Oscilloscope or Multimeter?
Multimeter

- Battery powered
- Hand-held
- Very portable
- Variety of measurements possible

DC Voltage  Continuity
AC Voltage  Resistance
DC Current  Capacitance
AC Current
Multimeter

Measurement given as a single number

What about signals that change as a function of time?
Periodic, time-varying signals can sometimes be characterized by a single number: **Root-Mean-Square (RMS)**

\[ V(t) = V_p \sin(\omega t) \]
The average voltage of a pure sine wave is identically zero.

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We know that an AC voltage can deliver plenty of power to a load
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How do we calculate this power if the average voltage and current is zero?
This is easy in a DC circuit: Use Ohm's Law

\[ \text{POWER} = \frac{V_{dc}^2}{R} \]
Power dissipated in an AC circuit is time dependent:

\[ P(t) = V_{ac}I_{ac} = \frac{V_{ac}^2}{R} \]
What is the energy delivered in one period? Temporally integrate the power over one period:

\[
\frac{1}{T} \int_0^T P(t) dt = \frac{1}{TR} \int_0^T V_p^2 \sin^2(\omega t) dt = \frac{V_p^2}{2R}
\]

DC power dissipation = \( \frac{V_{dc}^2}{R} \)

AC power dissipation = \( \frac{V_p^2}{2R} \)

AC voltage producing power dissipation equivalent

\[
V_{RMS} = \frac{V_p}{\sqrt{2}}
\]
• An RMS measurement assumes a stable, periodic signal
• Characterized by a single value of voltage, current
• Measured with a multimeter or oscilloscope

The situation is often not that convenient!
OSCILLOSCOPE

DISPLAY

TIME

VOLTAGE

CONTROLS

INPUTS
OSCILLOSCOPE

DISPLAY

CONTROLS

INPUTS
ANALOG: Cathode ray tube, swept electron beam

DIGITAL: A/D converter, LCD display

Although physical operation is completely different, controls are nearly identical
DISPLAY ADJUSTMENT

CONTROLS

VOLTS/DIV
DISPLAY ADJUSTMENT

CONTROLS

VOLTS/DIV
DISPLAY ADJUSTMENT

CONTROLS

SEC/DIV
DISPLAY ADJUSTMENT

CONTROLS

SEC/DIV
DC coupling, AC coupling, and Ground
EXAMPLE: Sinusoidal wave source + DC offset
DC COUPLING

CONTROLS

Offset

Ground

DC
AC
GND
AC COUPLING

CONTROLS

DC
AC
GND
GROUND: Defines location of 0 Volts
GROUND can be positioned at any convenient level

CONTROLS
DC
AC
GND
Why bother with AC coupling when DC coupling shows everything?
Often we have very weak modulation of a DC signal.
AC couple and change the vertical scale
AC coupling implemented with an RC high-pass filter
AC coupling implemented with an RC high-pass filter

Switch to select DC or AC coupling

Scope input connection

$C$ and $R$ connected to ground

To amplifier
Harmonic analysis of RC high-pass filter

\[
\frac{V_{OUT}(\omega)}{V_{IN}(\omega)} = \frac{R}{R + 1/j\omega C}
\]
Harmonic analysis of RC high-pass filter

\[ \frac{V_{OUT}(\omega)}{V_{IN}(\omega)} = \frac{R}{R + 1/j\omega C} \]

\[ R = 1 \text{ k}\Omega, \quad C = 10 \text{ nF} \]
Harmonic analysis of RC high-pass filter

\[
\frac{V_{OUT}(\omega)}{V_{IN}(\omega)} = \frac{R}{R + 1/j\omega C}
\]

A typical oscilloscope has an RC high-pass cutoff in the range 1—10 Hz when AC coupling is used.

Be careful when measuring slow signals: AC coupling blocks more than just DC.
INPUT RESISTANCE: 50 Ω or 1 MΩ?
All oscilloscopes have stray (unavoidable) capacitance at the input terminals: $C_{\text{input}} = 15–20$ pF
All oscilloscopes have stray (unavoidable) capacitance at the input terminals

\[ Z_{in} = \frac{R_{in}}{1 + j\omega R_{in}C_{in}} \]

- 1 MΩ rolloff ~ 8 kHz
- 50 Ω rolloff ~ 160 MHz

Compensation possible with scope probe
Why do we use 1 MΩ if frequency response is so low?

**ANSWER:** Signal level (voltage) will drop enormously at 50 Ω unless source can provide enough current.

Source: eg. optical detector
TRIGGERING

**Auto**: Scope gives continually updated display

**Normal**: User controls when the slope triggers; Level, Slope
Trigger source: Channel 1, Channel 2, etc

**Line**: Triggers on 60 Hz AC

**Single event**

**External**

Use **Auto-Set** only when all else fails!
Setting normal trigger level
Example: Measure fall time of square wave
SOLUTION: Trigger on negative slope
DIGITAL SCOPE:
SAMPLING BANDWIDTH
Sample spacing: $T$ (sec)

Sampling bandwidth $= 1 / T$ (samples/sec)
Sample spacing: $T$ (sec)

Sampling bandwidth = $1 / T$ (samples/sec)
SAMPLING BANDWIDTH

Reduce sample bandwidth 2x  \(\Leftrightarrow\)  Increase period 2x
Reduce sample bandwidth 2x  ⇔  Increase period 2x
ANALOG BANDWIDTH ≠ SAMPLING BANDWIDTH

Analog amplification
(Bandwidth limited)

Analog-Digital Conversion
ADC

(Sample rate limited)

DISPLAY
(Record length limited)
ANALOG BANDWIDTH $\neq$ SAMPLING BANDWIDTH

Analog amplification (Bandwidth limited)

Analog-Digital Conversion (Sample rate limited)

DISPLAY (Record length limited)

There is usually a switch to further limit the input bandwidth.
Nyquist theorem
Sampling theorem

Temporal spacing of signal sampling

$$\Delta t \leq \frac{1}{2\nu}$$
Nyquist theorem
Sampling theorem

Temporal spacing of signal sampling

\[ \Delta t > \frac{1}{2\nu} \]
Nyquist theorem
Sampling theorem

Temporal spacing
of signal sampling

\[ \Delta t > \frac{1}{2\nu} \]

ALIASING
DIGITAL SCOPE: MEASUREMENT MENU

- Period
- Frequency
- Average amplitude
- Peak amplitude
- Peak-to-peak amplitude
- Horizontal and vertical adjustable cursors

- Rise time
- Fall time
- Duty cycle
- RMS
- Max/Min signals
DIGITAL SCOPE: MATH MENU

Channel addition

Channel subtraction

Fast Fourier Transform (FFT):
Observe frequency spectrum of time signal
Spectrum Analyzer (Agilent N9320)

Operates like a radio with a very fast tuner
Spectrum Analyzer (Agilent N9320)

**MENU SETUP**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start frequency</td>
<td>Vertical scale (dB or linear)</td>
</tr>
<tr>
<td>Stop frequency</td>
<td>Autoscale vertical axis</td>
</tr>
<tr>
<td>Averaging</td>
<td>Preamp available</td>
</tr>
<tr>
<td>Markers</td>
<td>Peak search</td>
</tr>
</tbody>
</table>

**Operating range:** 9 kHz – 3 GHz

Auto-tune rarely works

You should estimate where the expected signal will be