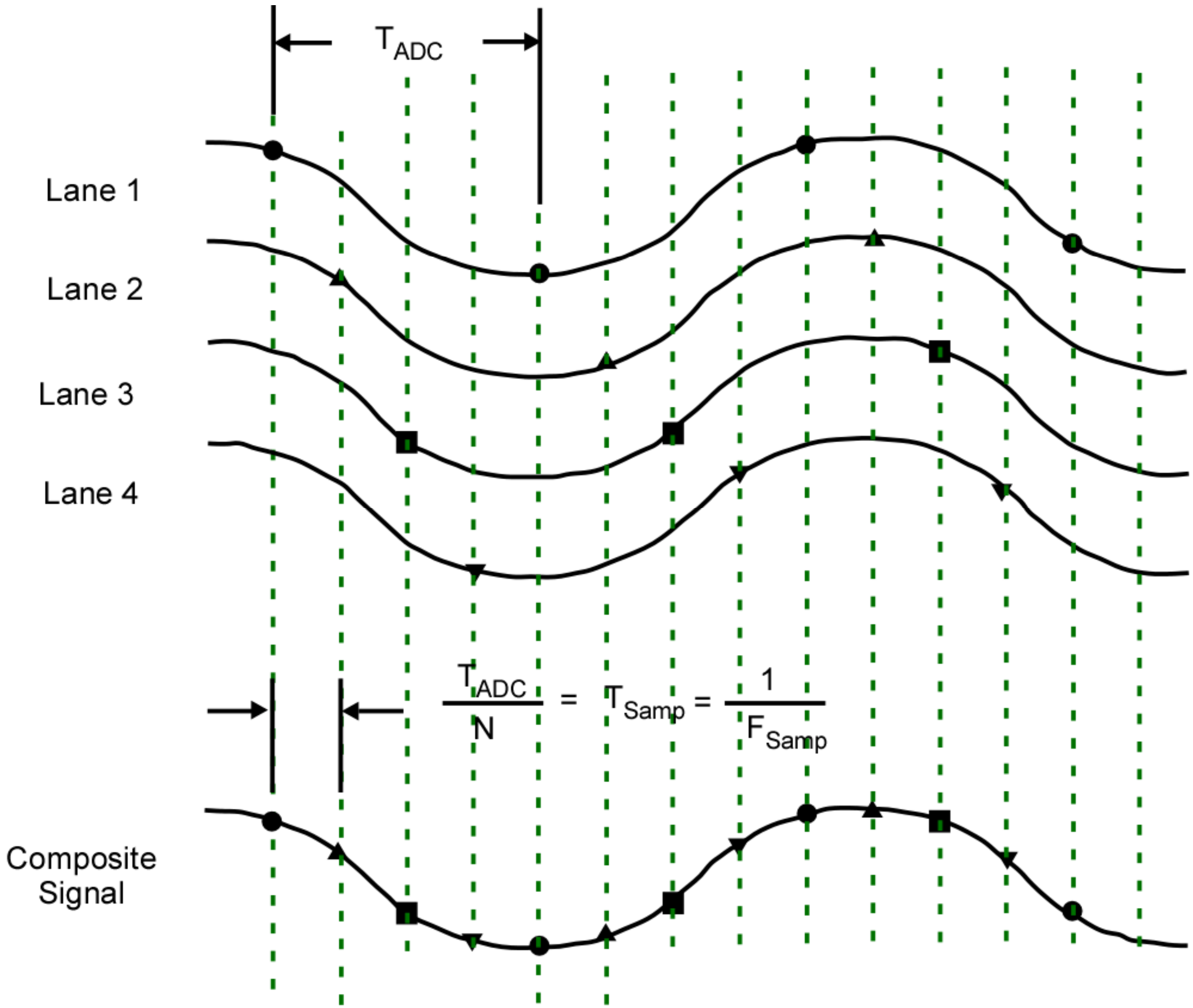
# Interleaving Architecture



# High-Speed Scope Digitizers

- SiGe-Based Technologies
  - Fastest ADCs run at 3.125 Gsamples/s
  - Typically 8-16 digitizers
- CMOS Designs
  - ADCs sample at lower rate
  - 80 digitizers or more

# Timing Diagram



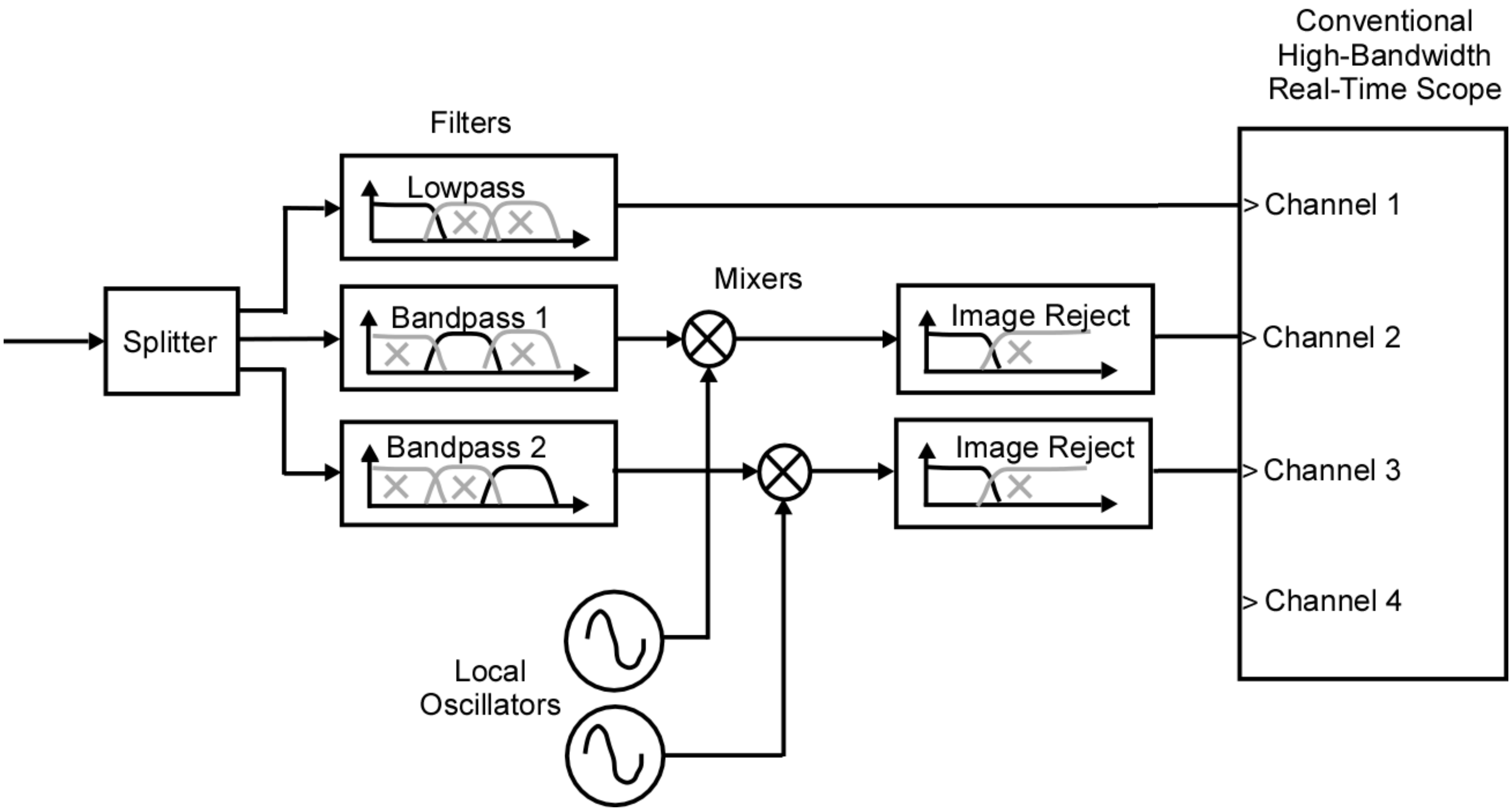
# Sampling Procedure

Once waveform samples have been reassembled into a representation of the waveform, they are stored to digital memory

The maximum number of samples is the *record length*

Record length are typically in excess of 100 million samples

# Frequency Interleaving



# Nyquist Criterion

A signal of bandwidth *B* that has been sampled at regular intervals *T* can be exactly recovered if the sampling rate satisfies

$$F_N = \frac{1}{T} > 2 * B$$

$F_N$ : Nyquist rate

$T$ : sampling interval

$B$ : bandwidth

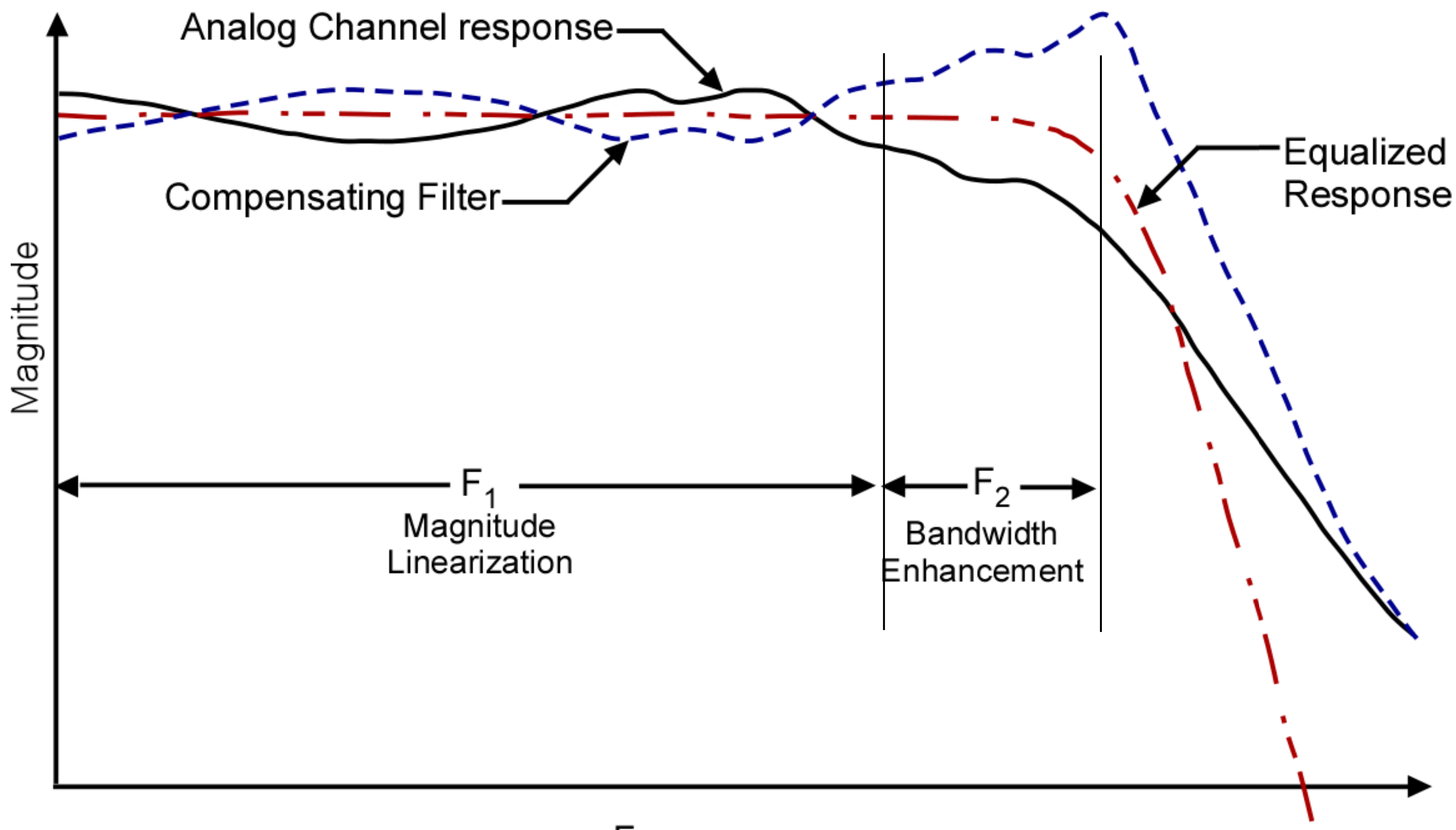
# High-Speed Oscilloscopes

- Oscilloscopes use DSP techniques to:
  - Extend their analog bandwidth
  - Flatten their amplitude

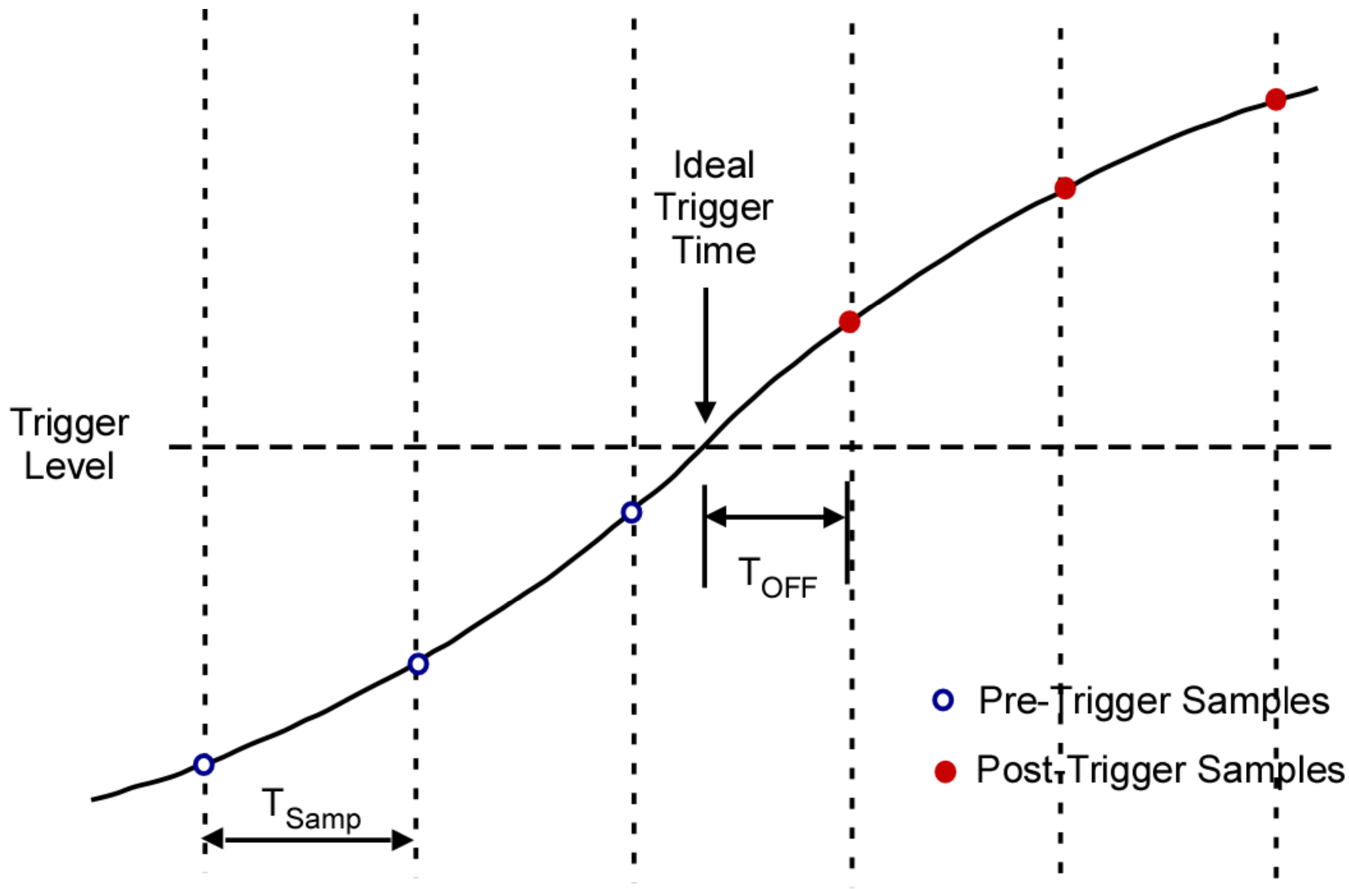
- Practice has benefits

- However, limitations should be understood

# Scope Channel Equalization



# Edge Triggering




**$T_{OFF}$ is recorded with high resolution but is subject to noise**

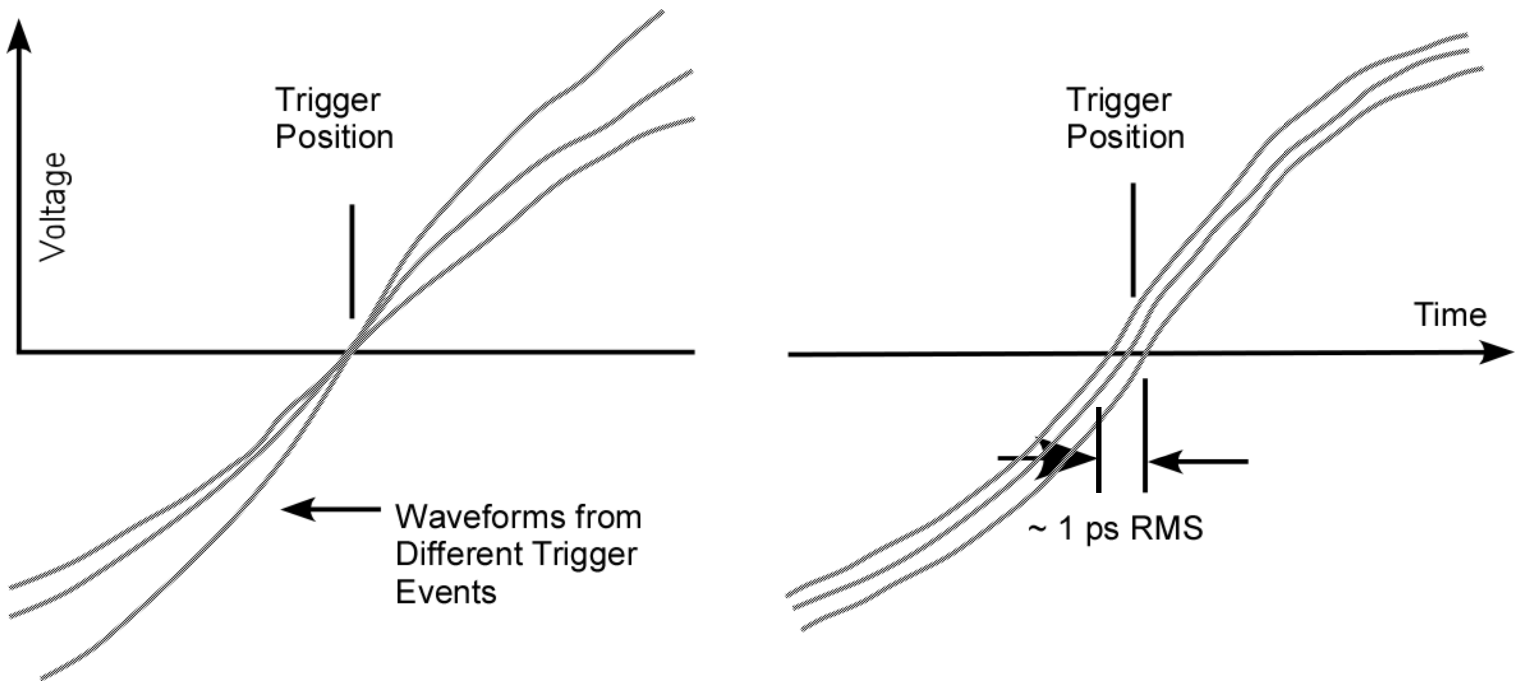
# Trigger Jitter

Trigger jitter is the amount of effective timing instability between the trigger path and the signal capture path

In eye diagram construction, multiple waveform acquisitions are overlayed. Trigger jitter is then an externally introduced noise that cannot be distinguished from the true jitter

Typical value: ~ 1 ps RMS

# Trigger Jitter



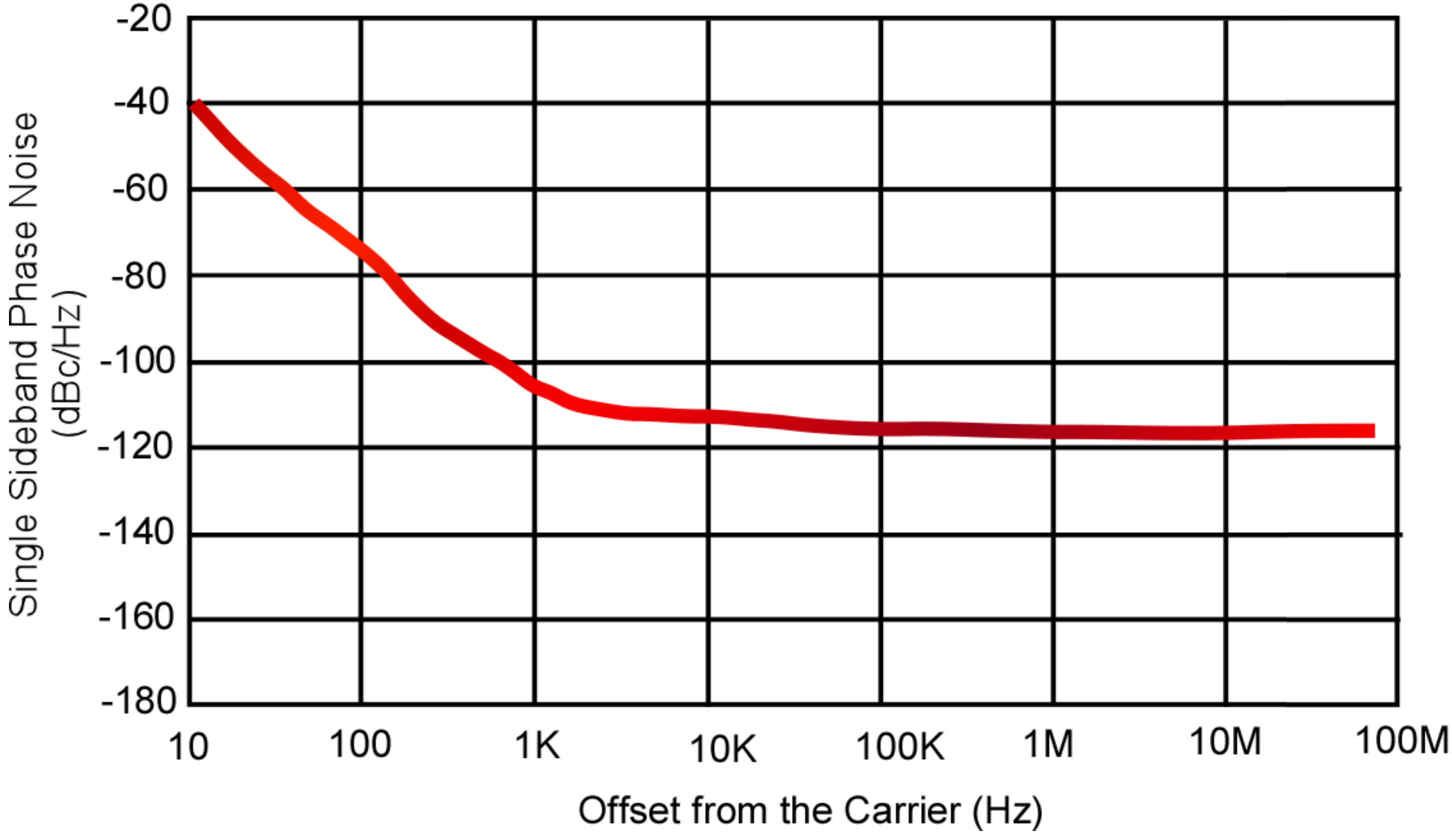
# Sample Jitter

Much of the timing instability in an oscilloscope is a combination of *phase noise* in the instrument's time base and *aperture jitter* in the track-and-hold circuits

They exhibit a Gaussian probability distribution

*Interleaving errors* from the digitizers are another large source of errors. They are deterministic and are manifested as deterministic jitter→ can be calibrated out

# Oscillator Phase Noise

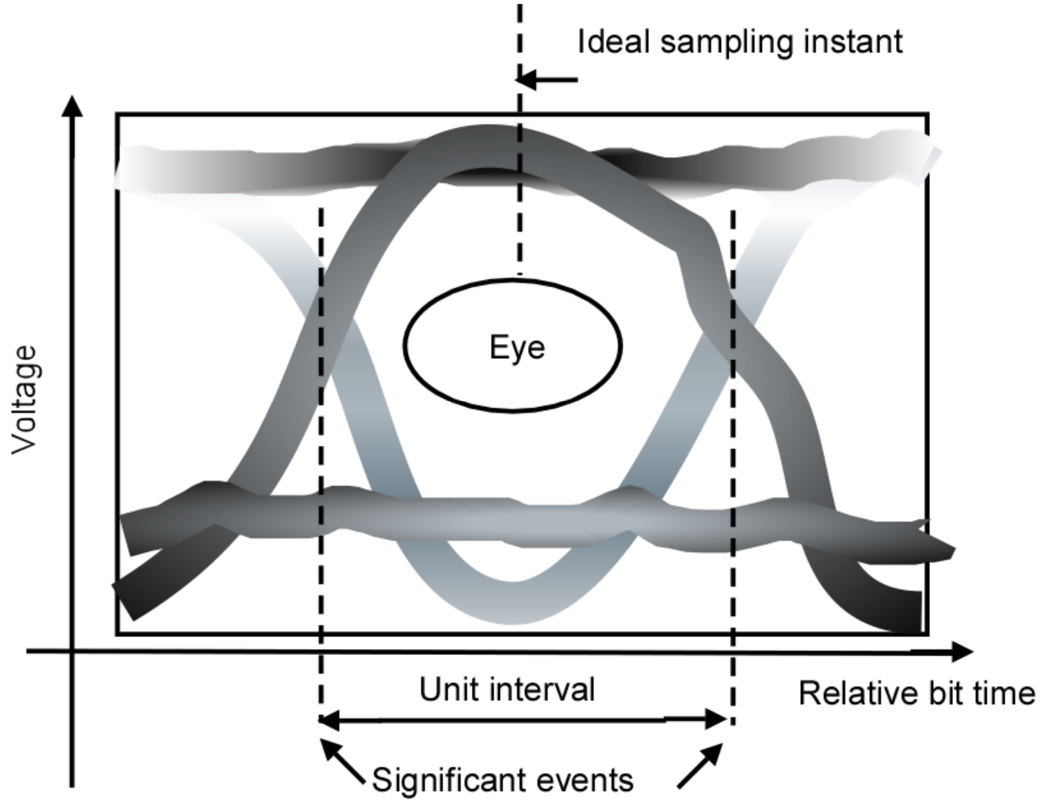


# Sample Jitter

- Gaussian Errors
  - Phase noise
  - Aperture jitter in track-and-hold circuits
- Deterministic Errors
  - Interleaving mismatches
  - Can be calibrated out

# Eye Diagram

**An eye diagram is a time-folded representation of a signal that carries digital information**



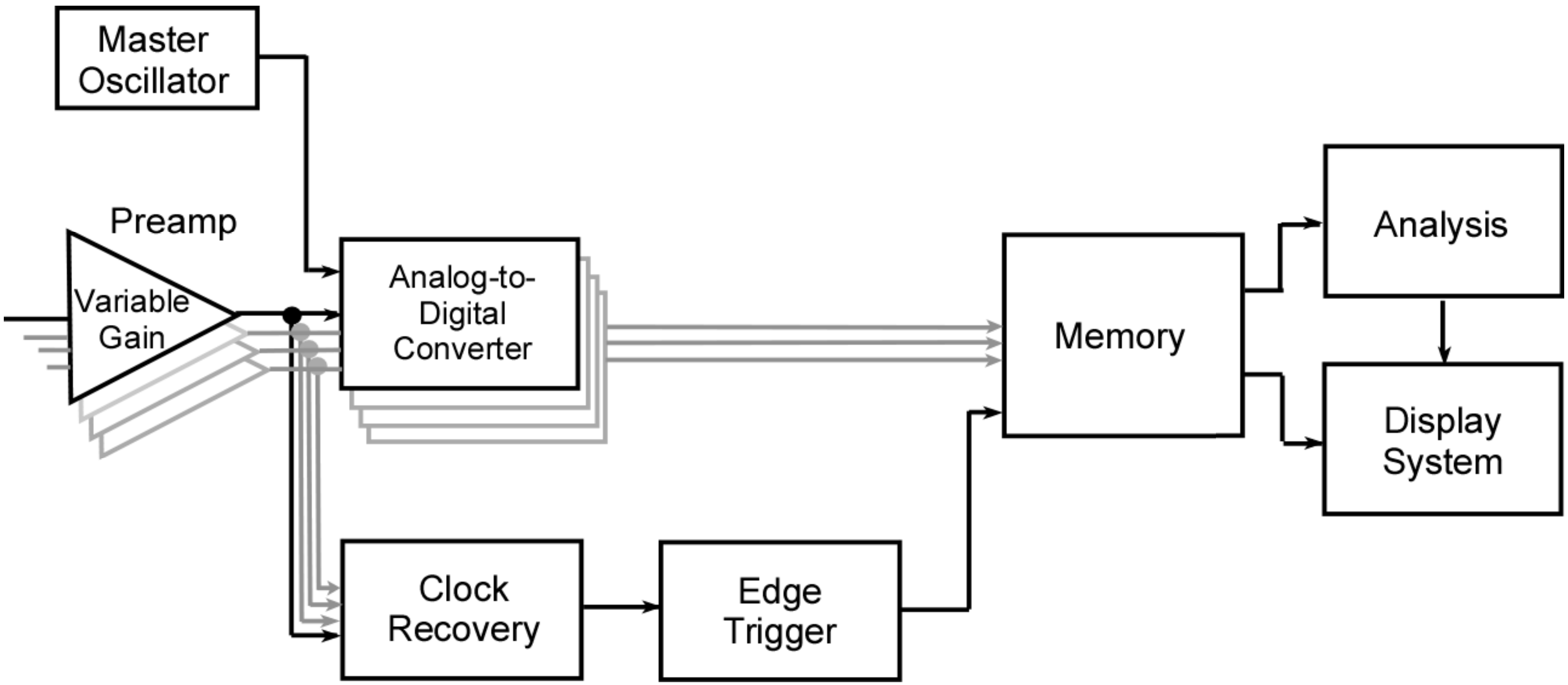

**Eye is horizontally centered on the ideal sampling instant**

# Eye Diagram

- Unit interval (UI) of a bit sequence is typically independent of the waveform sampling interval of the measurement instrument.
  - Waveform sampling interval must be no more than one half the unit interval to avoid aliasing
  - Rule of thumb for eye diagrams is to sample 5 to 10 times the bit rate
  - For 2.5 Gb/s, the sampling rate should be 20 GSamples/s

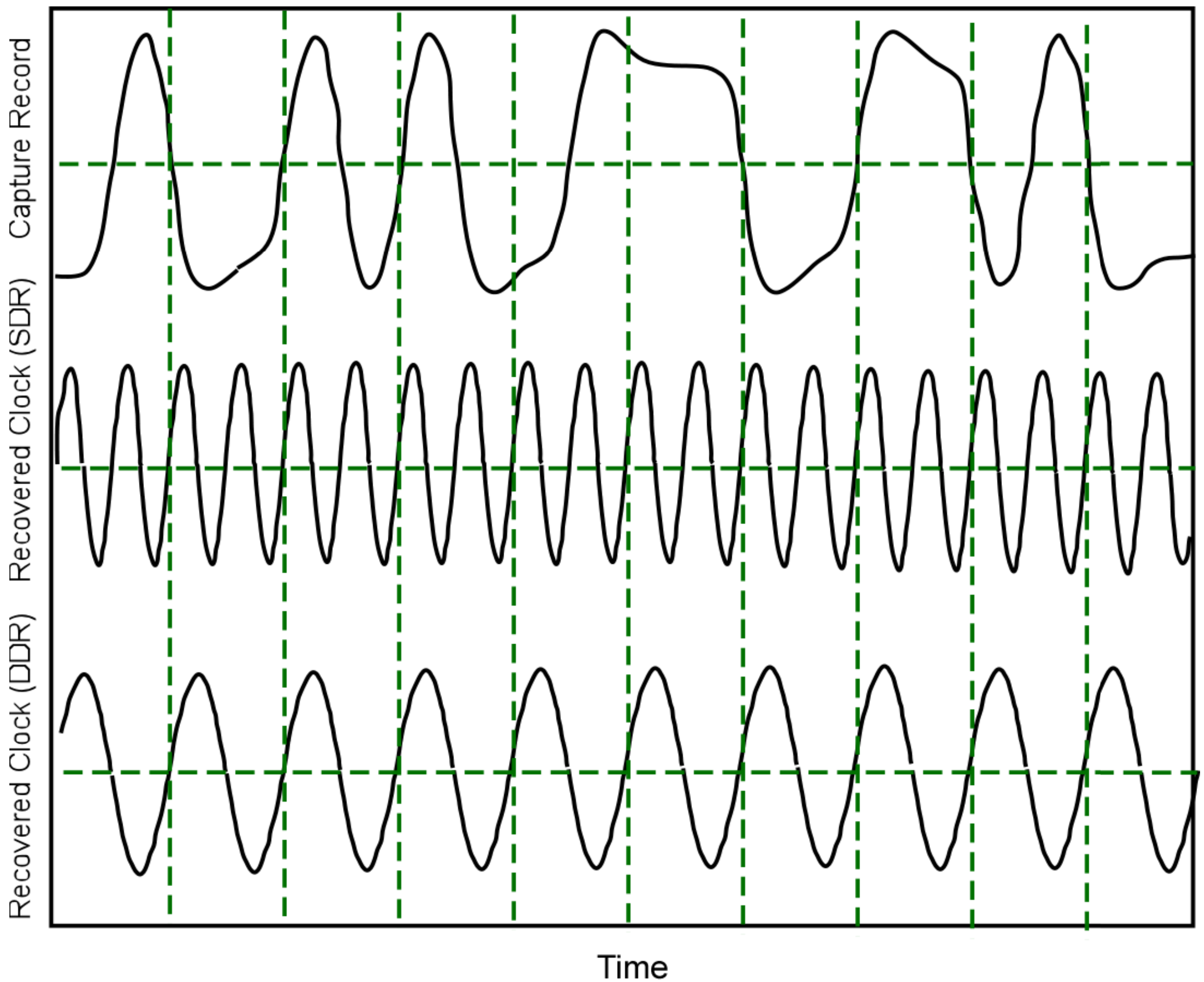
**Large eye openings ensure that the receiving device can reliably decide between high and low logic states even when the decision threshold fluctuates or the decision time instant varies.**

# Eye Diagram Construction

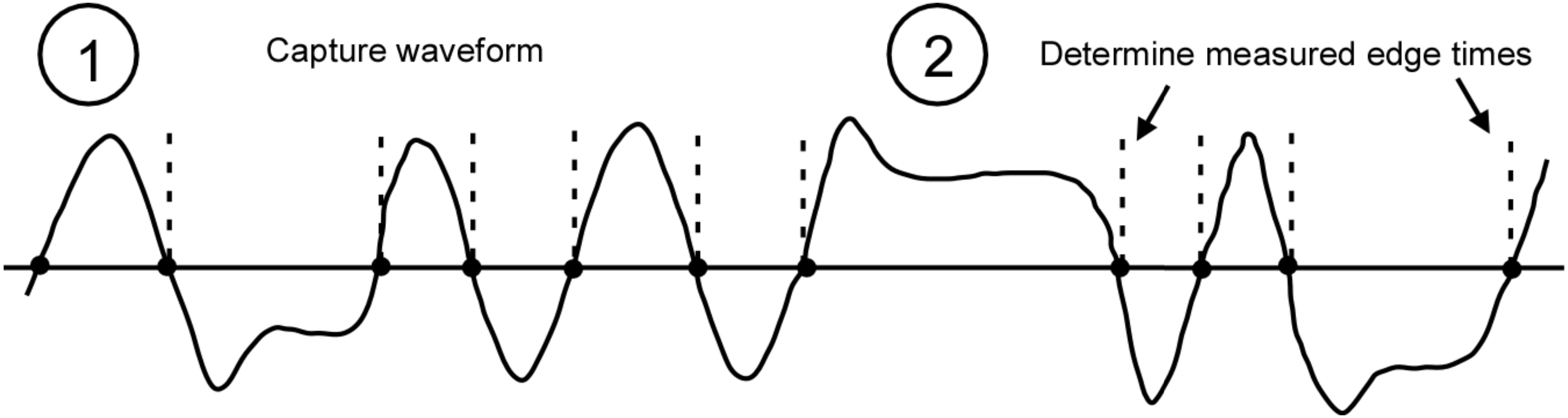



**Eye diagram construction in real-time oscilloscope is based on hardware clock recovery and trigger circuitry**

# Eye Diagram Construction



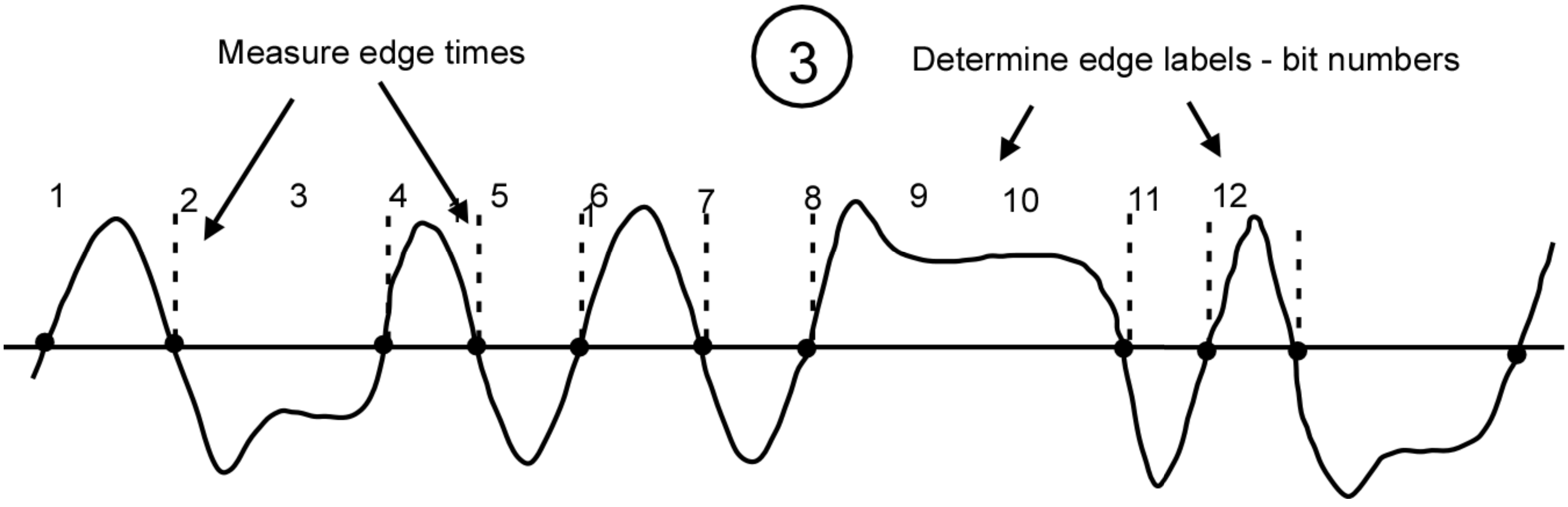
# Eye Diagram Construction




## 1. Capture of the Waveform Record

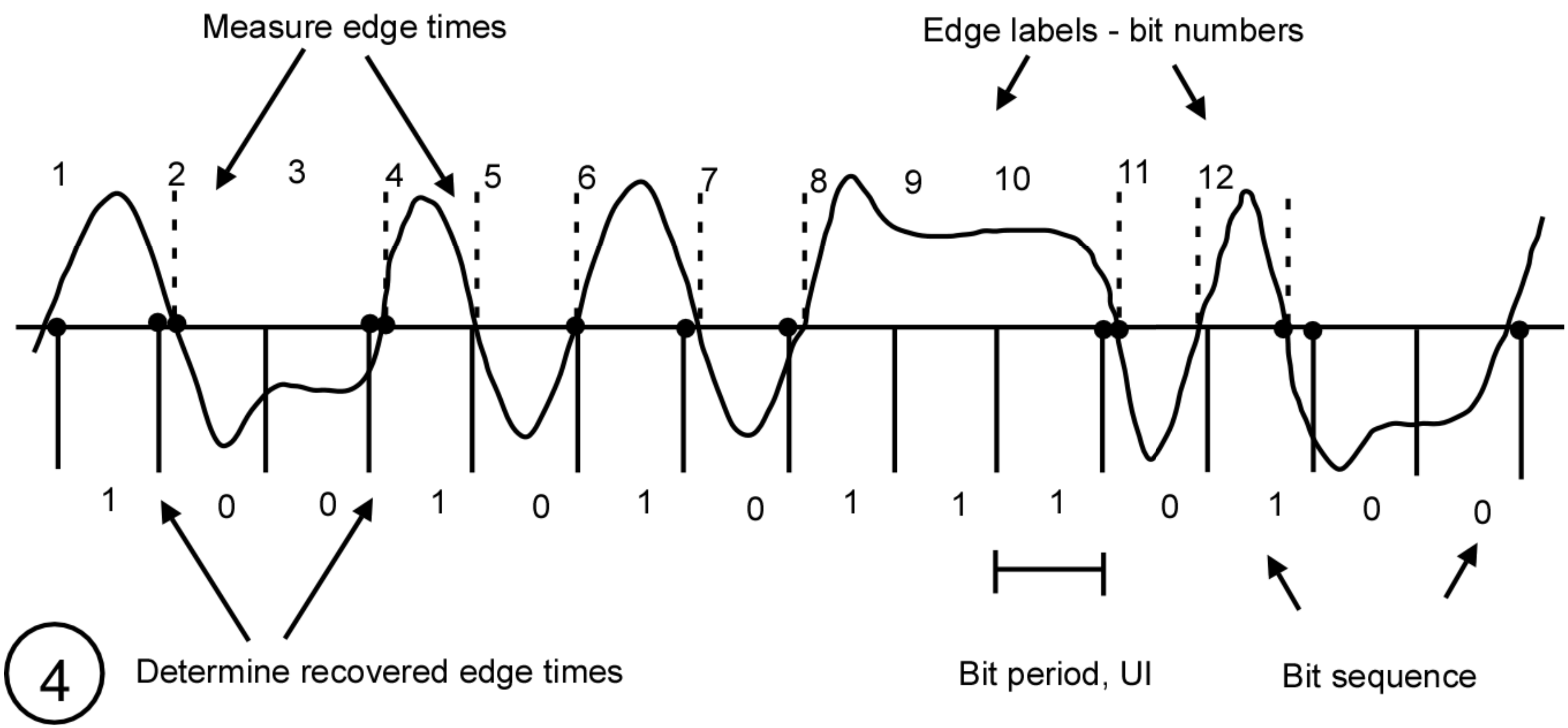
## 2. Determine the Edge Times

# Eye Diagram Construction



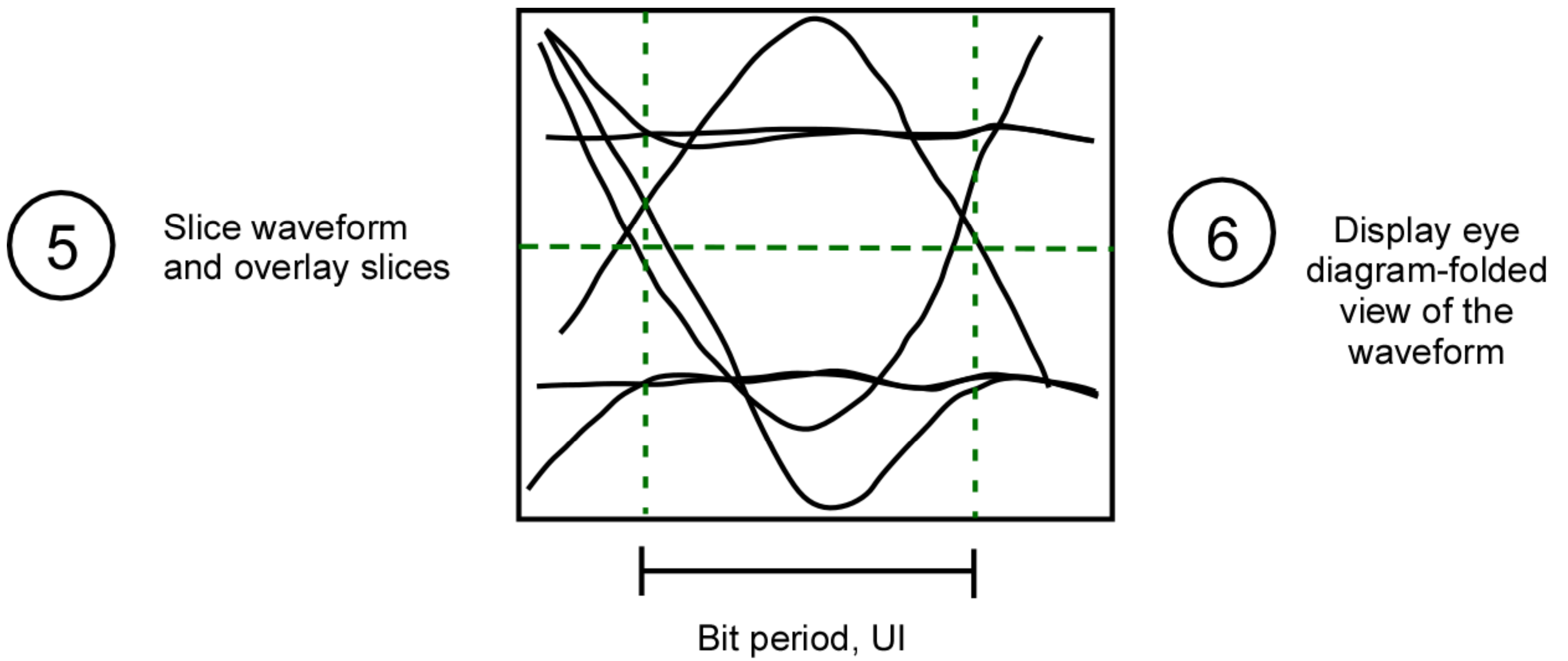

## 3. Determine the Bit Labels

# Eye Diagram Construction




## 4. Clock Recovery

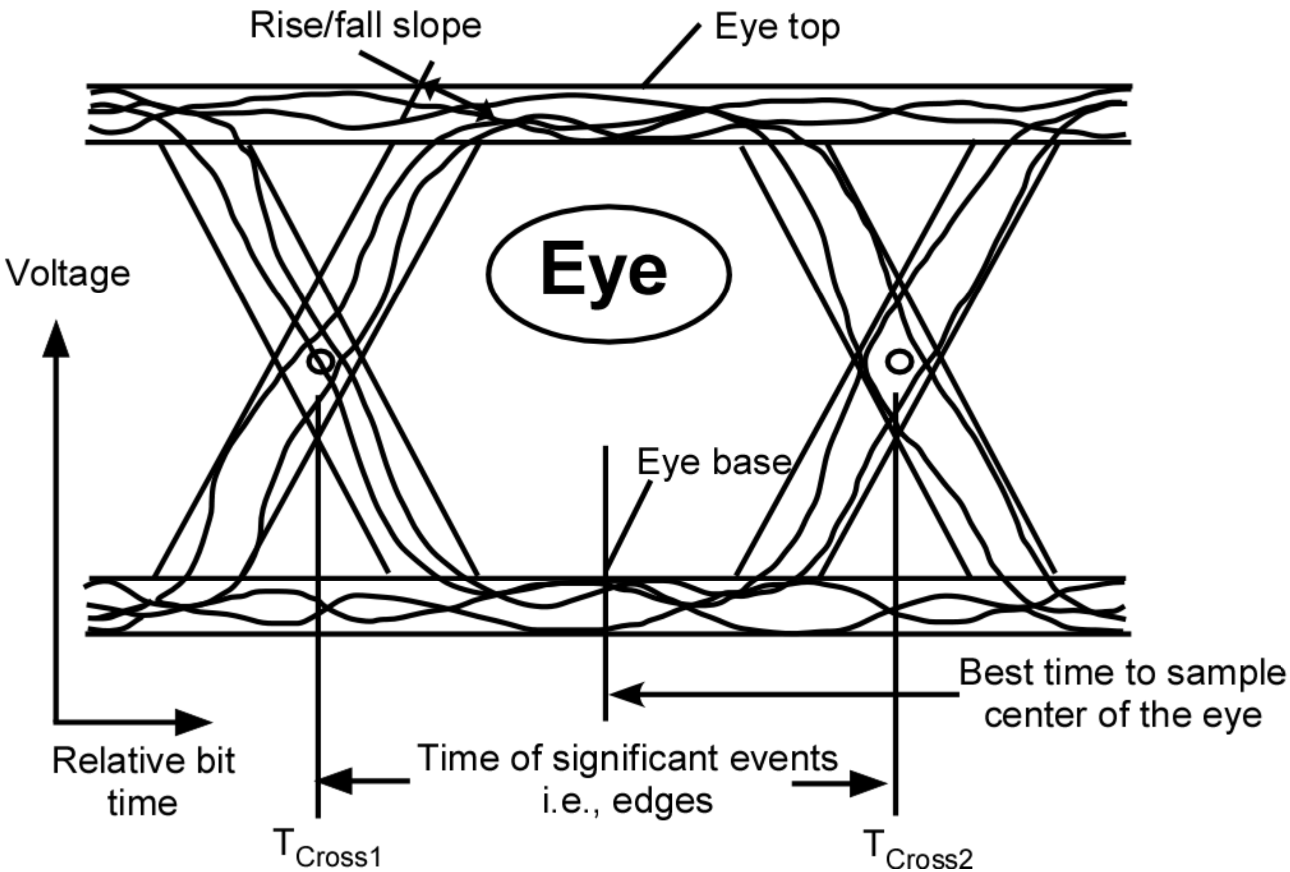
# Eye Diagram Construction



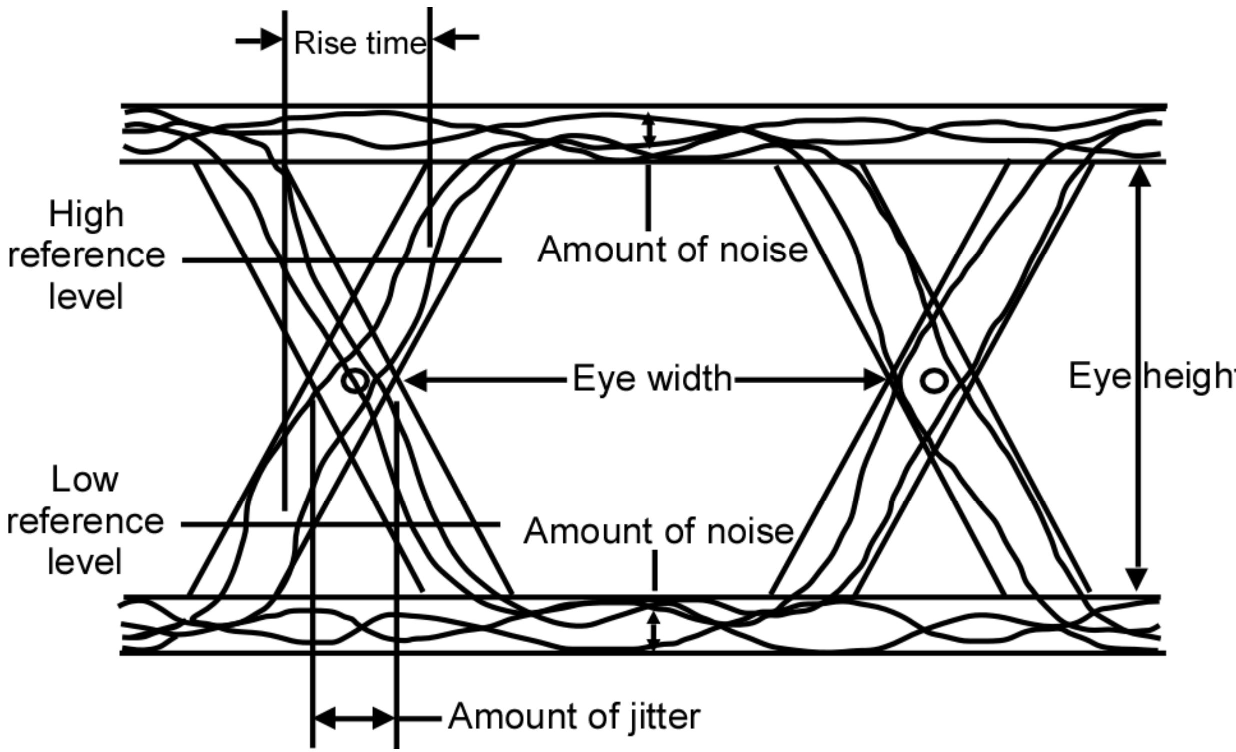

## 5. Slice Overlay

## 6. Display

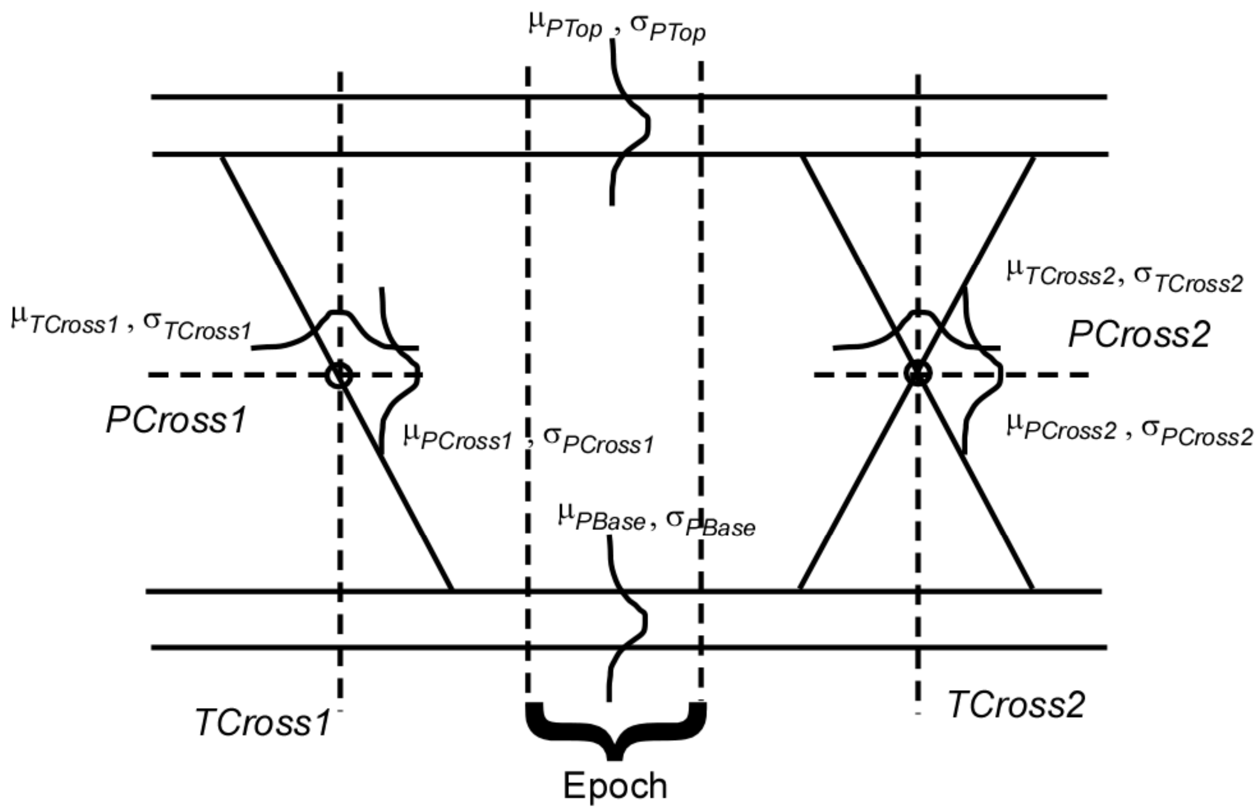
# Eye Diagram Measurements



# Eye Diagram Measurements



# Reference Levels



# Eye Height

**Eye Height is the measuremnt of the eye height in volts**

$$Eye\ Height = \left(\mu_{PTop} - 3\sigma_{PTop}\right) - \left(\mu_{PBase} + 3\sigma_{PBase}\right)$$

$\mu_{PTop}$ : mean value of eye top

$\sigma_{PTop}$ : standard deviation of eye top

$\mu_{PBase}$ : mean value of eye base

$\sigma_{PBase}$ : standard deviation of eye base

# Eye Width

***Eye Width*** **is the measuremnt of the eye width in seconds**

$$Eye\,Width = \left(\mu_{TCross2} - 3\sigma_{TCross2}\right) - \left(\mu_{TCross1} + 3\sigma_{TCross1}\right)$$

***Crossing percent*** **measurement is the eye crossing point expressed as a percentage of the eye height**

$$\text{Crossing Percent} = \frac{\left(\mu_{PCross1} - \mu_{PBase}\right)}{\left(\mu_{PTop} - \mu_{PBase}\right)} \times 100\%$$

# Jitter Measurements

***Jitter peak-to-peak*** **is the peak-to-peak value for the edge jitter in the current horizontal units**

$$\text{Jitter pp} = \max\left(TCross1\right) - \min\left(TCross1\right)$$

***Jitter root mean square*** **is the RMS value of the edge jitter in the current horizontal units**

$$\text{Jitter RMS} = \sigma_{TCross1}$$

***Jitter 6σ*** **represents the same measurement reporting the $6\sigma_{\text{TCross1}}$ value**

# Noise Measurements

***Noise peak-to-peak*** **is the peak-to-peak value of the noise at the top or base of the signal as specified by the user**

$$\text{Noise pp} = \begin{cases} \max(PTop) - \min(PTop), \; or \\ \max(PBase) - \min(PBase) \end{cases}$$

***Noise root mean square*** **is the RMS value of the noise at the top or base of the signal**

$$\text{Noise RMS} = \begin{cases} \sigma_{PTop} \\ \text{or} \\ \sigma_{PBase} \end{cases}$$

# Noise Measurements

***Signal-to-noise ratio*** **is the ratio of the signal amplitude to the noise at either the top or the base of the signal**

$$\text{S/N Ratio} = \frac{\left(\mu_{PTop} - \mu_{PBase}\right)}{\left(\sigma_{PTop} - \sigma_{PBase}\right)}$$

***Duty cycle distortion*** **is the peak-to-peak time variation of the first eye crossing measured at the mid-voltage reference as a percent of the eye period**

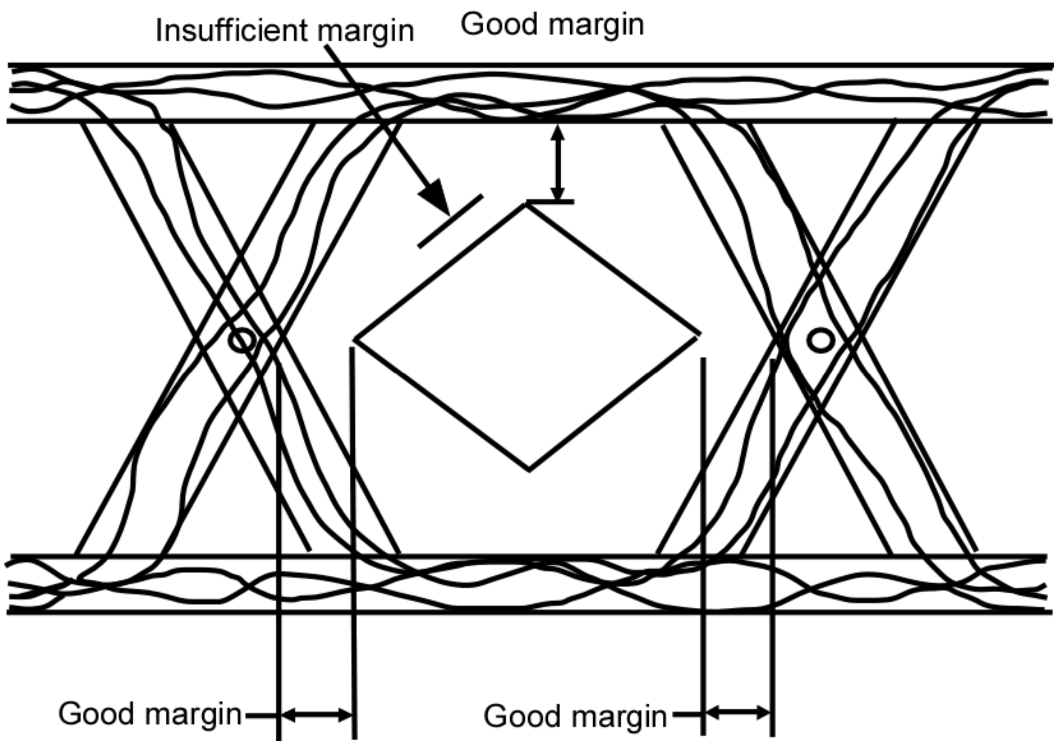
$$\text{DCD} = \frac{\text{TDCD}_{\text{p-p}}}{\left(\mu_{TCross2} - \mu_{TCross1}\right)} \times 100\%$$

# Eye Quality Factor

***Quality factor*** **is the ratio of the eye size to noise**

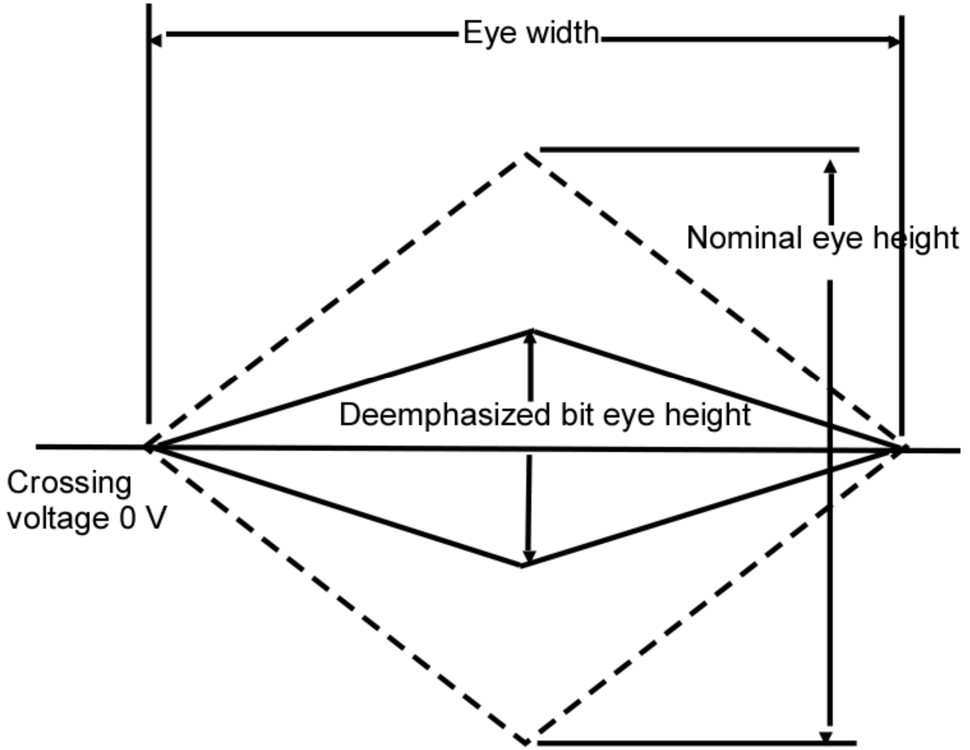
$$\text{Quality Factor} = \frac{\left(\mu_{PTop} - \mu_{PBase}\right)}{\left(\sigma_{PTop} + \sigma_{PBase}\right)}$$

# Margin Testing



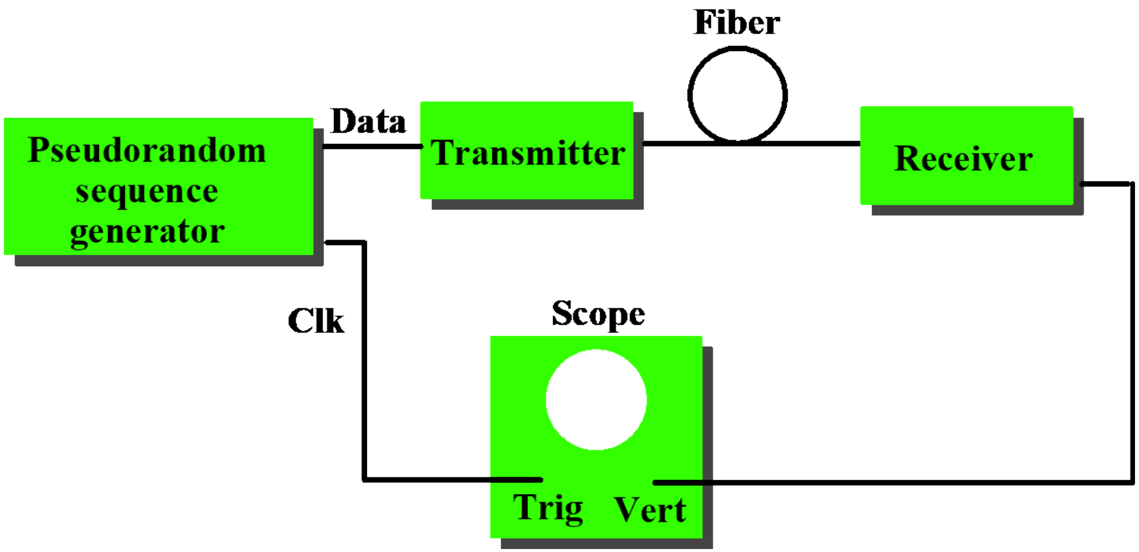

## Eye diagram with low margin

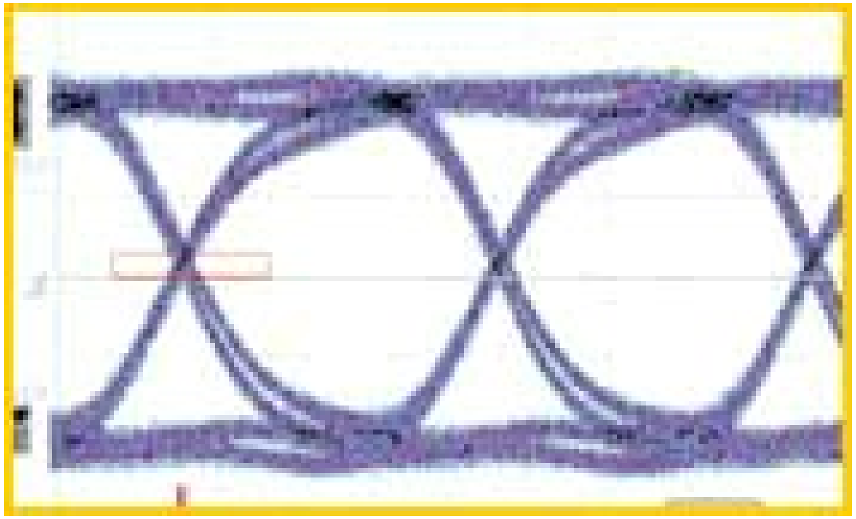
# Eye Diagram Specifications




**PCI Express 2.0 eye diagram specification for full and deemphasized signals**

# Eye Pattern Analysis



# Bit Error Ratio

- Bit error ratio (BER) is the fundamental measure of the overall transmission quality of the system
  - A single number that counts how many bits got right and how many errors were made
  - The BER is a measure of the percentage of bits that a system does not transmit or receive correctly
  - Instead of viewing the BER as a percentage, we can also consider it as a probability for a single bit to be received in error.

$$N_{Err} = N_{bits} \cdot BER$$

$N_{Err}$: Average number of errors
$N_{bits}$: Number of transmitted bits

# Bit Error Rate

- Bit error rate relates the number of errors to the test time
  - Different from bit error ratio

$$BERate = \frac{N_{Err}}{t}$$

$N_{Err}$: Number of errors
$t$: Test time

- Bit error rate can be calculated from bit error ratio using the data rate

$$BERate\left[\frac{Errors}{s}\right] = BER\left[\frac{Errors}{Bits}\right] \cdot Datarate\left[\frac{Bits}{s}\right]$$

For PCI Express, BER=$10^{-12}$, BERate=0.025 Errors/s

# Bit Error Ratio

## Mean Time between Errors as a Function for Multigigabit Data Rates

| BER | 1 Gbit/s | 2.5 Gbit/s | 5 Gbit/s | 10 Gbit/s | 40 Gbit/s |
|---|---|---|---|---|---|
| $10^{-8}$ | 100 ms | 40 ms | 20 ms | 10 ms | 2.5 ms |
| $10^{-9}$ | 1 s | 400 ms | 200 ms | 100 ms | 25 ms |
| $10^{-10}$ | 10 s | 4 s | 2 s | 1 s | 250 ms |
| $10^{-11}$ | 1.66 min | 40 s | 20 s | 10 s | 2.5 s |
| $10^{-12}$ | 16.67 min | 6.67 min | 3.33 min | 1.67 min | 25 s |
| $10^{-13}$ | 2.78 h | 1.11 h | 33.3 min | 16.67 min | 4.17 min |
| $10^{-14}$ | 1.16 d | 11.11 h | 5.56 h | 2.78 h | 41.67 min |
| $10^{-15}$ | 11.57 d | 4.63 d | 2.31 d | 1.16 d | 6.94 h |
| $10^{-16}$ | 3.86 mo | 1.54 mo | 23.15 d | 11.57 d | 2.89 d |
| $10^{-17}$ | 3.17 y | 1.27 y | 7.72 mo | 3.86 mo | 28.93 d |
| $10^{-18}$ | 31.7 y | 12.7 y | 6.34 y | 3.17 y | 9.64 mo |
| | | | | | |

Source: D. Derickson and M. Muller, "Digital Communications Test and Measurement", Prentice Hall, 2007