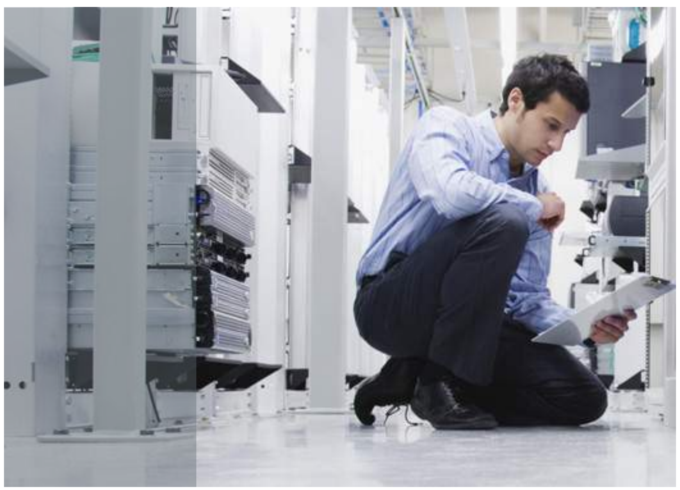
Fundamentals of Signal Integrity

- Powerful and Complete Portfolio to Overcome Signal Degradation Challenges



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What is Signal Integrity?

The term “integrity” means “complete and unimpaired.”

A digital signal with good integrity has:

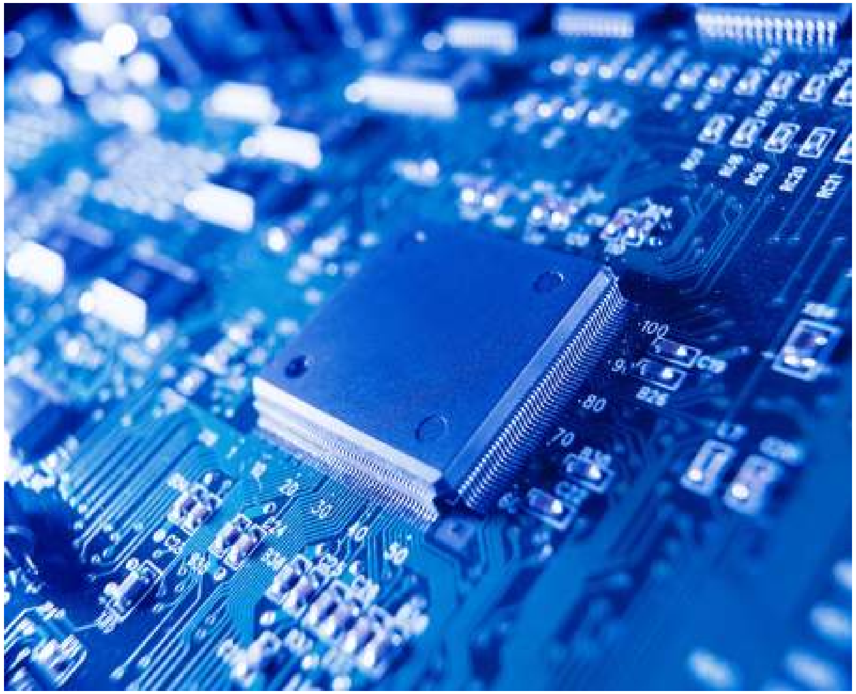
- Clean, fast transitions
- Stable, valid logic levels
- Accurate placement in time
- Free of transients

Digital Technology and the Information Age

- Consumer demand for more features and services drives the need for more bandwidth
- Technology breakthroughs enable the Information Age
  - ***FASTER*** processor speeds
  - ***FASTER*** memory throughput
  - ***FASTER*** internal bus speeds
- Evolving devices push to higher data rates

Rising Bandwidth Challenges Digital Design

- Digital technology is evolving fast
  - Bus cycle times are 1000X
  - Transactions take nanoseconds
  - Edge speeds are 100X
- Circuit board technology has not kept pace
  - Still need space for ICs, connectors, passives, bus traces
  - Propagation time of inter-chip buses remains virtually unchanged



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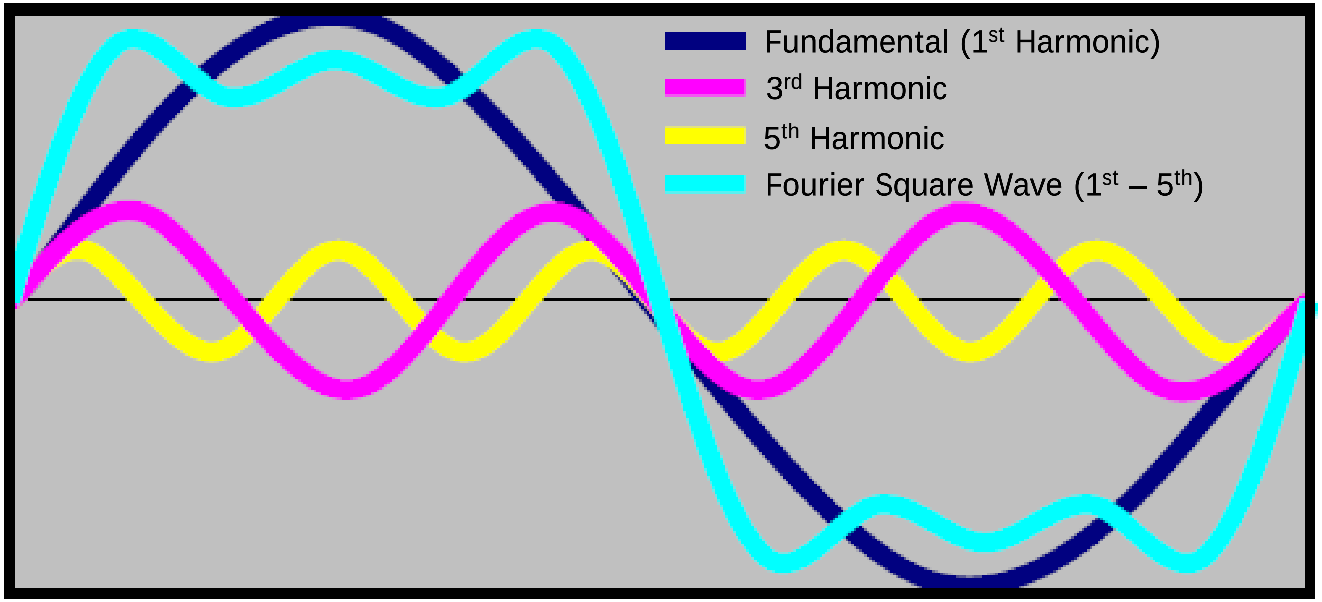
Faster Speeds, Higher Frequencies

- Fast transitions are created by high frequency components
  - – 5th harmonic of the clock rate carries significant energy



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Higher Frequencies, More Problems

- Circuit board traces become transmission lines
- Impedance discontinuities along the signal path:
  - Create reflections
  - Degrade signal edges
  - Increase crosstalk
- EMI goes up
- Ground bounce increases with higher currents

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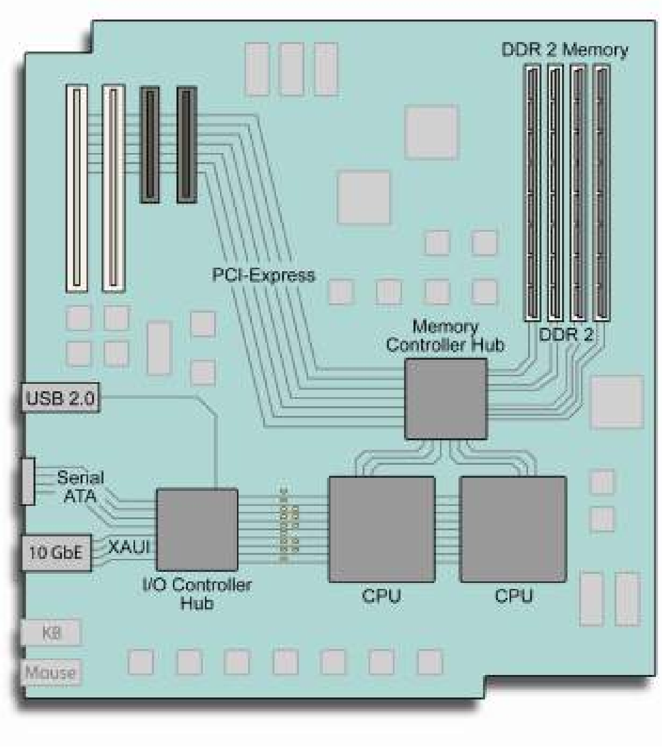
Every Design Detail Is Important

At clock frequencies in the hundreds of megahertz and above, every design detail is important:

- Clock distribution
- Signal path design
- Stubs
- Noise margin
- Impedances and loading
- Transmission line effects
- Signal path return currents
- Termination
- Decoupling
- Power distribution



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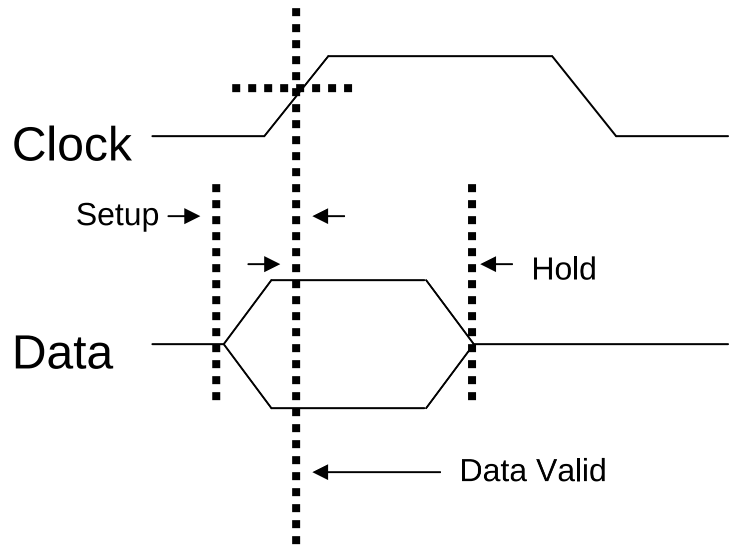
Problems Created by Digital Timing Issues

- Bus contention
- Setup and hold violations
- Metastability
- Undefined conditions
- Inter-symbol interference (ISI)

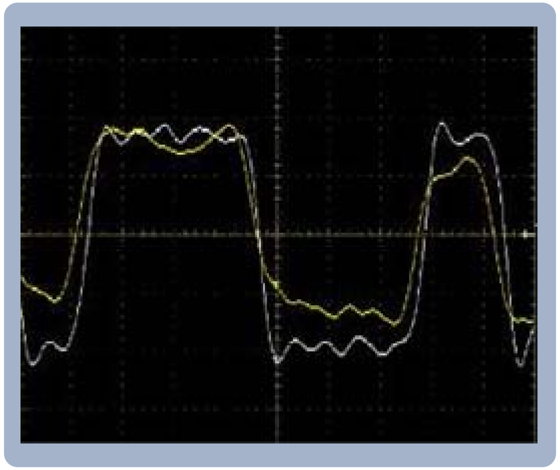


Setup and hold timing diagram

Common Causes of Analog Deviations

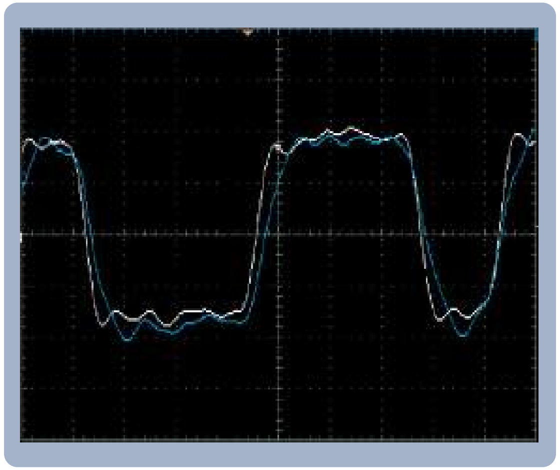
Amplitude Problems:

- Ringing
- Droop
- Runt pulses



Edge Aberrations:

- Board layout issues
- Improper termination
- Circuit problems



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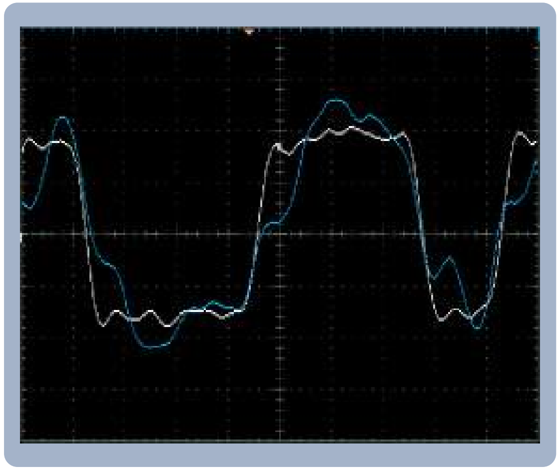
Common Causes of Analog Deviations

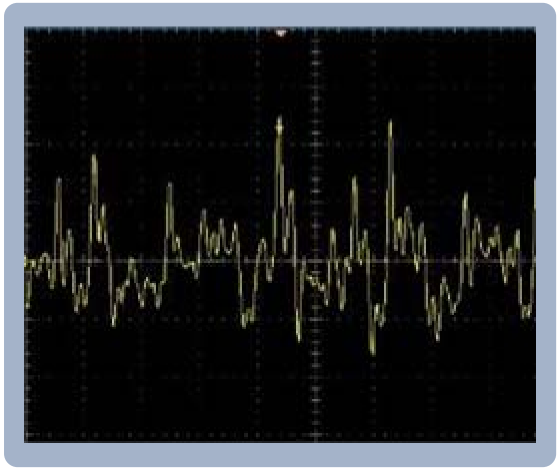
Reflections:

- Board layout issues
- Improper termination



Crosstalk:

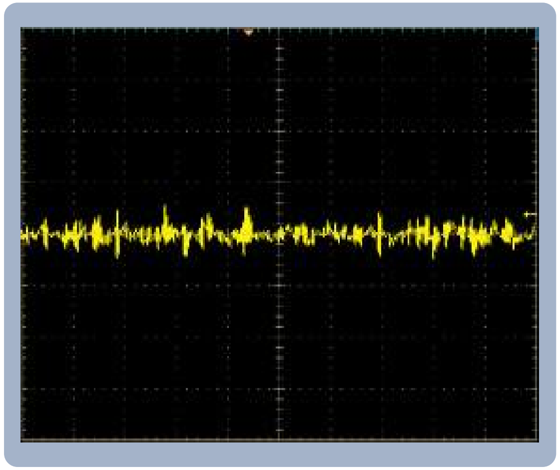
- Signal coupling
- EMI



Common Causes of Analog Deviations

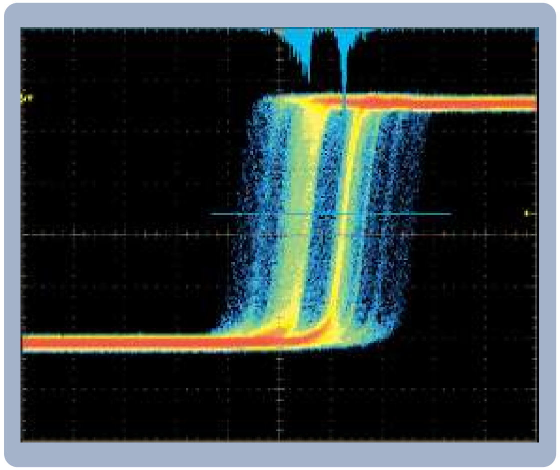
Ground Bounce:

- Excessive current draw
- Resistance in power supply and ground return paths



Jitter:

- Noise
- Crosstalk
- Timing instability



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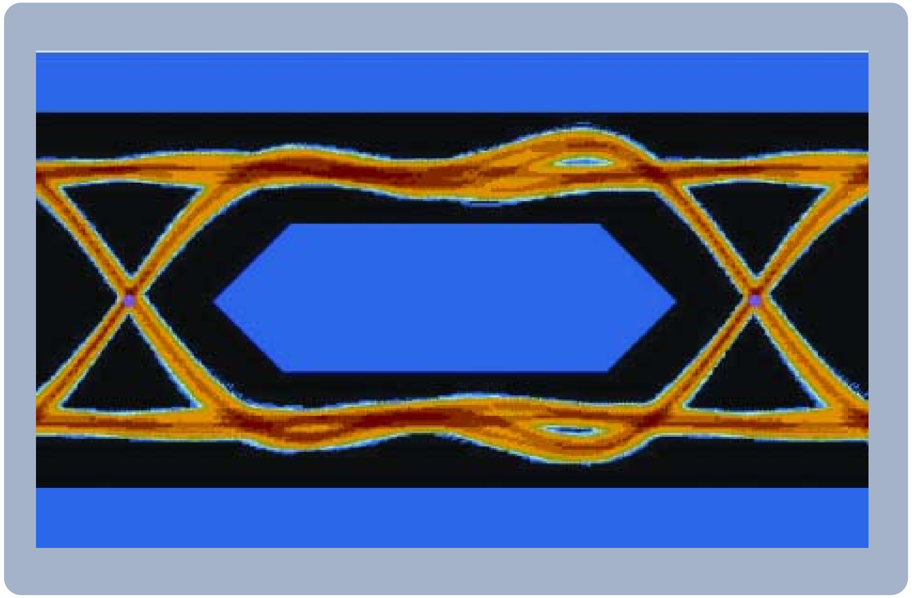
Eye Diagrams:
A Shortcut For Detecting Problems Quickly

- Visual tool to observe signal integrity on a clocked bus
- Overlays waveform traces from many successive unit intervals
- Signal integrity factors cause "blur":
  - Jitter (horizontal)
  - Noise (vertical)



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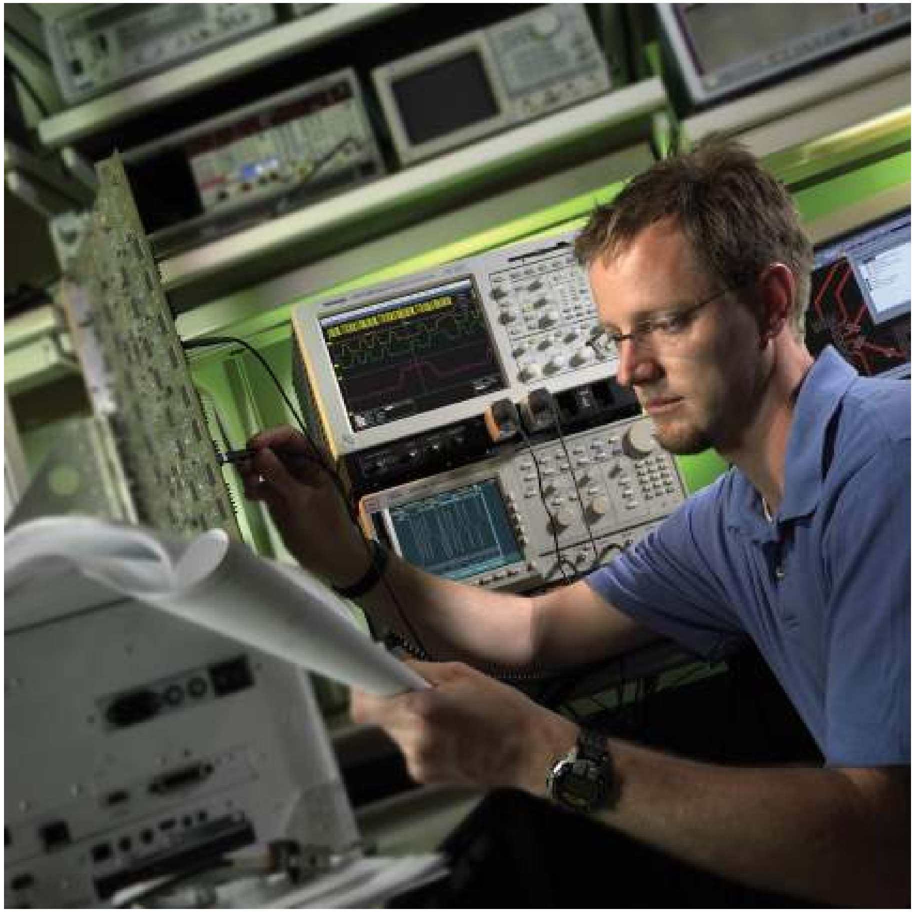
Signal Integrity Measurement Requirements

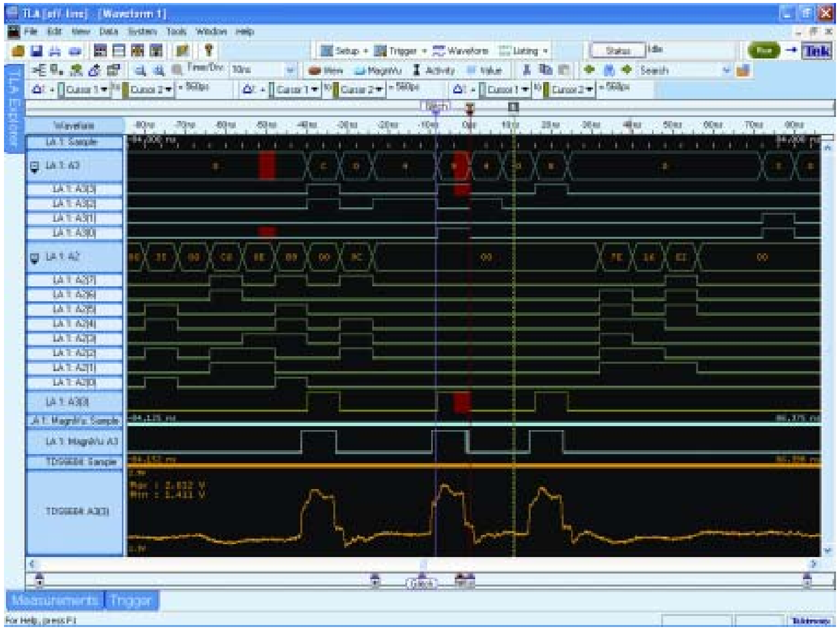
- Direct signal observations and measurements:
  - Logic analyzers
  - Oscilloscopes
  - Spectrum analyzers
- Probes
- Application software
  - Jitter
- Signal sources
- Time-domain reflectometry



Logic Analyzers Discover Digital Faults

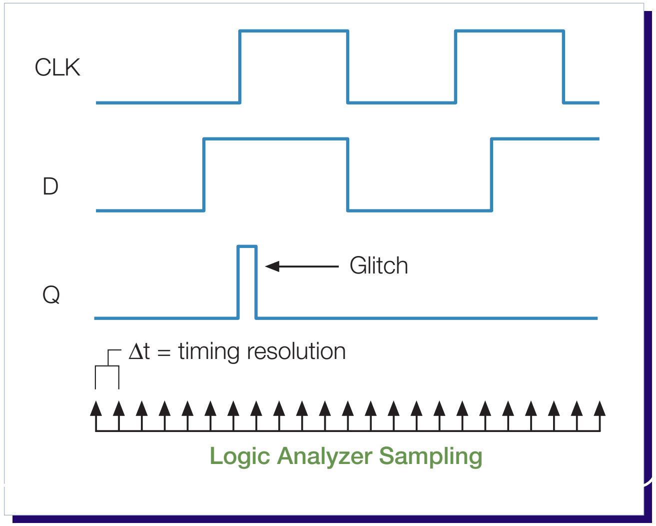
The logic analyzer is the first line of defense for digital troubleshooting.

- Detects threshold crossings then displays logic signals
- Digital waveforms can be compared to expected data
- Two different acquisition modes:
  - State (synchronous)
  - Timing (asynchronous)



Logic Analyzers: Key Performance Considerations

- Timing Resolution
  - Determines ability to detect and display glitches
  - Higher timing resolution, higher probability of capturing an event



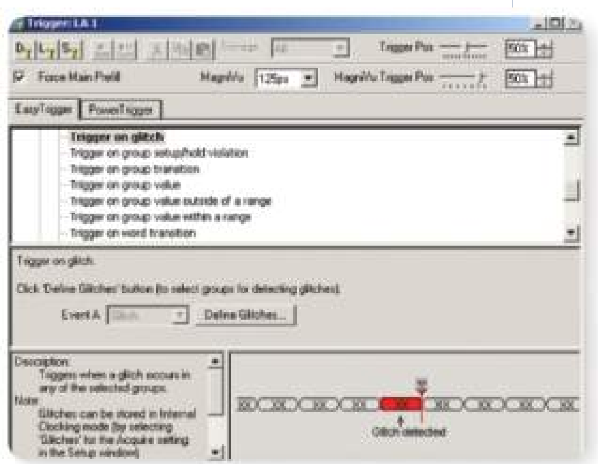
- Memory Depth
  - Determines how much “time” and detail can be captured in acquisition
  - Higher memory depth, higher probability of capturing an event

t = memory X timing resolution

Logic Analyzers: Key Performance Considerations

- Triggering Flexibility
  – Enables fast, efficient detection of unseen problems
  – Trigger sets condition at which LA acquires data
  – Triggers can be applied across hundreds of channels at once

Important Trigger Types:
- Glitch
- Setup and hold violation
- Channel edge
- Channel value
- Bus value
- Multi-group value
- Or, you define!



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Logic Analyzers Discover Digital Faults

Key parameters to evaluate when choosing a logic analyzer:

- Channel Count
- Timing Resolution
- Memory Depth
- Triggering
- Analog Multiplexing

Tektronix TLA7000 Series

Probing Solutions for Logic Analyzers

The Logic Analyzer probe must deliver the signal with highest possible fidelity.

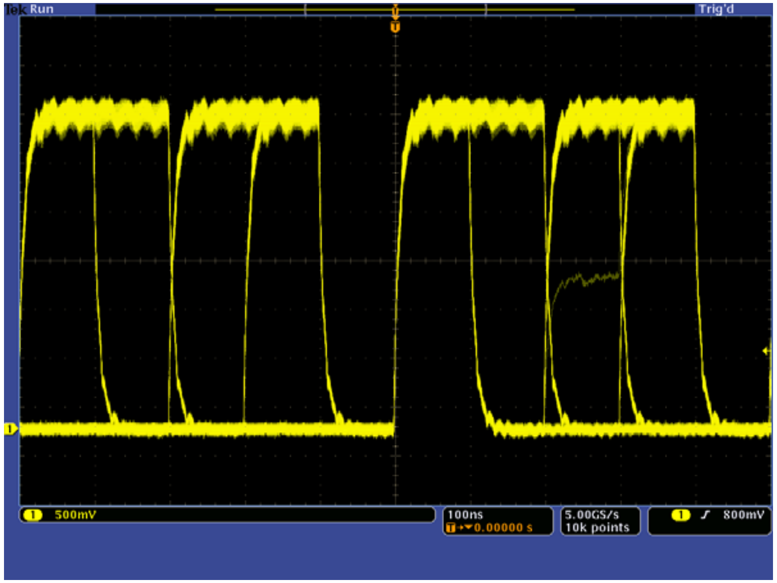
- With some, any pin can be used for digital ***and*** analog acquisition
- High performance digital requires a dedicated test point. Test options:
  - Install pins on device → affect signal
  - Install MICTOR → add cost, affect signal
  - Use connectorless probe → least affect on signal, need land pads on board

Tektronix high-density D-Max™ Probing Technology offers a small footprint and minimal affect on the signal

Digitizing Oscilloscopes Isolate Analog Deviations

The digitizing oscilloscope provides insight into the analog domain.

- Displays waveform details, edges and noise
- Detects and displays transients
- Precisely measures timing relationships



Different Types of Oscilloscopes

- Digital storage oscilloscope (DSO)
  - Low-repetition rate signals with fast edges or narrow pulses
  - Capture one-time events and transients
- Digital phosphor oscilloscope (DPO)
  - Digital troubleshooting
  - Find intermittent signals
  - Eye diagram and mask testing
- Sampling oscilloscope
  - Capture repetitive signals with high frequency components
  - Uses sequential equivalent-time sampling to achieve bandwidths up to 100 GHz

Tektronix DPO4000 Series

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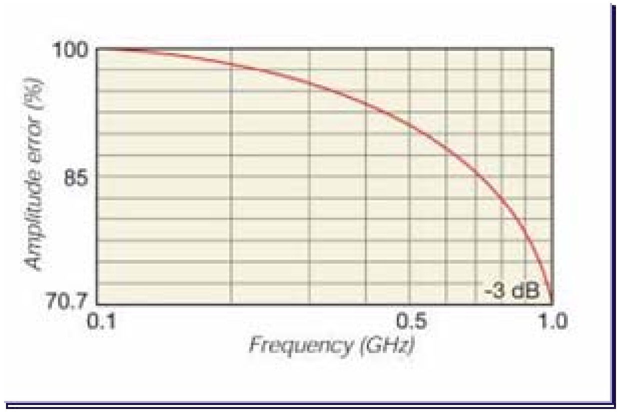
Oscilloscopes: Key Performance Considerations

- Oscilloscope Bandwidth
  - Must have sufficient bandwidth to capture high frequency components
  - Oscilloscopes have a low-pass frequency response
  - Bandwidth specified at -3 dB point



- The 5 Times Rule
  - For less than +/- 2% measurement error

Bandwidth ≥ 5th Harmonic

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Oscilloscopes: Key Performance Considerations

- Rise Time
  - Many logic families have faster rise times than clock rates suggest
- Required Rise Time

$$\text{Rise Time} = \frac{\text{Signal Rise Time}}{5}$$

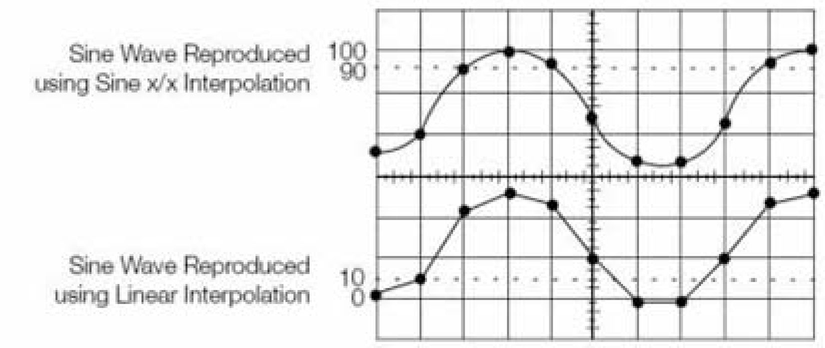
- Measured Rise Time

$$\text{Measured Rise Time} = \sqrt{\left[\text{Oscilloscope Rise Time}\right]^2 + \left[\text{Signal Rise Time}\right]^2}$$

Logic Family	Typical Signal Rise Time
TTL	2 ns
CMOS	1.5 ns
GTL	1 ns
LVDS	400 ps
ECL	100 ps
GaAs	40 ps

Oscilloscopes: Key Performance Considerations

- Sample Rate
  - Determines how frequently an oscilloscope takes a sample
  - Faster sample rate, greater resolution and waveform detail



- Required Sample Rate

Sample Rate $>$ **2.5 x** $f_{Highest}$

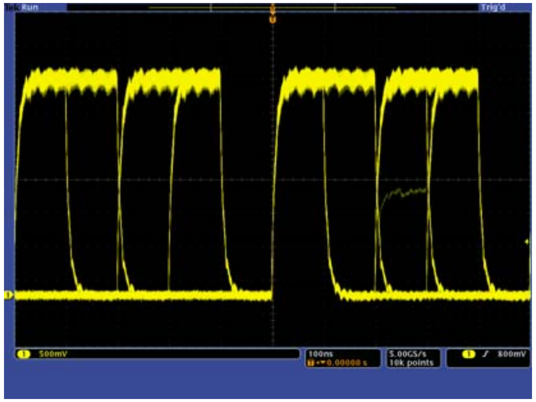
For sin(x)/x interpolation

Sample Rate $>$ **10 x** $f_{Highest}$

For linear interpolation

Oscilloscopes: Key Performance Considerations

- Waveform Capture Rate
  - Determines how frequently the oscilloscope captures a signal
  - Higher waveform capture rate, greater probability of quickly capturing transient anomalies



- Record Length
  - Determines how much “time” and detail can be captured in a single acquisition
  - Longer record length, longer time window with high resolution

$$t = \frac{\textbf{Record Length}}{\textbf{Sample Rate}}$$

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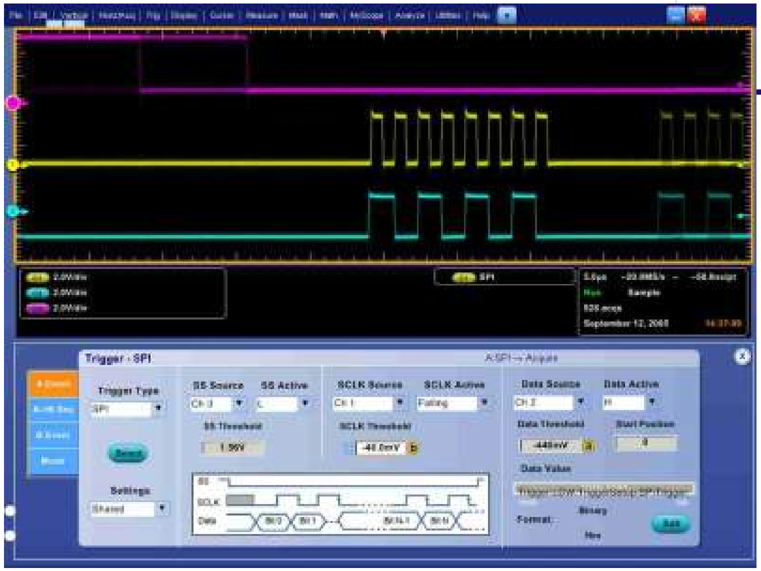
Oscilloscopes: Key Performance Considerations

- Triggering Flexibility
  - Enables fast, efficient detection of unseen problems
  - Trigger sets condition at which oscilloscope acquires data

Important Trigger Types:
- Edge level
- Slew rate
- Pulse characteristics
- Glitch
- Runt
- Setup and hold violation
- Serial digital patterns



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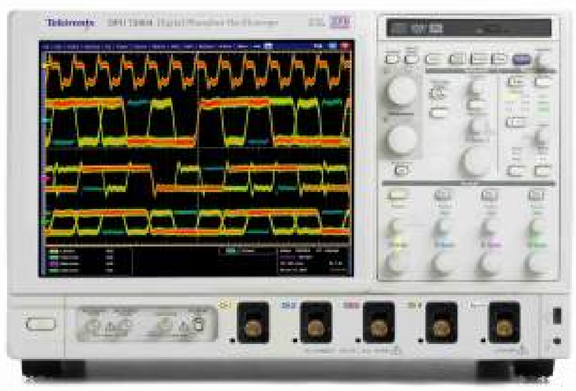
Digitizing Oscilloscopes Isolate Analog Deviations

Key parameters to evaluate when choosing an oscilloscope:

- Bandwidth
- Rise Time
- Sample Rate
- Waveform Capture Rate
- Record Length
- Triggering



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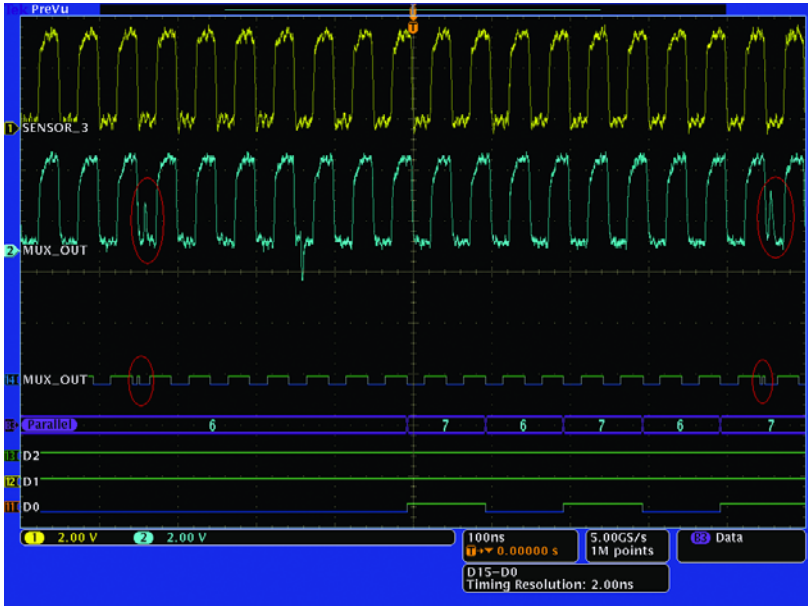
Mixed Signal Oscilloscopes Visualize Analog and Digital Domains

The mixed signal oscilloscope provides time-correlated insight into both domains.

- Good for devices with just a few logic lines
- Offers simultaneous analysis of analog and digital domains
- Signals are time-correlated



Oscilloscope Probing Solutions

The oscilloscope probe is the first link in the measurement chain.

- Must preserve the bandwidth and rise time of the oscilloscope
- Probe capacitance and inductance are key performance considerations
  - Increase with frequency
  - Will change the signal and its measurement result
    - Slower rise time
    - Decreased amplitude
    - Resonance
  - Lead length inductance can also distort the signal
- Ultra-low capacitance probes are recommended for high-speed measurements

Tektronix offers a wide range of probes and accessories

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Spectrum Analyzers Unmask the Frequency Domain

A spectrum analyzer's frequency resolution makes it an invaluable tool for tracking down many elusive events.

- Offers narrow frequency resolution to see subtle frequency events
  - Clock phase-slip
  - Microphonics
  - PLL settling
  - Frequency tolerance of clock dither
- Excellent dynamic range enables measurement of low-level signals
  - Impulse noise
  - Clock glitches
  - Crosstalk signals in presence of high amplitude signals

Tektronix RSA6100A Series

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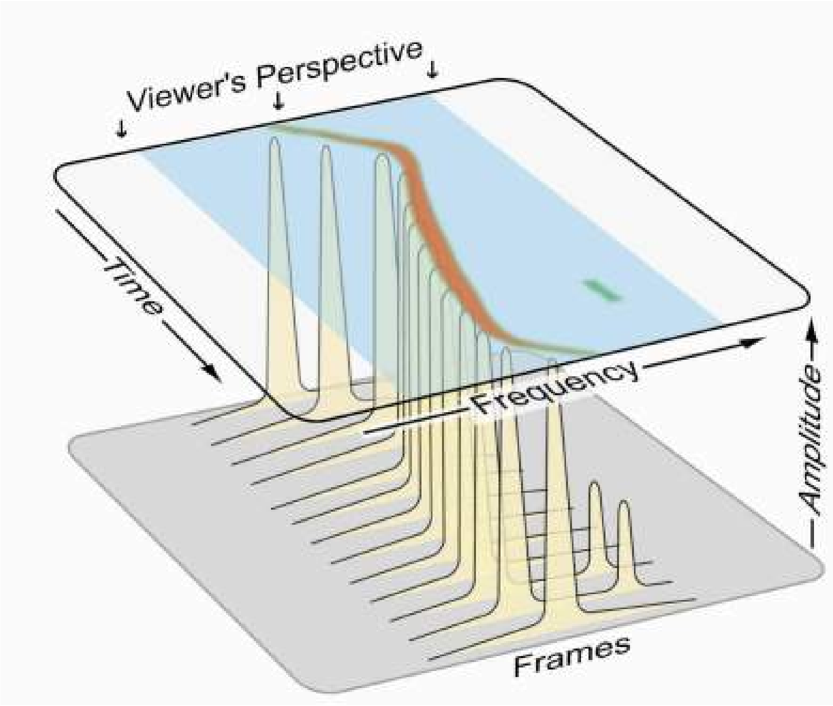
Different Types of Spectrum Analyzers

- Traditional swept spectrum analyzers
  – Best suited for observing controlled, static signals
  – Makes power vs. frequency measurements at one point in time
- Vector signal analyzers
  – Provides a snapshot of the signal in frequency or modulation domain
  – Requires batch processing
- Real-time spectrum analyzers
  – Measures signal changes over time
  – Provides frequency, time, modulation, statistical and code domain analysis
  – Discovers, triggers and isolates elusive events

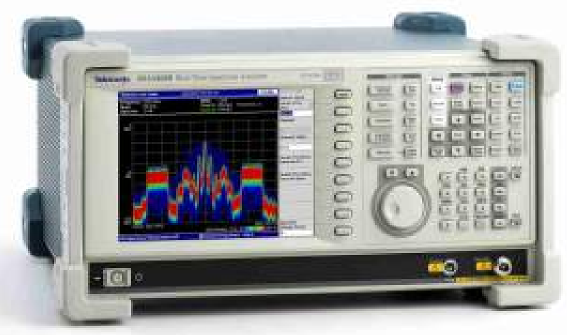


A real-time spectrum analyzer measures changes over time

Real-Time Spectrum Analyzers

Key parameters to evaluate when choosing an RTSA:

- Capture Bandwidth & Frequency Range
  – Must be sufficient for the signal: fundamental frequency, modulation type, frequency spread and PLL tuning steps
- Sample Rate
  – Must exceed Nyquist criteria for the capture bandwidth
- Analysis Interval
  – Needs to be long enough for narrowest resolution bandwidth when using repetitive FFTs
- Minimum Event Duration
  – Narrowest, non-repetitive rectangular pulse which can be captured with 100% certainty at a specified accuracy
  – Depends on RTSA's DFT transform rate



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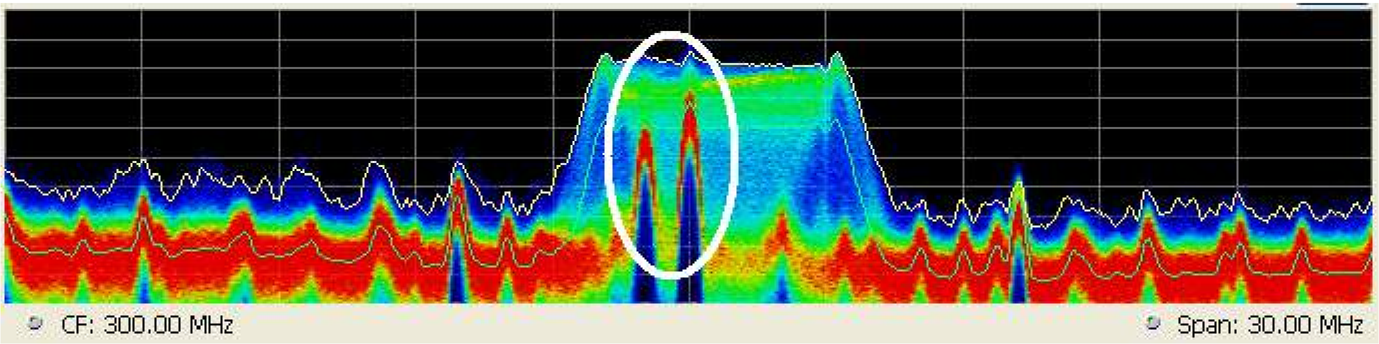
DPX Technology:
A Revolutionary Tool for Signal Discovery

- An intuitive, live color view of signal transients changing over time in the frequency domain
- Reveals signal details that are missed by traditional spectrum analyzers and vector signal analyzers



Integrated Measurement Tools

There is a high degree of interaction among digital and analog signal effects.

- Logic Analyzer + Oscilloscope
  - Good for devices with many digital signals
  - Analyze up to hundreds of digital lines and see the time-correlated analog signals
- Add RTSA for cross-domain analysis
  - Trigger in the frequency domain and capture time-correlated frequency, time and digital signals

iLink™ Toolset: Two Powerful Measurement Tools Team Up

- A unique logic analyzer/oscilloscope integration package
- Speeds problem detection and troubleshooting
- A comprehensive package:
  - **iCapture™ Multiplexing**
    Simultaneous digital and analog acquisition through a single probe
  - **iView™ Display**
    Time-correlated logic analyzer and oscilloscope measurements on the logic analyzer display
  - **iVerify™ Analysis**
    Multi-channel bus analysis and validation using oscilloscope-generated eye diagrams

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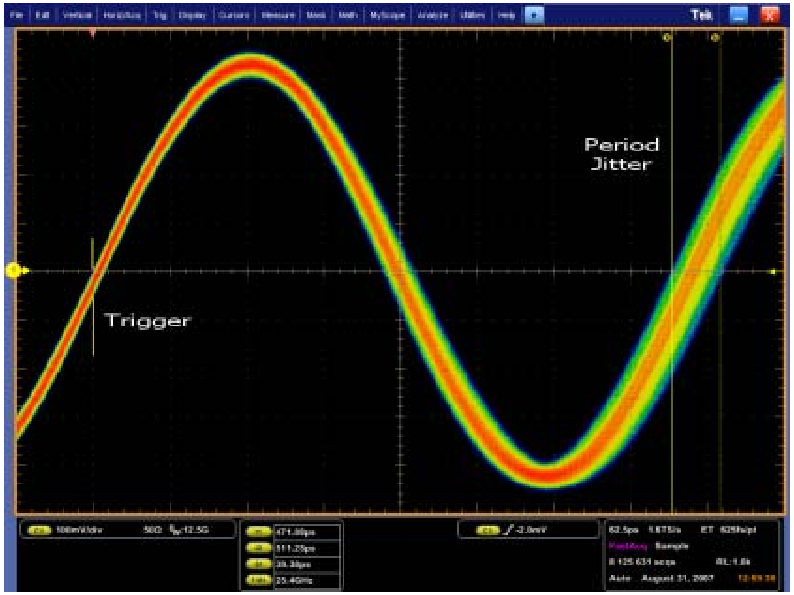
Jitter Analysis Tools Simplify Complex Measurements

Timing jitter can play a large role in system stability.

- Causes of jitter:
  - Clock circuitry
  - Power supply noise
  - Crosstalk
  - Phase lock loop (PLL) circuits
- Jitter affects:
  - Data
  - Addresses
  - Enable lines
  - Any signal in the system!
- In high-speed designs, jitter is a fundamental performance limit



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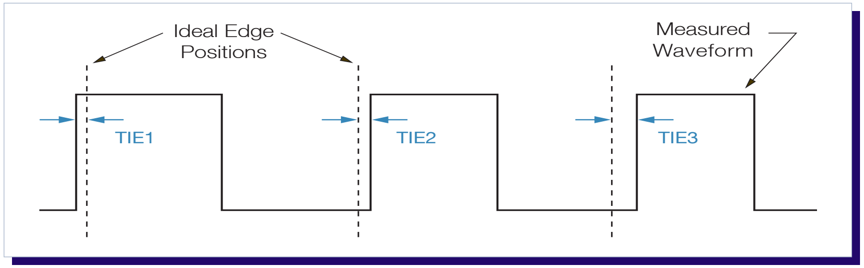
Measuring Jitter

- Two categories of jitter:
  - Deterministic jitter is predictable and consistent
  - Random jitter fits a Gaussian distribution
- Spectrum approach with an oscilloscope
  - Single-shot acquisition of the data signal is taken
  - Record is parsed to determine TIE for each clock edge
  - TIE results are FFT'd to compute spectrum of the signal's jitter
  - BER can be estimated
- For more dynamic range, use a RTSA
  - Noise floor of a RTSA is lower
  - Able to measure low-level spurious signals embedded in noise
  - Can also measure small signal in the presence of larger ones



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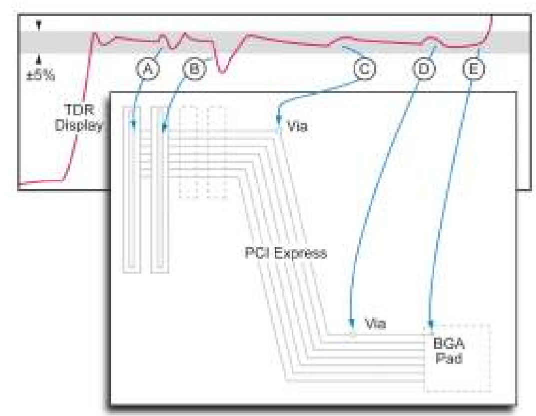
Time Domain Reflectometer for Impedance Measurements

A TDR solution measures reflections when a signal travels through the transmission environment.

- Making impedance measurements:
  - TDR module sends a fast step pulse through the medium
  - Sampler in TDR module measures reflected signals
- TDR display is a voltage waveform
  - Shows incident step and reflections
  - Reflections increase or decrease step amplitude
    - Resistance change
    - Inductive or capacitive nature of discontinuity
  - Left-most events are physically closest to step generator
- Same tools can also measure the transmission of the signal (TDT)



Time Domain Reflectometer for Impedance Measurements

Key parameters to evaluate when choosing a TDR module:

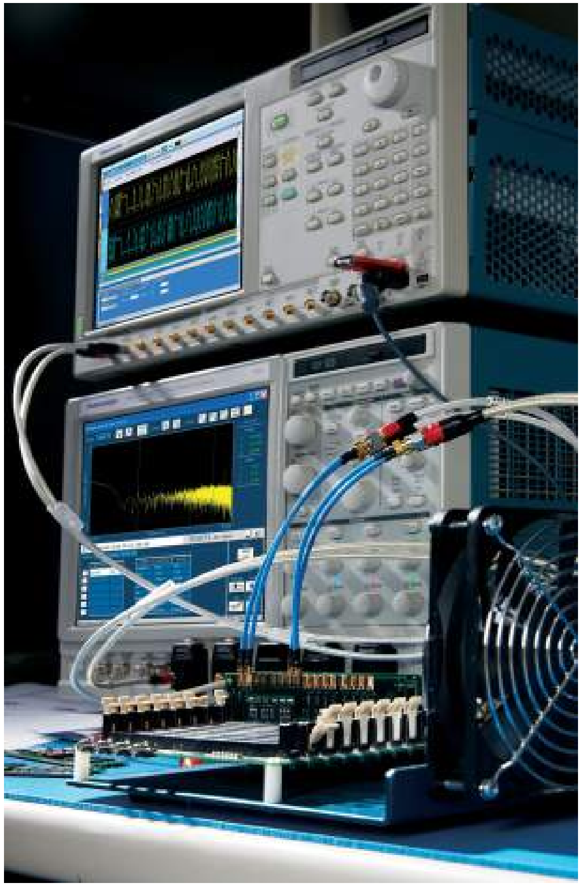
- Channel Count
  - Differential paths
  - Crosstalk and through measurements
  - Multi-lane buses
- Rise Time
  - Determines smallest spacing between two discontinuities that can be distinguished
- Incident Step Quality
  - Must have a fast rise time, accurate amplitude and be free of aberrations
- Differential TDR Measurements
  - True differential measurements determine the DUT's real-world response
  - TDR instrument must be capable of launching simultaneous and complementary incident pulses

Tektronix 80E10 TDR Module

Signal Generators Complete the Measurement System

An acquisition instrument can only make a measurement if there is a signal.

- Signal generator applications:
  - Check characteristics of a trace or connector
  - Replicate sensor signals
  - Simulate missing system inputs
  - Functional verification and characterization
  - Stress testing
- Types of signal generators:
  - Arbitrary waveform generator (AWG)
  - Arbitrary function generator (AFG)
  - Pulse generator
  - Pattern generator
- Methods to generate signals:
  - Create new signals
  - Synthesize real-world signals
  - Generate ideal or stressed reference signals



Signal Generators Complete the Measurement System

Key parameters to evaluate when choosing a signal generator:

- Channel Count
- Memory Depth
  - Determines maximum number of samples to define a waveform
  - Complex waveforms require deep memory
- Sample Rate
  - Must be > 2X highest spectral frequency component to satisfy Nyquist
- Bandwidth
  - Must be wider than the maximum frequency that the sample rate supports
- Sequence Controller
  - Causes segments of waveform memory to repeat, generating a waveform of almost unlimited length

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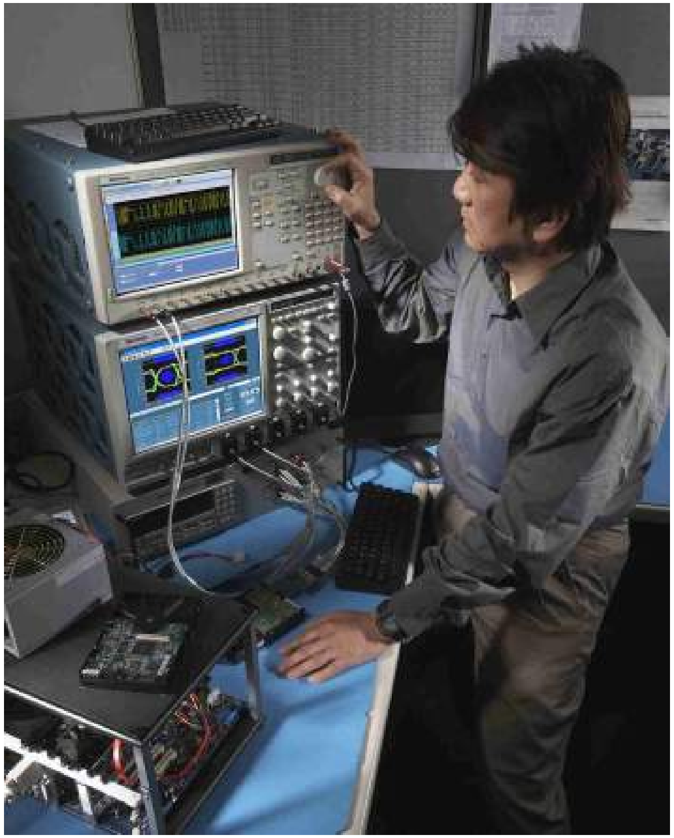
Summary

- Signal integrity measurements are critical in developing today's digital systems

- A powerful measurement tool set is needed:
  - Logic analyzers
  - Digitizing oscilloscopes
  - Real-time spectrum analyzers
  - Time-domain reflectometers
  - Signal generators
  - High-fidelity probes
  - Analysis software



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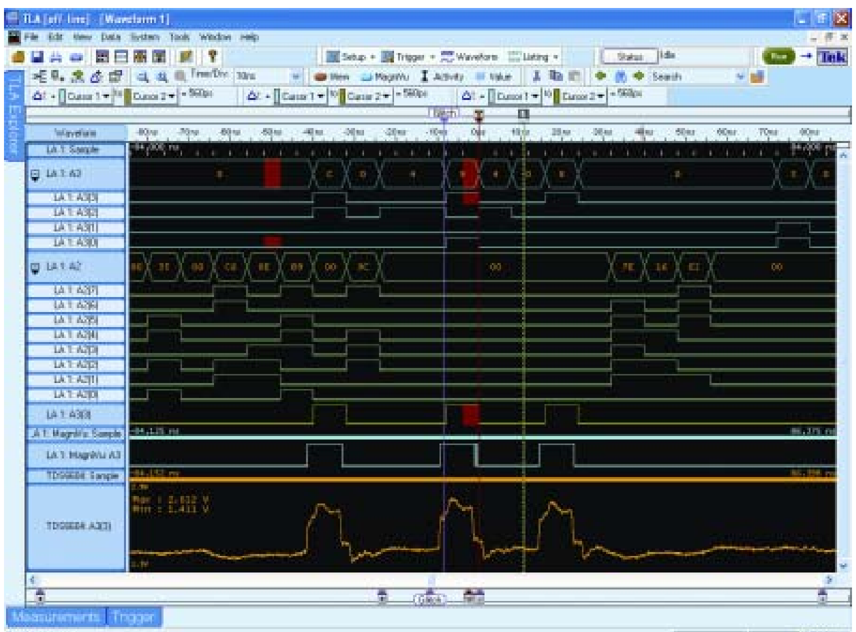
Resolving Digital Timing Issues with Logic Analyzers

- Powerful tools to trigger, store, and view many digital signals
  - But, amplitude errors and glitches can appear to be valid logic levels



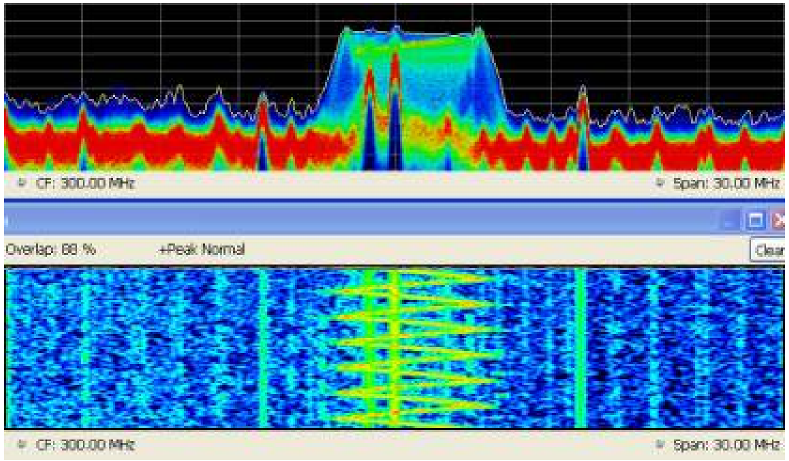
Need to look at the analog domain …

Isolating Analog Deviations with Oscilloscopes

- Display waveform details, edges and noise
- Detect and display transients
- Powerful triggering and analysis features

Common RTSA Measurement Tasks

- Observing signals masked by noise
- Seeing tonal clock signals masked within spread spectrum signals
- Finding and analyzing transient and dynamic signals
- Capturing burst transmissions, glitches and switching transients
- Characterizing PLL settling times, frequency drift and microphonics
- Frequency-stepped clock signals
- Testing and diagnosing transient EMI effects
- Characterizing time-variant modulation schemes
- Isolating software and hardware interactions



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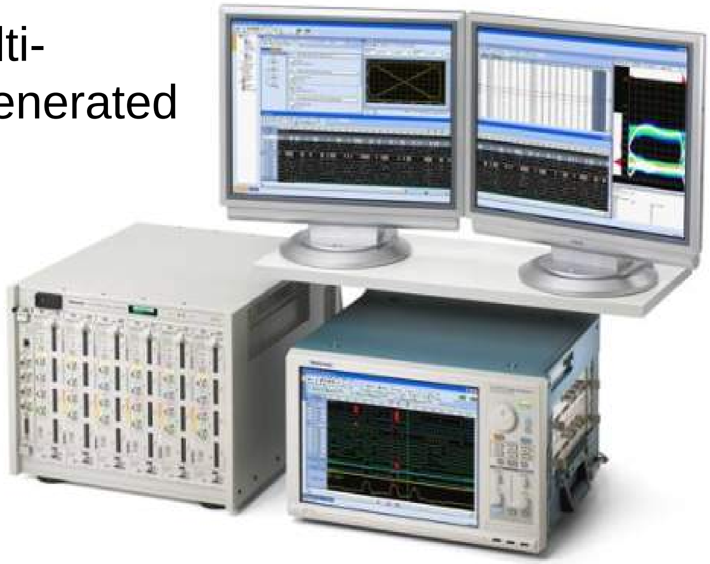
Digital Validation and Debug: TLA Series Logic Analyzers

- Find elusive glitches and events with MagniVu™ acquisition's high speed timing resolution of 20 ps
- Eliminate double probing with iCapture™ multiplexing to achieve simultaneous digital and analog acquisition through a single logic analyzer probe
- Gain complete system visibility with digital/analog correlation using iView™ display
- Quickly find signal integrity issues with multi-channel bus analysis using oscilloscope-generated eye diagram in iVerify™ analysis



Analog Debug and Design Validation: Tektronix DPO and DSA Series Oscilloscopes

- Pinpoint timing anomalies with full sample rate and record length across all channels
- Quickly find intermittent events with DPX® acquisition technology that displays up to 250,000 wfms/s
- Efficiently analyze waveform data with controls to easily view, search and navigate long record lengths
- Save time by capturing, sharing, and analyzing waveforms later with PC connectivity tools

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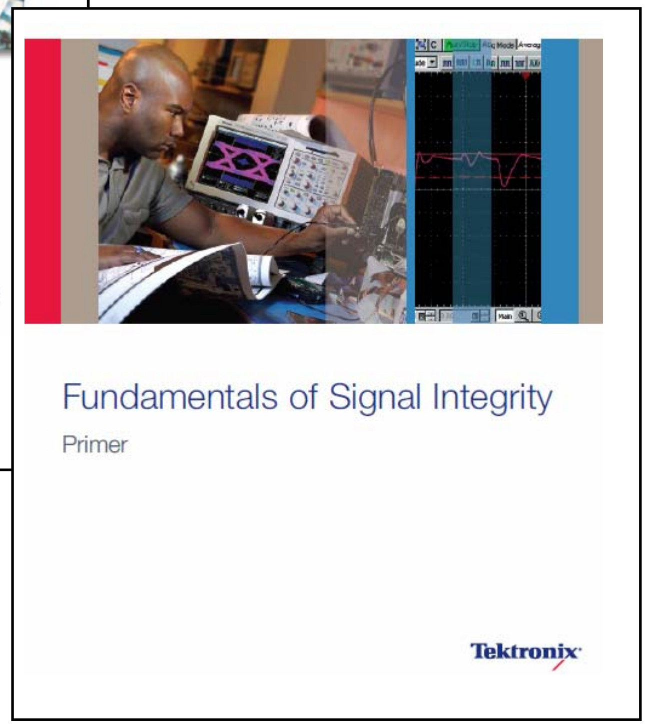
Additional Resources

- http://www.tektronix.com/si



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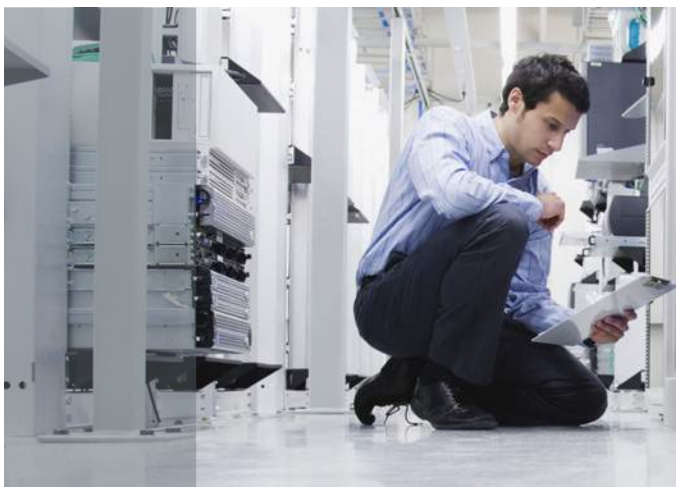
Thank You!



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