MEASUREMENT AND STANDARDS

I. MEASUREMENT PRINCIPLES

1. MEASUREMENT SYSTEMS

- Measurement is a process of associating a number with a quantity by comparing the quantity to a standard

![Simplified measuring system diagram]

**FIGURE 1-1**
Simplified measuring system.

- Instrument refers to all elements in the system
- **Measurand**: physical quantity to be measured
- Signal conditioning: filtering, amplification, noise reduction, linearization, ...
- Signal processing: A/D, digital processing, displaying, ...
- User: human observer, control mechanism, computer, ...
- Transmission path can be wire or wireless
2. **SYSTEM RESPONSE**

- Each elements contributes to the overall system response
- Transfer function = output/input
- Frequency response: as in amplifiers
- **Transient response**: response time to an abrupt input change
- **Input threshold**: smallest detectable value of input
- **Sensitivity**
- **Noise**: unwanted signal
- **Dynamic range**: range of input causes system response
- **Resolution**: minimum discernible change in the measurand that can be detected
3. **CHARACTERISTICS OF SIGNALS**

- Continuous (changes smoothly, no interruption) or discrete (finite steps, in quantized manner)
- Analog or digital
- Periodic signals
- Frequency and period
- Peak, peak-to-peak, average, rms values
- **Time-domain**: signals have quantities vary as a function of time

- **Frequency-domain**: spectrum view of the signal (amplitude vs. frequency). Analyzed with Fourier series.

- **Data domain**: encoded data as a series of data points
4. **TRANSDUCERS**

A device receives energy from a measurand and responses to the data by converting it into some usable form for measuring system (temperature to resistance).
5. **TRANSMISSION**

- Transfers electrical signal from one point to another
- Poses problem for low level signals and long distance
  - Attenuation of the signal
  - Decrease system high frequency response
  - Noise pickup
- Introduces disturbed parameters
- Introduces propagation delay

**Type of transmission lines:**

- Coaxial cable
- Twisted-pair wiring
- Flat cable
- Fiber optic
- Radio frequencies
6. **INSTRUMENTS**

- **Measuring instrument:**
  - device converts a quantity to be measured into some usable form for interpretation (DMMs, oscilloscope)

- **Stimulus instrument:**
  - source of test signals (function generators, oscillators,...)

- **Electronic instruments:**
  - high speed, operation over large distance, internal signal processing, sensitivity, versatility, reliability, ...

- Can be passive or active instrument
7. **THE USERS**

- Multiple humans or machines
- Process, store, control, ....

![Block diagram demonstrating the process of signals from a transducer to a user via signal conditioning and transmission paths.]
8. BLOCK DIAGRAMS

- Many levels of abstraction.
- Show flow of information and basic functional relationship in the system.
- Represent a complete device or a specific functional unit.
- Lines connect blocks, dots represents pickup points.
- Summing points with add or subtraction.
(a) AM radio.

(b) Control system for oven.

(c) Four-channel data-acquisition system.
II. **STANDARDS AND CALIBRATION OF INSTRUMENTS**

- Measurements are based on comparison of the quantity to be measured to a known quantity called standard.
- Universal standards.
- More accuracy, wider range, greater diversity.
2. **Units of measurement**

- Quantity measurement uses specified measurement units.
- Domain system: International System of Units (SI systems).
- **6 fundamental units:**

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>BASE UNIT</th>
<th>ABBREVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>meter</td>
<td>m</td>
</tr>
<tr>
<td>Mass</td>
<td>kilogram</td>
<td>kg</td>
</tr>
<tr>
<td>Time</td>
<td>second</td>
<td>s</td>
</tr>
<tr>
<td>Electric current</td>
<td>ampere</td>
<td>A</td>
</tr>
<tr>
<td>Temperature</td>
<td>kelvin</td>
<td>K</td>
</tr>
<tr>
<td>Luminous intensity</td>
<td>candela</td>
<td>cd</td>
</tr>
<tr>
<td>Amount of substance</td>
<td>mole</td>
<td>mol</td>
</tr>
</tbody>
</table>

- **2 supplementary units:**

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>BASE UNIT</th>
<th>ABBREVIATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane angle</td>
<td>radian</td>
<td>r</td>
</tr>
<tr>
<td>Solid angle</td>
<td>steradian</td>
<td>sr</td>
</tr>
</tbody>
</table>
### 27 derived units:

**TABLE 3–4**
Derived units adopted by the CGPM.

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>NAME OF UNIT</th>
<th>UNIT SYMBOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>square meter</td>
<td>m²</td>
</tr>
<tr>
<td>Volume</td>
<td>cubic meter</td>
<td>m³</td>
</tr>
<tr>
<td>Frequency</td>
<td>hertz</td>
<td>Hz (s⁻¹)</td>
</tr>
<tr>
<td>Density</td>
<td>kilogram per cubic meter</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Speed</td>
<td>meter per second</td>
<td>m/s</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>radian per second</td>
<td>rad/s</td>
</tr>
<tr>
<td>Acceleration</td>
<td>meter per second squared</td>
<td>m/s²</td>
</tr>
<tr>
<td>Angular acceleration</td>
<td>radian per second squared</td>
<td>rad/s²</td>
</tr>
<tr>
<td>Force</td>
<td>newton</td>
<td>N (kg · m/s²)</td>
</tr>
<tr>
<td>Pressure</td>
<td>newton per square meter</td>
<td>N/m²</td>
</tr>
<tr>
<td>Viscosity (dynamic)</td>
<td>newton second per square meter</td>
<td>N · s/m²</td>
</tr>
<tr>
<td>Viscosity (kinematic)</td>
<td>meter squared per second</td>
<td>m²/s</td>
</tr>
<tr>
<td>Work, energy, quantity of heat</td>
<td>joule</td>
<td>J (N · m)</td>
</tr>
<tr>
<td>Power</td>
<td>watt</td>
<td>W (J/S)</td>
</tr>
<tr>
<td>Quantity of electricity</td>
<td>coulomb</td>
<td>C (A · s)</td>
</tr>
<tr>
<td>Electric tension, potential difference</td>
<td>volt</td>
<td>V (J/C)</td>
</tr>
<tr>
<td>Electric field strength</td>
<td>volt per meter</td>
<td>V/m</td>
</tr>
<tr>
<td>Resistance</td>
<td>ohm</td>
<td>Ω (V/A)</td>
</tr>
<tr>
<td>Capacitance</td>
<td>farad</td>
<td>F (A · s/V)</td>
</tr>
<tr>
<td>Magnetic flux</td>
<td>weber</td>
<td>Wb (V · s)</td>
</tr>
<tr>
<td>Inductance</td>
<td>henry</td>
<td>H (V · s/A)</td>
</tr>
<tr>
<td>Magnetic flux density</td>
<td>tesla</td>
<td>T (Wb/m²)</td>
</tr>
<tr>
<td>Magnetic field strength</td>
<td>ampere per meter</td>
<td>A/m</td>
</tr>
<tr>
<td>Magnetomotive force</td>
<td>gilbert</td>
<td>Gb (A)</td>
</tr>
<tr>
<td>Luminous flux</td>
<td>lumen</td>
<td>lm (cd · sr)</td>
</tr>
<tr>
<td>Luminance</td>
<td>candela per square meter</td>
<td>cd/m²</td>
</tr>
<tr>
<td>Illumination</td>
<td>lux</td>
<td>lx (lm/m²)</td>
</tr>
</tbody>
</table>

**ADDITIONAL USEFUL ELECTRICAL UNITS**

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>NAME OF UNIT</th>
<th>UNIT SYMBOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductance</td>
<td>siemen</td>
<td>S</td>
</tr>
<tr>
<td>Gain/attenuation</td>
<td>decibel</td>
<td>dB</td>
</tr>
</tbody>
</table>
• Prefix is used to express very large or very small unit.

<table>
<thead>
<tr>
<th>MULTIPLYING FACTOR</th>
<th>PREFIX</th>
<th>SYMBOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000,000,000,000</td>
<td>tera</td>
<td>T</td>
</tr>
<tr>
<td>1,000,000,000</td>
<td>giga</td>
<td>G</td>
</tr>
<tr>
<td>1,000,000</td>
<td>mega</td>
<td>M</td>
</tr>
<tr>
<td>1,000</td>
<td>kilo</td>
<td>k</td>
</tr>
<tr>
<td>100</td>
<td>hecto</td>
<td>h</td>
</tr>
<tr>
<td>10</td>
<td>deca</td>
<td>da</td>
</tr>
<tr>
<td>0.1</td>
<td>deci</td>
<td>d</td>
</tr>
<tr>
<td>0.01</td>
<td>centi</td>
<td>c</td>
</tr>
<tr>
<td>0.001</td>
<td>milli</td>
<td>m</td>
</tr>
<tr>
<td>0.000001</td>
<td>micro</td>
<td>µ</td>
</tr>
<tr>
<td>0.000000001</td>
<td>nano</td>
<td>n</td>
</tr>
<tr>
<td>0.000000000001</td>
<td>pico</td>
<td>p</td>
</tr>
<tr>
<td>0.000000000000001</td>
<td>femto</td>
<td>f</td>
</tr>
<tr>
<td>0.0000000000000001</td>
<td>atto</td>
<td>a</td>
</tr>
</tbody>
</table>

• Use engineering notation for convenience and fast computation.
3. **Standard organizations**

- Requires a uniformity of measurement with international cooperation.
- International: CGPM (Conference General des Poids et Mesures).
- National: NIST in the US (National Institute of Standards and Technology).
4. **Types of standards**

- Rigorously traceable *through documentation to accepted international standards or definitions representing the fundamental units.*
- Attributes of all standards: *long-term stability, accuracy and insensitivity to environmental conditions.*

1. **International standards:**
   - Intrinsic standards: realized directly from their definitions rather than comparing them to an artifact maintained at a laboratory.
   - Prototype standards: based on physical objects

2. **National primary standards**
   - Primary standards: does not require any other reference for calibration.
   - Other primary reference standards of the fundamental units can be produced from their definition in nature.
3. **Secondary standards**
   - Secondary standard must be compared periodically to a primary standards (ex. rubidium frequency standard).
   - Transfer standards: moves from primary to be used in laboratory.
   - Retained by laboratories and industries.

4. **Working standards**
   - A device used to maintain a unit of measurement for routine calibration and certification work on test equipment.
   - Basic of the quality of measurement work for an organization.
5. Some standards

• **Frequency and time standards:**
  - Stable atomic clock used in Coordinated Universal Time (UTC)
  - Second, Hz
  - GPS frequency: $10^{-14}$ accuracy
• **Voltage and resistance standards**

➤ **Voltage**

**FIGURE 3–5**
Cross section of a saturated cadmium standard cell.

The voltage of the $n$th level of a Josephson junction voltage standard is given by

$$V_n = \left( \frac{h}{2e} \right) nf$$

where $V_n =$ voltage of the $n$th level, V

$n =$ step number

$e =$ the charge on an electron, $1.602 \times 10^{-19}$ C

$h =$ Planck’s constant, $6.626 \times 10^{-34}$ J/Hz

$f =$ frequency, Hz
**Resistance**

**FIGURE 3–7**
Hall effect. When a current flows in a flat plate situated in a perpendicular magnetic field, a voltage is induced perpendicular to the current and the magnetic field.

Voltage parallel to current
Voltage perpendicular to direction of current. This is the Hall voltage, $V_H$

Voltage by the square of the charge on an electron. That is

$$R_H = \left( \frac{h}{e^2} \right) n$$

where $R_H =$ Hall resistance

- $h =$ Planck’s constant, $6.626 \times 10^{-34}$ J/Hz
- $e =$ the charge on an electron, $1.602 \times 10^{-19}$ C
- $n =$ an integer
• **Capacitance and inductance standards**
  - Farad based on theoretical work
  - Henry: bridge of resistance and capacitance
  - Working standards in industries
• **Temperature standards**

  ➢ Based on linear relationship between pressure and temperature in ideal gas

  \[ PV = nRT \]

  - \( P \)= pressure
  - \( V \)= volume, l
  - \( n \)= number of moles in gas
  - \( R \)= universal gas constant
  - \( T \)= \( t^\circ K \)
6. **Calibrations**

- *Comparison of a measurement instrument to a standard or other instrument of know accuracy* in order to bring the instrument into substantial agreement with an established standard.

- Established standard is at least 4 times greater in accuracy

- Instrument calibration considerations:
  - Limit of accuracy of the instrument to be calibrated
  - Methods used to ensure required accuracy
  - Accuracy of the standard or instrument used as reference
  - Keeping records

- Accuracy contributing factors
  - Time since last calibrated
  - Difference between calibration environment and operating environment
  - Uncertainty of the standard used