Engineering Measurement Gauges

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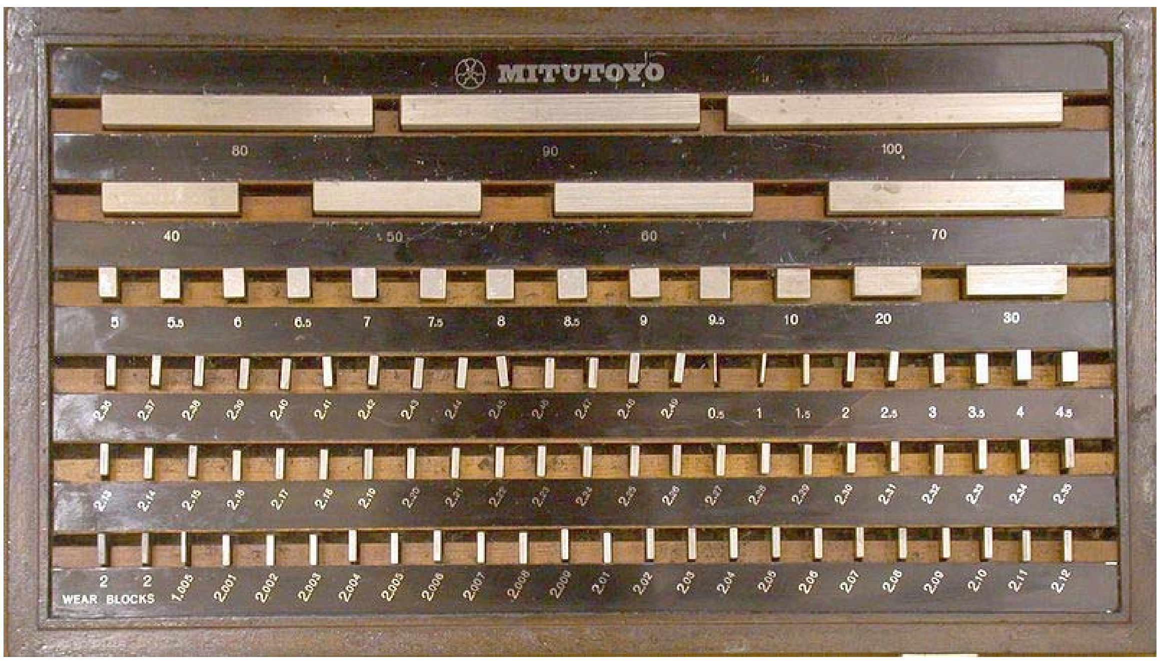
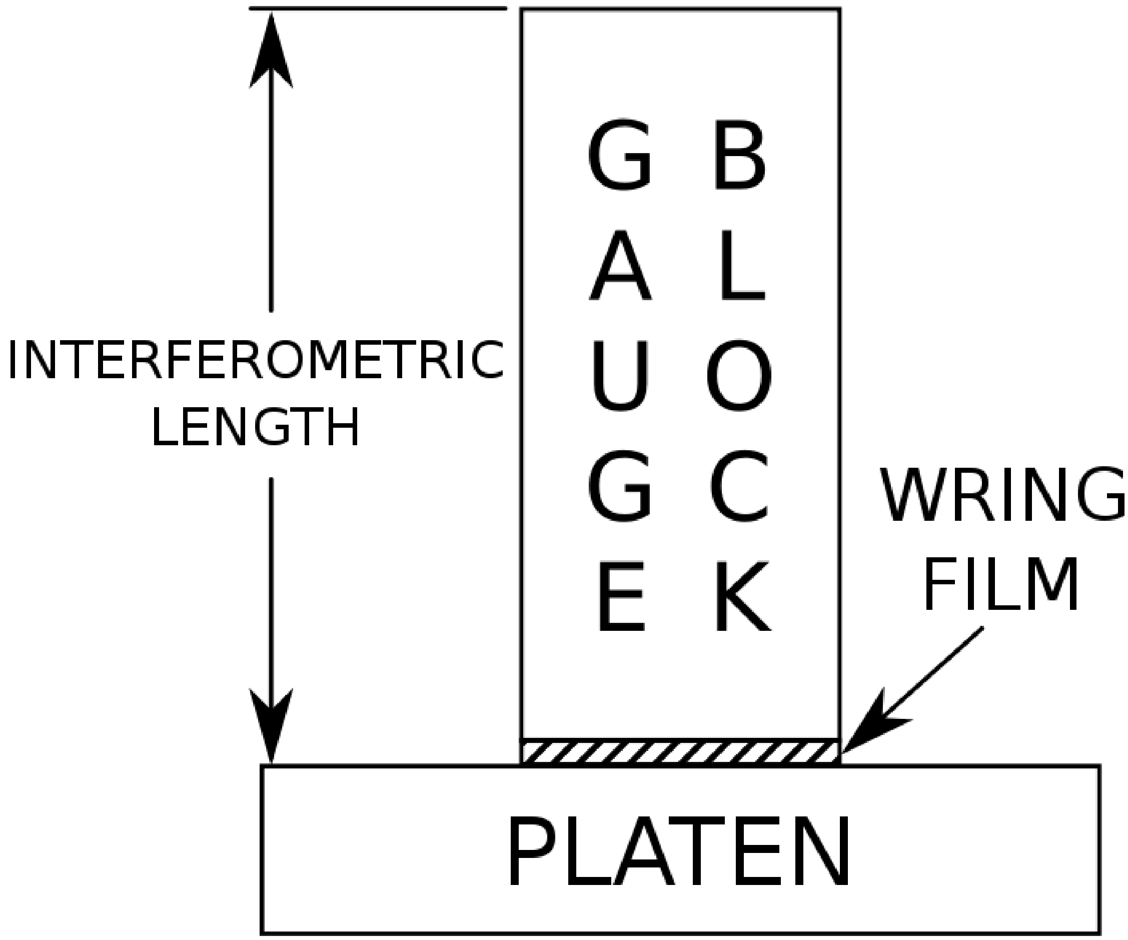
Gauge Block



Metric gauge block set

A **gauge block** (also known as a **gage block**, **Johansson gauge**, **slip gauge**, or **Jo block**) is a precision ground and lapped length measuring standard. It is used as a reference for the setting of measuring equipment used in machine shops, such as micrometers, sine bars, calipers, and dial indicators (when used in an inspection role).

Description

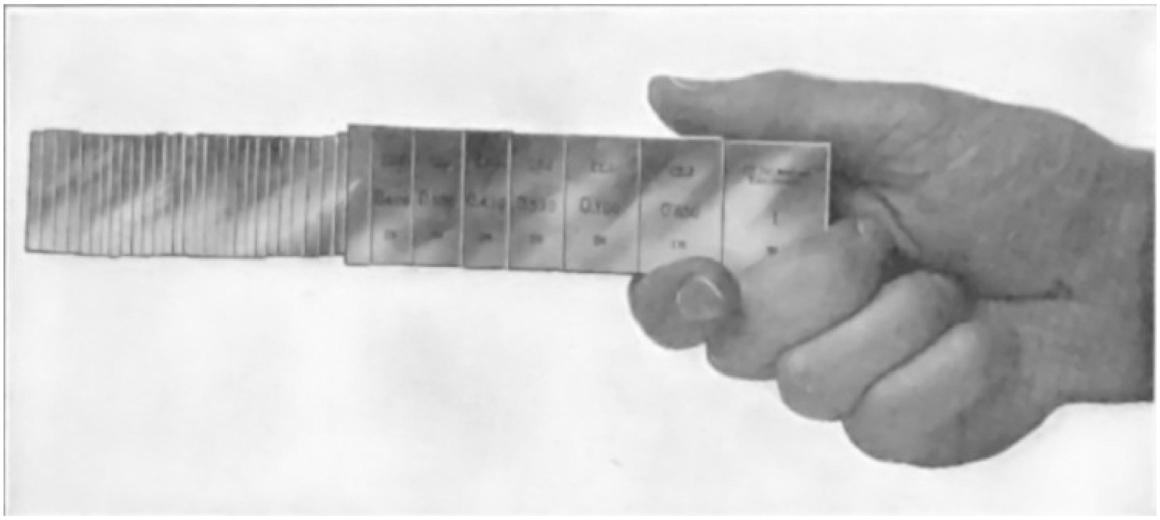


How gauge blocks are measured.

Each gauge block consists of a block of metal with two opposing faces ground precisely flat and parallel, a precise distance apart. Gauge blocks come in sets of blocks of various lengths, to allow a wide variety of standard lengths to be made up, along with two wear blocks. The length of each block is actually slightly shorter than the nominal length stamped on it, because the stamped length includes the length of one *wring film*, a film of lubricant which separates adjacent block faces in normal use. This nominal length is known as the *interferometric length*.

In use, the blocks are removed from the set, cleaned of their protective coating (petroleum jelly or oil) and *wrung together* to form a stack of the required dimension, with the minimum number of blocks. Gauge blocks are calibrated to be accurate at 68 °F (20 °C) and should be kept at this temperature when taking measurements. This mitigates the effects of thermal expansion. The wear blocks, made of a harder substance like silicon carbide, are included at each end of the stack, whenever possible, to protect the gauge blocks from being damaged in use.

Wringing



36 Johansson gauge blocks wrung together.

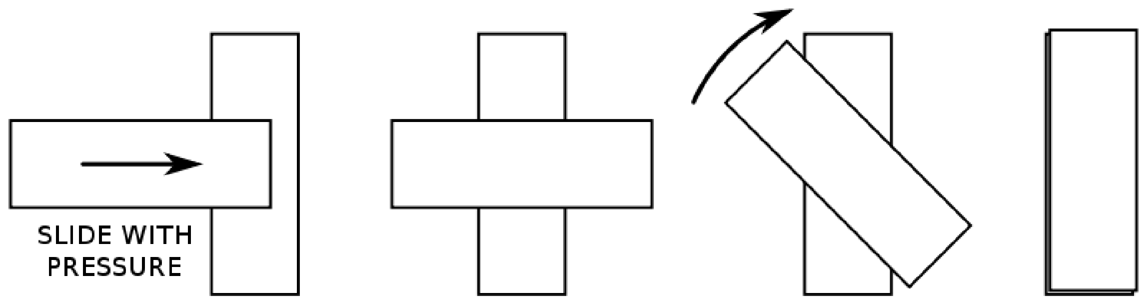
Wringing is the process of sliding two blocks together so that their faces lightly bond. Because of their ultraflat surfaces, when wrung, gauge blocks adhere to each other tightly. Properly wrung blocks mey withstand a 200 lbf (890 N) pull. While the exact mechanism that causes wringing is unknown, it is believed to be a combination of:

- Air pressure applies pressure between the blocks because the air is squeezed out of the joint.
- Surface tension from oil and water vapor that is present between the blocks.
- Molecular attraction occurs when two very flat surfaces are brought into contact. This force causes gauge blocks to adhere even without surface lubricants, and in a vacuum.

It is believed that the last two sources are the most significant.

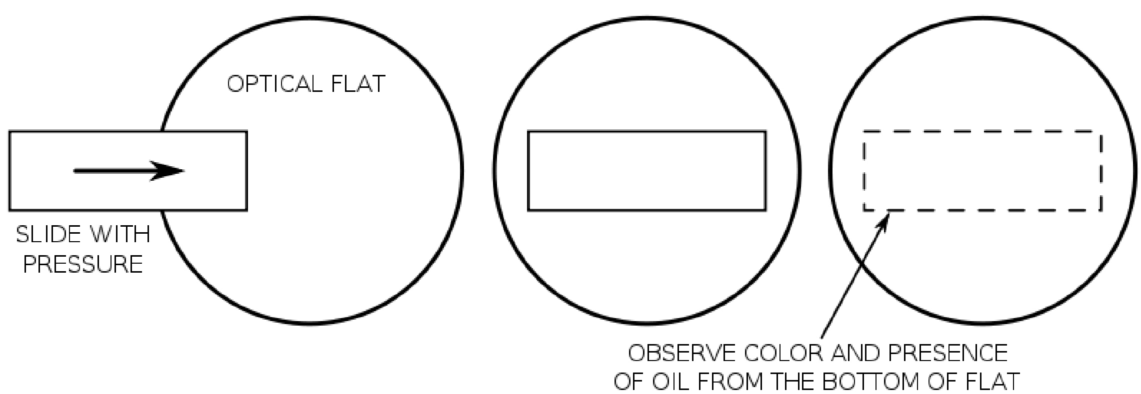
The process of wringing involves four steps:

1. Wiping a clean gauge block across an oiled pad.
2. Wiping any extra oil off the gauge block using a dry pad.
3. The block is then slid perpendicularly across the other block while applying moderate pressure until they form a cruciform.
4. Finally, the block is rotated until it is inline with the other block.

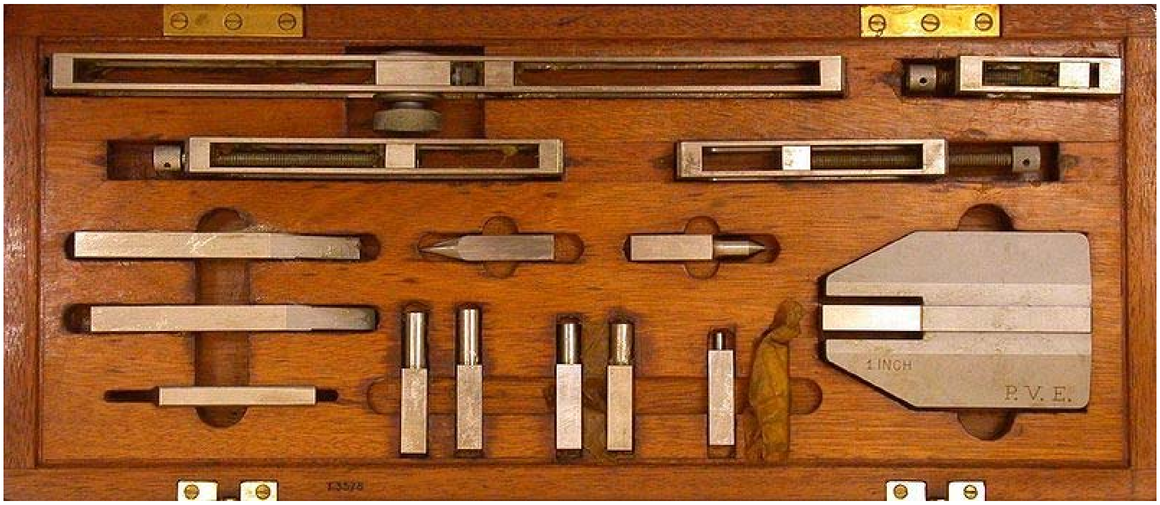


After use the blocks are re-oiled or greased to protect against corrosion. The ability for a given gauge block to wring is called *wringability*; it is officially defined as "the ability of two surfaces to adhere tightly to each other in the absence of external means." The minimum conditions for wringability are a surface finish of 1 microinch (0.025 µm) AA or better, and a flatness of at least 5 µin (0.13 µm).

There is a formal test to measure wringability. First, the block is prepared for wringing using the standard process. The block is then slid across a 2 in (51 mm) reference grade (1 µin (0.025 µm) flatness) quartz optical flat while applying moderate pressure. Then, the bottom of the gauge block is observed (through the optical flat) for oil or color. For Federal Grades 0.5, 1, and 2 and ISO grades K, 00, and 0 no oil or color should be visible under the gauge block. For Federal Grade 3 and ISO grades 1 and 2, no more than 20% of the surface area should show oil or color. Note that this test is hard to perform on gauge blocks thinner than 0.1 in (2.5 mm) because they tend not to be flat in the relaxed state.



Accessories



A gauge block accessory set

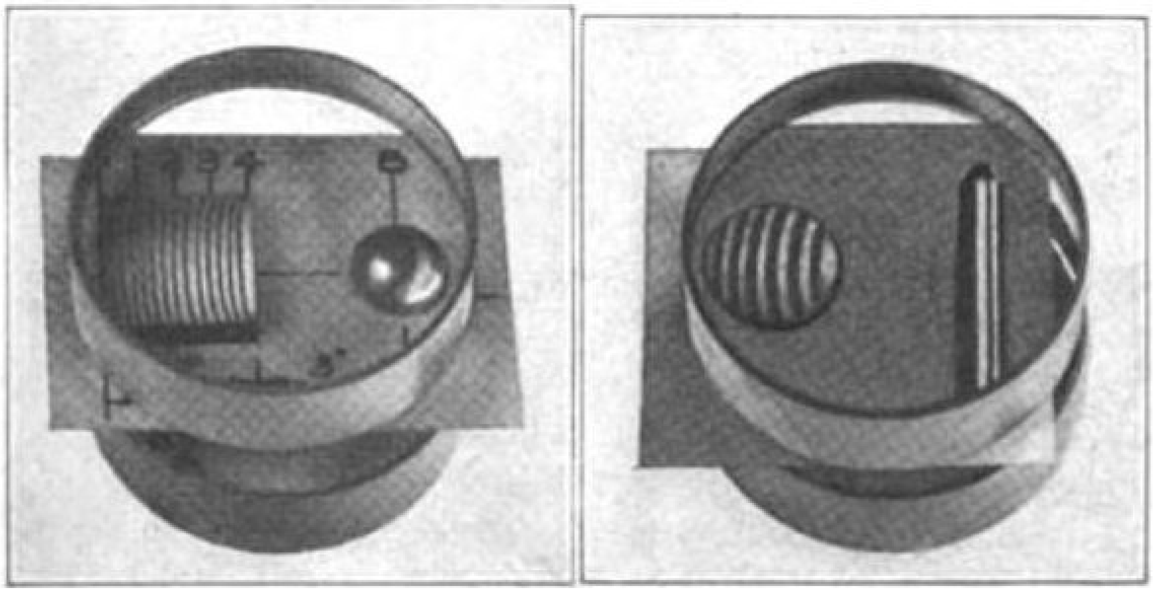
The pictured accessories provide a set of holders and tools to extend the usefulness of the gauge block set. They provide a means of securely clamping large *stacks* together along with reference points and scribers.

Slip gauges are made from a select grade of carbide with hardness of 1500 Vickers hardness. Long series slip gauges are made from high quality steel having cross section (35 x 9 mm) with holes for clamping two slips together.

A *gauge block stone* is used to remove nicks and burrs to maintain wringability.

There are two *wringing pads* used to prepare a gauge block for wringing. The first is an *oil pad*, which applies a light layer of oil to the block. The second is a *dry pad*, which removes any excess oil from the block after the oil pad has been used.

Grades



Gauge blocks *(left in each picture, under optical flats)* being used to measure the height of a ball bearing and a plug gage using interferometry.

They are available in various grades depending on their intended use. Various grading standards include: JIS B 7506-1997 (Japan)/DIN 861-1980 (Germany), ASME (US), BS 4311: Part 1: 1993 (UK). Tolerances will vary within the same grade as the thickness of the material increases.

- reference (AAA): small tolerance (±0.05 μm or ±0.000002 in) used to establish standards
- calibration (AA): (tolerance +0.10 μm to −0.05 μm) used to calibrate inspection blocks and very high precision gauging
- inspection (A): (tolerance +0.15 μm to −0.05 μm) used as toolroom standards for setting other gauging tools
- workshop (B): large tolerance (tolerance +0.25 μm to −0.15 μm) used as shop standards for precision measurement

More recent grade designations include (U.S. Federal Specification GGG-G-15C):

- 0.5 — generally equivalent to grade AAA
- 1 — generally equivalent to grade AA
- 2 — generally equivalent to grade A+
- 3 — compromise grade between A and B

and ANSI/ASME B89.1.9M, which defines both absolute deviations from nominal dimensions and parallelism limits as criteria for grade determination. Generally, grades are equivalent to former U.S. Federal grades as follows:

- 00 — generally equivalent to grade 1 (most exacting flatness and accuracy requirements)
- 0 — generally equivalent to grade 2
- AS-1 — generally equivalent to grade 3 (reportedly stands for American Standard - 1)
- AS-2 — generally less accurate than grade 3
- K — generally equivalent to grade 00 flatness (parallelism) with grade AS-1 accuracy

The ANSI/ASME standard follows a similar philosophy as set forth in ISO 3650.

History

The gauge block set, also known as "Jo Blocks", was developed by the Swedish inventor Carl Edvard Johansson. Johansson was employed in 1888 as an armourer inspector by the state arsenal Carl Gustafs stads Gevärsfaktori [Carl Gustaf Stad's Rifle Factory] in the town of Eskilstuna, Sweden. He was concerned with the expensive tools for measuring parts for the Remington rifles then in production under license at Carl Gustaf. When Sweden adopted a tailored variant of the Mauser carbine in 1894, Johansson was very excited about the chance to study Mauser's methods of measuring, in preparation for production under license at Carl Gustaf (which began several years later). However, a visit to the Mauser factory in Oberndorf am Neckar, Germany, turned out to be a disappointment. On the train home, he thought about the problem, and he came up with the idea of a set of blocks that could be combined to make up any measure.

There had already been a long history of increasing use of gauges up to this time, such as gauges for filing and go/no go gauges, which were custom-made individually in a toolroom for use on the shop floor; but there had never been super-precision gauge blocks that could be wrung together to make up different lengths, as Johansson now envisioned.

Back home, Johansson converted his wife's Singer sewing machine to a grinding and lapping machine. He preferred to carry out this precision work at home, as the grinding machines at the rifle factory were not good enough. His wife, Margareta, helped him a lot with the grinding besides the household work. Once Johansson had demonstrated his set at Carl Gustaf, his employer provided time and resources for him to develop the idea. Johansson was granted his first Swedish patent on 2 May 1901, SE patent No. 17017, called "Gauge Block Sets for Precision Measurement". Johansson formed the Swedish company CE Johansson AB (also known as 'CEJ') on 16 March 1917.

Johansson spent many years in America; during his life he crossed the Atlantic 22 times. The first CEJ gauge block set in America was sold to Henry M. Leland at the Cadillac Automobile Company around 1908. The first manufacturing plant in America for his gauge block sets was established in Poughkeepsie, Dutchess County, New York, in 1919. The economic environment of the post–World War I recession and depression of 1920–21 did not turn out so well for the company, so in 1923 he wrote a letter to Henry Ford of the Ford Motor Company, where he proposed a cooperation in order to save his company.

Henry Ford became interested, and on 18 November 1923 he began working for Henry Ford in Dearborn, Michigan. Hounshell (1984), citing Althin (1948) and various archive primary sources, says, "Henry Ford purchased the famous gaugemaking operation of the Swede C. E. Johansson in 1923 and soon moved it into the laboratory facility in Dearborn. Between 1923 and 1927, the Johansson division supplied 'Jo-blocks' to the Ford toolroom and any manufacturer who could afford them. It also made some of the Ford 'go' and 'no-go' gauges used in production as well as other precision production devices."

In 1936, at the age of 72, Johansson felt it was time to retire and go back to Sweden. He was awarded the large gold medal of the Royal Swedish Academy of Engineering Sciences in 1943, shortly after his death.

Gauge pins

Similar to gauge blocks, these are precision ground cylindrical bars for use in Go-NoGo gauges or similar applications.

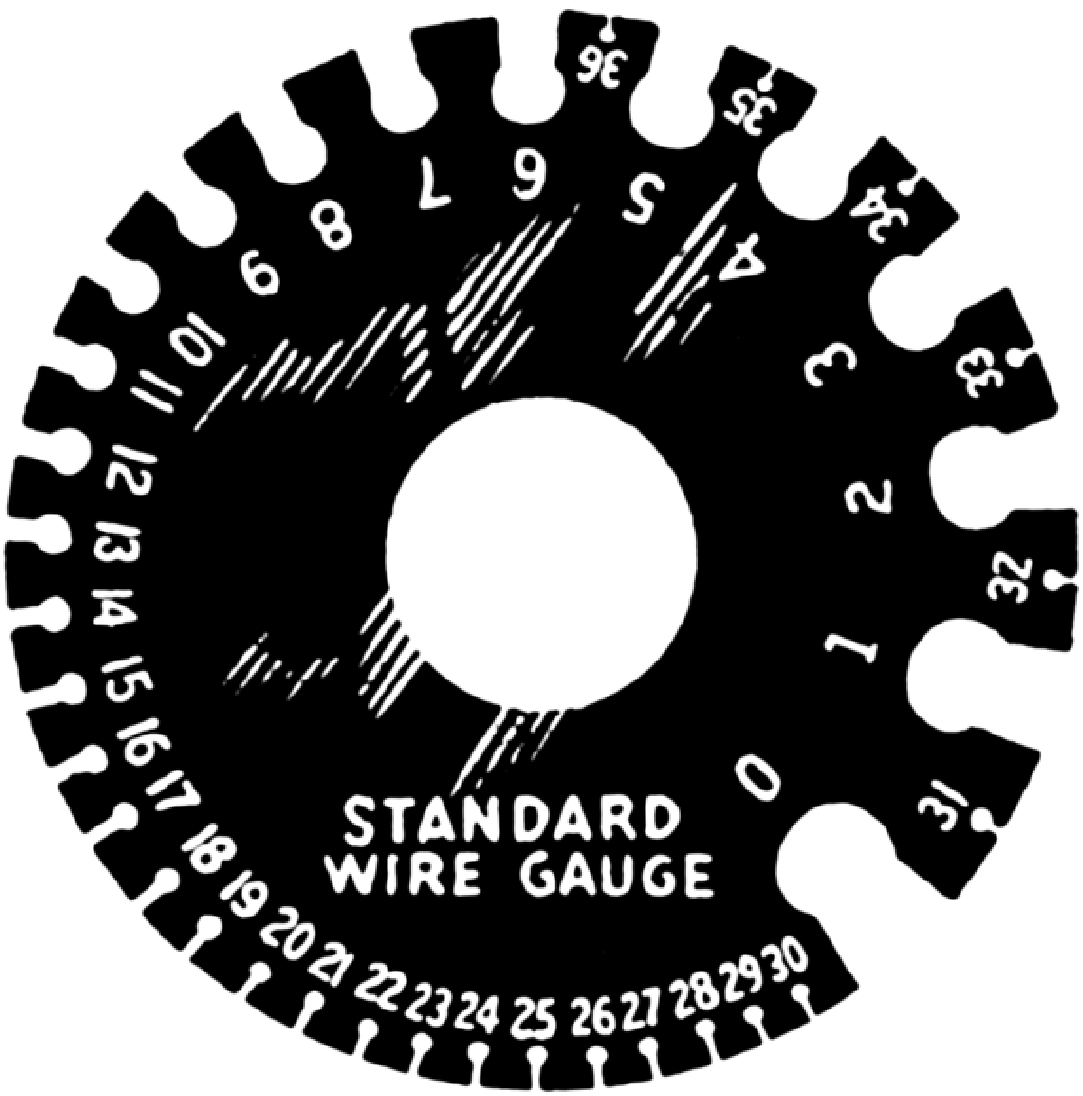
Gauge rollers and balls

These are supplied as sets of individual rollers or balls as used in roller or ball bearings

Chapter 2

Wire Gauge and Stream Gauge

Wire gauge



A device for measuring standard wire gauge.

Wire gauge is a measurement of how large a wire is, either in diameter or cross sectional area. This determines the amount of electric current a wire can safely carry, as well as its electrical resistance and weight per unit of length. Wire gauge is applicable to both electrical and non-electrical wires, being important to electrical wiring and to structural cable.

Types

Gauges may be broadly divided into two groups, the empirical and the geometric. The first includes all the older gauge measurements, notably the Birmingham (B.W.G.) and the Lancashire or Stubs. The origin of the B.W.G. is lost in obscurity. The numbers of wire were in common use earlier than 1735. It is believed that they originally were based on the series of drawn wires, No. 1 being the original rod, and succeeding numbers corresponding with each draw, so that No. 10, for example, would have passed ten times through the draw plate. But the Birmingham and the Lancashire gauge, the latter being based on an averaging of the dimensions collated from a large number of the former in the possession of Peter Stubs of Warrington, have long held the leading position, and are still retained and used probably to a greater extent than the more recent geometrical gauges.

The first attempt to adopt a geometrical system was made by Messrs Brown & Sharpe in 1855. They established a regular progression of thirty-nine steps between the English sizes, No. 0000 (460 mils or about 12 mm) and No. 36 (5 mils or about 0.13 mm). Each diameter was multiplied by 0.890526 to give the next lower size. This is now the American wire gauge, and is used to a considerable extent in the United States.

The Imperial Standard Wire Gauge, which has been sanctioned by the British Board of Trade, is one that was formulated by J. Latimer Clark. Incidentally, one of its recommendations is that it differs from pre-existing gauges scarcely more than they differ among themselves, and it is based on a rational system, the basis being the mil. No. 7/0, the largest size, is 0.50 in. (500 mils or 12.7 mm) in diameter, and the smallest, No. 50, is 0.001 in. (1 mil or about 25 µm) in diameter. Between these the diameter, or thickness, diminishes by 10.557%, and the weight diminishes by 20%.

The current British Standard for metallic materials, which includes wire, is BS 6722:1986, which is a solely metric standard. This replaces the now-withdrawn BS 3737:1964, which used the SWG system.

Measuring

In commerce, the sizes of wire are estimated by a device, also called gauges, which consist of plates of circular or oblong form having notches of different widths round their edges to receive wire and sheet metals of different thicknesses. Each notch is stamped with a number, and the wire or sheet, which just fits a given notch, is stated to be of, say, No. 10, 11, 12, etc., of the wire gauge.

The circular forms of wire gauge measurement devices are the most popular, and are generally 3 3/4 in. (95 mm) in diameter, with thirty-six notches; many have the decimal equivalents of the sizes stamped on the back. Oblong plates are similarly notched. Rolling mill gauges are also oblong in form. Many gauges are made with a wedge-like slot into which the wire is thrust; one edge being graduated, the point at which the movement of the wire is arrested gives its size. The graduations are those of standard wire, or in thousandths of an inch. In some cases both edges are graduated differently to serve for comparison between two systems of measurement. A few gauges are made with holes into which the wire has to be thrust. All gauges are hardened and ground to dimensions.

In some applications wire sizes are specified as the cross sectional area of the wire, usually in mm^2. Advantages of this system include the ability to readily calculate the physical dimensions or weight of wire, ability to take account of non-circular wire, and ease of calculation of electrical properties.

Stream gauge

Stream Gaging Station, Carnation, Washington

A **stream gauge**, or **stream gage**, refers to a site along a stream where measurements of water surface elevation ("stage") and/or volumetric discharge (flow) are made.

Measurement of discharge

Automated direct measurement of streamflow discharge is difficult at present. In place of the direct measurement of streamflow discharge, one or more surrogate measurements can be used to produce discharge values. In the majority of cases, a stage (the elevation of the water surface) measurement is used as the surrogate. Low gradient (or shallow-sloped) streams are highly influenced by variable downstream channel conditions. For these streams, a second stream gauge would be installed, and the slope of the water surface would be calculated between the gauges. This value would be used along with the stage measurement to more accurately determine the streamflow discharge. Within the last ten years, the technological advance of velocity sensors has allowed the use of water velocity as a reliable surrogate for streamflow discharge at sites with a stable cross-sectional area. These sensors are permanently mounted in the stream and measure velocity at a particular location in the stream and related to flow in a manner similar to the use of traditional water level.

December 12, 2001 photo of the USGS streamflow-gaging station at Huey Creek, McMurdo Dry Valleys, Antarctica.

In those instances where only a stage measurement is used as the surrogate, a **rating curve** must be constructed. A rating curve is the functional relation between stage and discharge. It is determined by making repeated discrete measurements of streamflow discharge using a velocimeter and some means to measure the channel geometry to determine the cross-sectional area of the channel. The technicians and hydrologists responsible for determining the rating curve visit the site routinely, with special trips to measure the hydrologic extremes (floods and droughts), and make a **discharge measurement** by following an explicit set of instructions.

Once the rating curve is established, it can be used in conjunction with stage measurements to determine the volumetric streamflow discharge. This record then serves as an assessment of the volume of water that passes by the stream gauge and is useful for many tasks associated with hydrology.

In those instances where a velocity measurement is additionally used as a surrogate, an **index velocity determination** is conducted. This analysis uses a velocity sensor, often either magnetic or acoustic, to measure the velocity of the flow at a particular location in the stream cross section. Once again, discrete measurements of streamflow discharge are made by the technician or hydrologist at a variety of stages. For each discrete determination of streamflow discharge, the mean velocity of the cross section is determined by dividing streamflow discharge by the cross-sectional area. A rating curve, similar to that used for stage-discharge determinations, is constructed using the mean velocity and the index velocity from the permanently mounted meter. An additional rating curve is constructed that relates stage of the stream to cross-sectional area. Using these two ratings, the automatically collected stage produces an estimate of the cross-sectional area, and the automatically collected index velocity produces an estimate of the mean velocity of the cross section. The streamflow discharge is computed as the estimate of the cross section area and the estimate of the mean velocity of the streamflow.

Equipment commonly used for stream gauging

Stream gauge B62, a combination weir at Doddieburn, on the Mzingwane River, Zimbabwe

Many permanent water control structures used to improve the reliability of using water level as a surrogate for flow (improving the reliability of the rating table) are:

- V-notch,
- broad-crested,
- sharp-crested and
- combination weirs
- Flumes

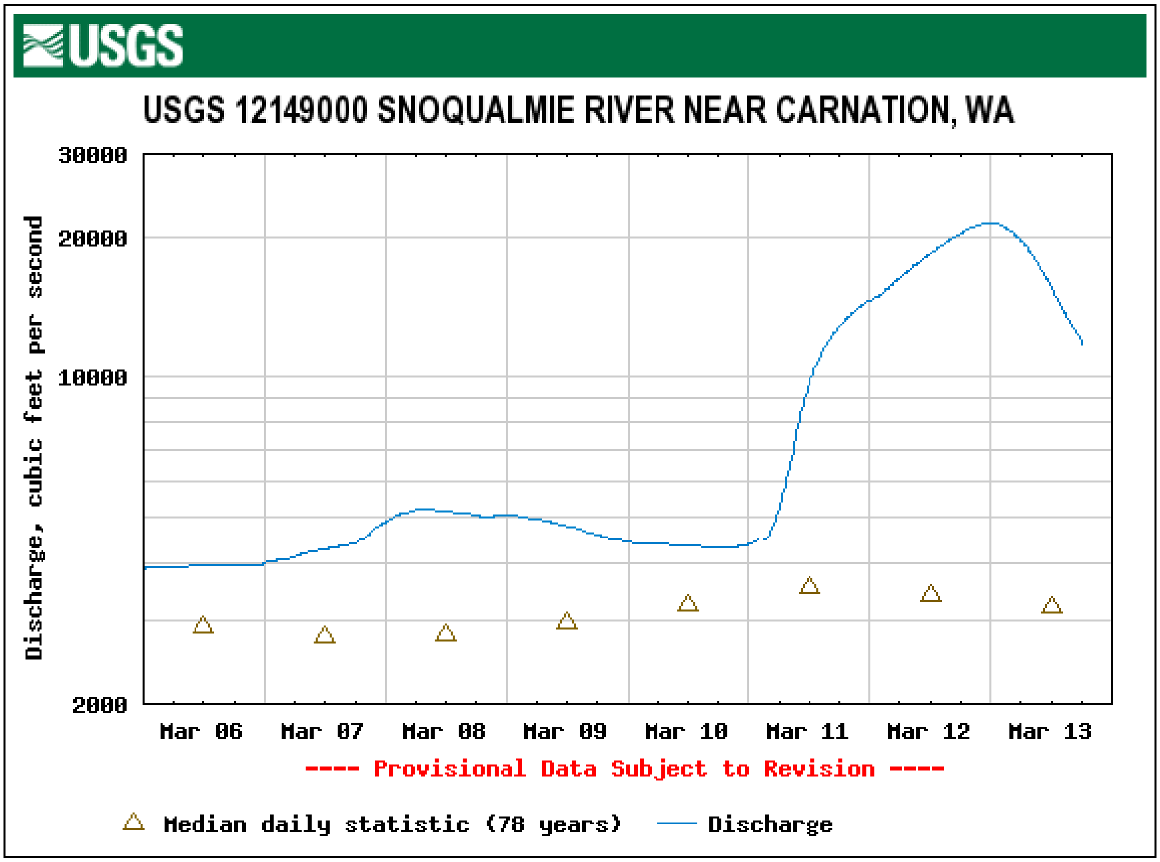
Other equipment commonly used at permanent stream gauge include:

- Cableways - for suspending a hydrographer and current meter over a river to make high flow measurement
- Water pressure measuring device (Bubbler) - to measure water level via pressure (typically done directly in-stream without a stilling well)
- Stilling well - to provide a calm water level that can be measured by a sensor
- Stage encoder - a potentiometer with a wheel and pulley system connected to a float in a stilling well to provide an electronic reading of the water level
- Simple ultrasonic devices - to measure water level in a stilling well or directly in a canal.
- Electromagnetic gauges

Discharge measurements of a stream or canal without an established stream gage can be made using a current meter or Acoustic Doppler Current Profiler. One informal methods that is not acceptable for any official or scientific purpose, but can be useful is the **float method**, in which a floating object such as a piece of wood or orange peel is observed floating down the stream.

National Stream Gauge Networks

United States



Hydrograph of the March 13, 2007 Snoqualmie River flood

In the United States, the U.S. Geological Survey (USGS) is the principal federal agency tasked with maintaining records of natural resources. Within the USGS, the Water Resources Division carries the responsibility for monitoring water resources.

To establish a stream gage, USGS personnel first choose a site on a stream where the geometry is relatively stable and there is a suitable location to make discrete direct measurements of streamflow using specialized equipment. Many times this will be at a bridge or other stream crossing. Technicians then install equipment that measures the **stage** (the elevation of the water surface) or, more rarely, the **velocity** of the flow. Additional equipment is installed to record and transmit these readings (via a telemeter) to the Water Science Center office where the records are kept. The USGS has a Water Science Center office in every state within the USA.

Zimbabwe

In Zimbabwe, the national stream gauge network is the responsibility of the Zimbabwe National Water Authority. This is an extensive network covering all major rivers and catchments in the country. However, a review of existing gauges raised serious concerns about the reliability of the data of a minority of stations, due in part to ongoing funding problems.

Chapter 3

Pressure Measurement

The construction of a bourdon tube gauge, construction elements are made of brass

Many techniques have been developed for the measurement of pressure and vacuum. Instruments used to measure pressure are called **pressure gauges** or **vacuum gauges**.

A **manometer** could also be referring to a pressure measuring instrument, usually limited to measuring pressures near to atmospheric. The term *manometer* is often used to refer specifically to liquid column hydrostatic instruments.

A **vacuum gauge** is used to measure the pressure in a vacuum—which is further divided into two subcategories: high and low vacuum (and sometimes ultra-high vacuum). The applicable pressure range of many of the techniques used to measure vacuums have an overlap. Hence, by combining several different types of gauge, it is possible to measure system pressure continuously from 10 mbar down to 10^{-11} mbar.

Absolute, gauge and differential pressures - zero reference

Although no pressure is an absolute quantity, everyday pressure measurements, such as for tire pressure, are usually made relative to ambient air pressure. In other cases measurements are made relative to a vacuum or to some other ad hoc reference. When distinguishing between these zero references, the following terms are used:

- **Absolute pressure** is zero referenced against a perfect vacuum, so it is equal to gauge pressure plus atmospheric pressure.
- **Gauge pressure** is zero referenced against ambient air pressure, so it is equal to absolute pressure minus atmospheric pressure. Negative signs are usually omitted.
- **Differential pressure** is the difference in pressure between two points.

The zero reference in use is usually implied by context, and these words are only added when clarification is needed. Tire pressure and blood pressure are gauge pressures by convention, while atmospheric pressures, deep vacuum pressures, and altimeter pressures must be absolute. Differential pressures are commonly used in industrial process systems. Differential pressure gauges have two inlet ports, each connected to one of the volumes whose pressure is to be monitored. In effect, such a gauge performs the mathematical operation of subtraction through mechanical means, obviating the need for an operator or control system to watch two separate gauges and determine the difference in readings. Moderate vacuum pressures are often ambiguous, as they may represent absolute pressure or gauge pressure without a negative sign. Thus a vacuum of 26 inHg gauge is equivalent to an absolute pressure of 30 inHg (typical atmospheric pressure) − 26 inHg = 4 inHg.

Atmospheric pressure is typically about 100 kPa at sea level, but is variable with altitude and weather. If the absolute pressure of a fluid stays constant, the gauge pressure of the same fluid will vary as atmospheric pressure changes. For example, when a car drives up a mountain (atmospheric air pressure decreases), the (gauge) tire pressure goes up. Some standard values of atmospheric pressure such as 101.325 kPa or 100 kPa have been defined, and some instruments use one of these standard values as a constant zero reference instead of the actual variable ambient air pressure. This impairs the accuracy of these instruments, especially when used at high altitudes.

Use of the atmosphere as reference is usually signified by a (g) after the pressure unit e.g. 30 psi g, which means that the pressure measured is the total pressure minus atmospheric pressure. There are two types of gauge reference pressure: vented gauge (vg) and sealed gauge (sg).

A vented gauge pressure transmitter for example allows the outside air pressure to be exposed to the negative side of the pressure sensing diaphragm, via a vented cable or a hole on the side of the device, so that it always measures the pressure referred to ambient barometric pressure. Thus a vented gauge reference pressure sensor should always read zero pressure when the process pressure connection is held open to the air.

A sealed gauge reference is very similar except that atmospheric pressure is sealed on the negative side of the diaphragm. This is usually adopted on high pressure ranges such as hydraulics where atmospheric pressure changes will have a negligible effect on the accuracy of the reading, so venting is not necessary. This also allows some manufacturers to provide secondary pressure containment as an extra precaution for pressure equipment safety if the burst pressure of the primary pressure sensing diaphragm is exceeded.

There is another way of creating a sealed gauge reference and this is to seal a high vacuum on the reverse side of the sensing diaphragm. Then the output signal is offset so the pressure sensor reads close to zero when measuring atmospheric pressure.

A sealed gauge reference pressure transducer will never read exactly zero because atmospheric pressure is always changing and the reference in this case is fixed at 1 bar.

An absolute pressure measurement is one that is referred to absolute vacuum. The best example of an absolute referenced pressure is atmospheric or barometric pressure.

To produce an absolute pressure sensor the manufacturer will seal a high vacuum behind the sensing diaphragm. If the process pressure connection of an absolute pressure transmitter is open to the air, it will read the actual barometric pressure.

Units

Pressure units

	Pascal (Pa)	**Bar (bar)**	**Technical atmosphere (at)**	**Atmosphere (atm)**	**Torr (Torr)**	**Pound-force per square inch (psi)**
1 Pa	≡ 1 N/m^2	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}
1 bar	100,000	≡ 10^6 dyn/cm^2	1.0197	0.98692	750.06	14.5037744
1 at	98,066.5	0.980665	≡ 1 kgf/cm^2	0.96784	735.56	14.223
1 atm	101,325	1.01325	1.0332	≡ 1 atm	760	14.696
1 torr	133.322	1.3332×10^{-3}	1.3595×10^{-3}	1.3158×10^{-3}	≡ 1 Torr; ≈ 1 mmHg	19.337×10^{-3}
1 psi	6.894×10^3	68.948×10^{-3}	70.307×10^{-3}	68.046×10^{-3}	51.715	≡ 1 lbf/in^2

Example reading: 1 Pa = 1 N/m^2 = 10^{-5} bar = 10.197×10^{-6} at = 9.8692×10^{-6} atm = 7.5006×10^{-3} torr = 145.04×10^{-6} psi
etc.

The SI unit for pressure is the pascal (Pa), equal to one newton per square metre (N·m^{-2} or kg·m^{-1}·s^{-2}). This special name for the unit was added in 1971; before that, pressure in SI was expressed in units such as N/m². When indicated, the zero reference is stated in parenthesis following the unit, for example 101 kPa (abs). The pound per square inch (psi) is still in widespread use in the US and Canada, notably for cars. A letter is often appended to the psi unit to indicate the measurement's zero reference; psia for absolute, psig for gauge, psid for differential, although this practice is discouraged by the NIST.

Because pressure was once commonly measured by its ability to displace a column of liquid in a manometer, pressures are often expressed as a depth of a particular fluid (e.g. inches of water). The most common choices are mercury (Hg) and water; water is nontoxic and readily available, while mercury's density allows for a shorter column (and so a smaller manometer) to measure a given pressure.

Fluid density and local gravity can vary from one reading to another depending on local factors, so the height of a fluid column does not define pressure precisely. When 'millimetres of mercury' or 'inches of mercury' are quoted today, these units are not based on a physical column of mercury; rather, they have been given precise definitions that can be expressed in terms of SI units. The water-based units usually assume one of the older definitions of the kilogram as the weight of a litre of water.

Although no longer favoured by measurement experts, these **manometric units** are still encountered in many fields. Blood pressure is measured in millimetres of mercury in most of the world, and lung pressures in centimeters of water are still common. Natural gas pipeline pressures are measured in inches of water, expressed as '"WC' ('Water Column'). Scuba divers often use a manometric rule of thumb: the pressure exerted by ten metres depth of water is approximately equal to one atmosphere. In vacuum systems, the units torr, micrometre of mercury (micron), and inch of mercury (inHg) are most commonly used. Torr and micron usually indicates an absolute pressure, while inHg usually indicates a gauge pressure.

Atmospheric pressures are usually stated using kilopascal (kPa), or atmospheres (atm), except in American meteorology where the hectopascal (hPa) and millibar (mbar) are preferred. In American and Canadian engineering, stress is often measured in kip. Note that stress is not a true pressure since it is not scalar. In the cgs system the unit of pressure was the barye (ba), equal to 1 $dyn \cdot cm^{-2}$. In the mts system, the unit of pressure was the pieze, equal to 1 sthene per square metre.

Many other hybrid units are used such as $mmHg/cm^2$ or grams-force/cm^2 (sometimes as kg/cm^2 and g/mol2 without properly identifying the force units). Using the names kilogram, gram, kilogram-force, or gram-force (or their symbols) as a unit of force is forbidden in SI; the unit of force in SI is the newton (N).

Static and dynamic pressure

Static pressure is uniform in all directions, so pressure measurements are independent of direction in an immovable (static) fluid. Flow, however, applies additional pressure on surfaces perpendicular to the flow direction, while having little impact on surfaces parallel to the flow direction. This directional component of pressure in a moving (dynamic) fluid is called dynamic pressure. An instrument facing the flow direction measures the sum of the static and dynamic pressures; this measurement is called the total pressure or stagnation pressure. Since dynamic pressure is referenced to static pressure, it is neither gauge nor absolute; it is a differential pressure.

While static gauge pressure is of primary importance to determining net loads on pipe walls, dynamic pressure is used to measure flow rates and airspeed. Dynamic pressure can be measured by taking the differential pressure between instruments parallel and perpendicular to the flow. Pitot-static tubes, for example perform this measurement on airplanes to determine airspeed. The presence of the measuring instrument inevitably acts to divert flow and create turbulence, so its shape is critical to accuracy and the calibration curves are often non-linear.

Applications

- Altimeter
- Barometer
- MAP sensor
- Pitot tube
- Sphygmomanometer

Instruments

Many instruments have been invented to measure pressure, with different advantages and disadvantages. Pressure range, sensitivity, dynamic response and cost all vary by several orders of magnitude from one instrument design to the next. The oldest type is the liquid column (a vertical tube filled with mercury) manometer invented by Evangelista Torricelli in 1643. The U-Tube was invented by Christian Huygens in 1661.

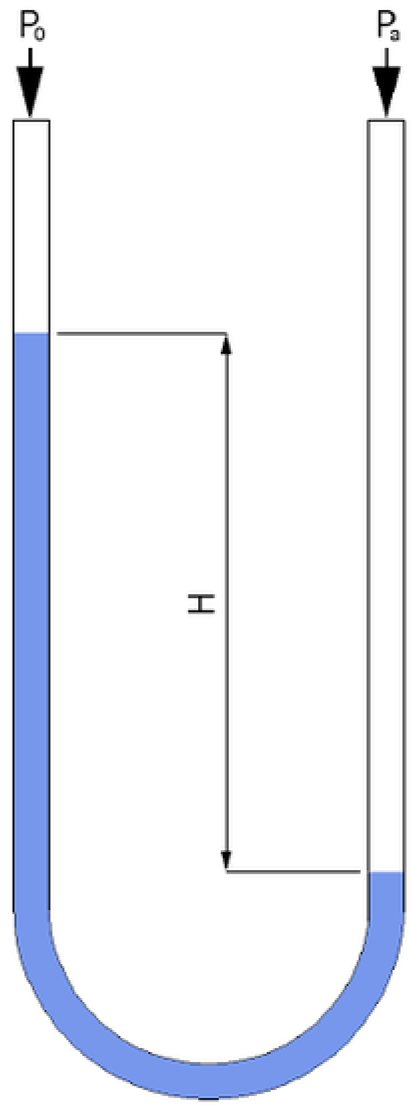
Hydrostatic

Hydrostatic gauges (such as the mercury column manometer) compare pressure to the hydrostatic force per unit area at the base of a column of fluid. Hydrostatic gauge measurements are independent of the type of gas being measured, and can be designed to have a very linear calibration. They have poor dynamic response.

Piston

Piston-type gauges counterbalance the pressure of a fluid with a solid weight or a spring. Another name for piston gauge is deadweight tester. For example, dead-weight testers used for calibration or tire-pressure gauges.

Liquid column



The difference in fluid height in a liquid column manometer is proportional to the pressure difference. $H = \frac{P_a - P_o}{g\rho}$

Liquid column gauges consist of a vertical column of liquid in a tube whose ends are exposed to different pressures. The column will rise or fall until its weight is in equilibrium with the pressure differential between the two ends of the tube. A very simple version is a U-shaped tube half-full of liquid, one side of which is connected to the region of interest while the reference pressure (which might be the atmospheric pressure or a vacuum) is applied to the other. The difference in liquid level represents the applied pressure. The pressure exerted by a column of fluid of height *h* and density *ρ* is given by the hydrostatic pressure equation, $P = hg\rho$. Therefore the pressure difference between the applied pressure P_a and the reference pressure P_0 in a U-tube manometer can be found by solving $P_a - P_0 = hg\rho$. In other words, the pressure on either end of the liquid (shown in blue in the figure to the right) must be balanced (since the liquid is static) and so $P_a = P_0 + hg\rho$. If the fluid being measured is significantly dense, hydrostatic corrections may have to be made for the height between the moving surface of the manometer working fluid and the location where the pressure measurement is desired.

Although any fluid can be used, mercury is preferred for its high density (13.534 g/cm^3) and low vapour pressure. For low pressure differences well above the vapour pressure of water, water is commonly used (and "inches of water" is a common pressure unit). Liquid-column pressure gauges are independent of the type of gas being measured and have a highly linear calibration. They have poor dynamic response. When measuring vacuum, the working liquid may evaporate and contaminate the vacuum if its vapor pressure is too high. When measuring liquid pressure, a loop filled with gas or a light fluid must isolate the liquids to prevent them from mixing. Simple hydrostatic gauges can measure pressures ranging from a few Torr (a few 100 Pa) to a few atmospheres. (Approximately 1,000,000 Pa)

A single-limb liquid-column manometer has a larger reservoir instead of one side of the U-tube and has a scale beside the narrower column. The column may be inclined to further amplify the liquid movement. Based on the use and structure following type of manometers are used

1. Simple Manometer
2. Micromanometer
3. Differential manometer
4. Inverted differential manometer

A McLeod gauge, drained of mercury

McLeod gauge

A McLeod gauge isolates a sample of gas and compresses it in a modified mercury manometer until the pressure is a few mmHg. The gas must be well-behaved during its compression (it must not condense, for example). The technique is slow and unsuited to continual monitoring, but is capable of good accuracy.

Useful range: above 10^{-4} torr (roughly 10^{-2} Pa) as high as 10^{-6} Torr (0.1 mPa),

0.1 mPa is the lowest direct measurement of pressure that is possible with current technology. Other vacuum gauges can measure lower pressures, but only indirectly by measurement of other pressure-controlled properties. These indirect measurements must be calibrated to SI units via a direct measurement, most commonly a McLeod gauge.

Aneroid

Aneroid gauges are based on a metallic pressure sensing element which flexes elastically under the effect of a pressure difference across the element. "Aneroid" means "without fluid," and the term originally distinguished these gauges from the hydrostatic gauges described above. However, aneroid gauges can be used to measure the pressure of a liquid as well as a gas, and they are not the only type of gauge that can operate without fluid. For this reason, they are often called **mechanical** gauges in modern language. Aneroid gauges are not dependent on the type of gas being measured, unlike thermal and ionization gauges, and are less likely to contaminate the system than hydrostatic gauges. The pressure sensing element may be a **Bourdon tube**, a diaphragm, a capsule, or a set of bellows, which will change shape in response to the pressure of the region in question. The deflection of the pressure sensing element may be read by a linkage connected to a needle, or it may be read by a secondary transducer. The most common secondary transducers in modern vacuum gauges measure a change in capacitance due to the mechanical deflection. Gauges that rely on a change in capacitances are often referred to as Baratron gauges.

Bourdon

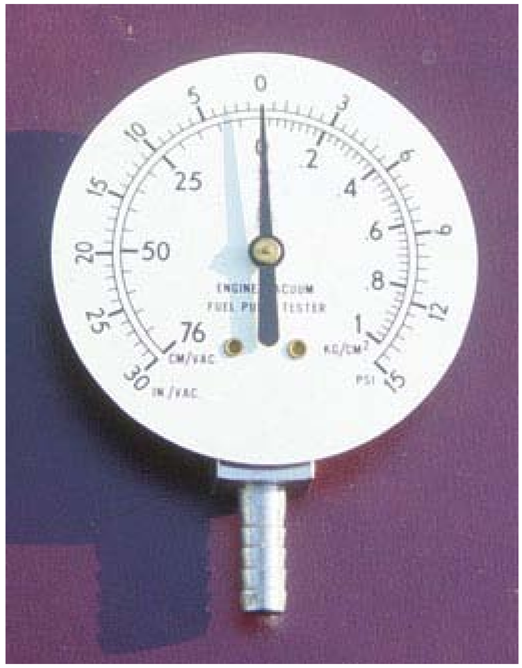
Membrane-type manometer

The Bourdon pressure gauge uses the principle that a flattened tube tends to change to a more circular cross-section when pressurized. Although this change in cross-section may be hardly noticeable, and thus involving moderate stresses within the elastic range of easily workable materials, the strain of the material of the tube is magnified by forming the tube into a C shape or even a helix, such that the entire tube tends to straighten out or uncoil, elastically, as it is pressurized. Eugene Bourdon patented his gauge in France in 1849, and it was widely adopted because of its superior sensitivity, linearity, and accuracy; Edward Ashcroft purchased Bourdon's American patent rights in 1852 and became a major manufacturer of gauges. Also in 1849, Bernard Schaeffer in Magdeburg, Germany patented a successful diaphragm pressure gauge, which together with the Bourdon gauge, revolutionized pressure measurement in industry. But in 1875 after Bourdon's patents expired, his company Schaeffer and Budenberg also manufactured Bourdon tube gauges.

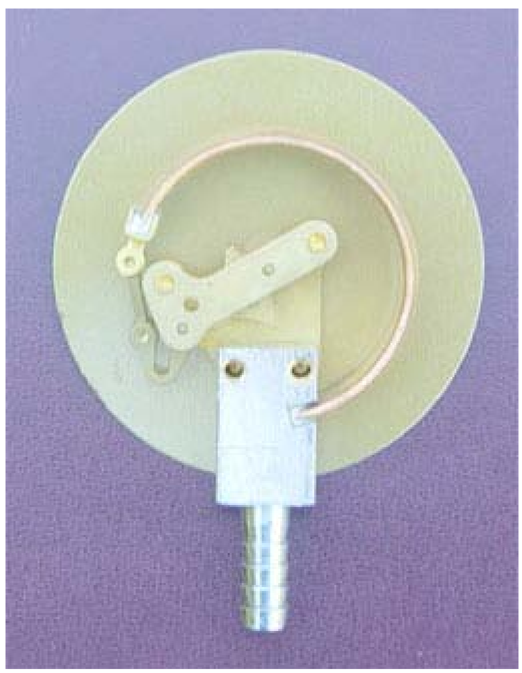
In practice, a flattened thin-wall, closed-end tube is connected at the hollow end to a fixed pipe containing the fluid pressure to be measured. As the pressure increases, the closed end moves in an arc, and this motion is converted into the rotation of a (segment of a) gear by a connecting link which is usually adjustable. A small diameter pinion gear is on the pointer shaft, so the motion is magnified further by the gear ratio. The positioning of the indicator card behind the pointer, the initial pointer shaft position, the linkage length and initial position, all provide means to calibrate the pointer to indicate the desired range of pressure for variations in the behaviour of the Bourdon tube itself. Differential pressure can be measured by gauges containing two different Bourdon tubes, with connecting linkages.

Bourdon tubes measure gauge pressure, relative to ambient atmospheric pressure, as opposed to absolute pressure; vacuum is sensed as a reverse motion. Some aneroid barometers use Bourdon tubes closed at both ends. When the measured pressure is rapidly pulsing, such as when the gauge is near a reprocating pump, an orfice restriction in the connecting pipe is frequently used to avoid unnecessary wear on the gears and provide an average reading; when the whole gauge is subject to mechanical vibration, the entire case including the pointer and indicator card can be filled with an oil or glycerin. Typical high-quality modern gauges provide an accuracy of ±2% of span, and a special high-precision gauge can be as accurate as 0.1% of full scale.

In the following illustrations the transparent cover face of the pictured combination pressure and vacuum gauge has been removed and the mechanism removed from the case. This particular gauge is a combination vacuum and pressure gauge used for automotive diagnosis:



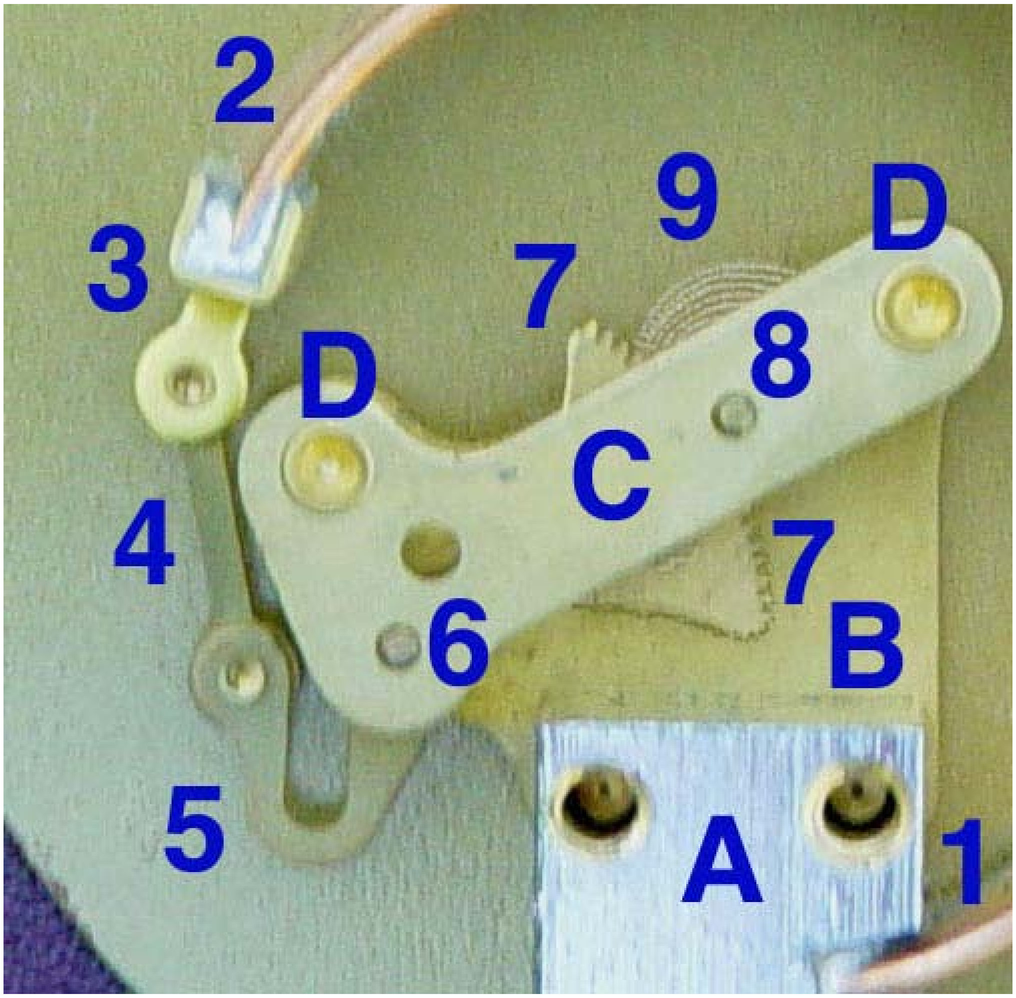
Indicator side with card and dial



Mechanical side with Bourdon tube

- the left side of the face, used for measuring manifold vacuum, is calibrated in centimetres of mercury on its inner scale and inches of mercury on its outer scale.
- the right portion of the face is used to measure fuel pump pressure and is calibrated in fractions of 1 kgf/cm² on its inner scale and pounds per square inch on its outer scale.

Mechanical details



Mechanical details

Stationary parts:

- A: Receiver block. This joins the inlet pipe to the fixed end of the Bourdon tube (1) and secures the chassis plate (B). The two holes receive screws that secure the case.
- B: Chassis plate. The face card is attached to this. It contains bearing holes for the axles.
- C: Secondary chassis plate. It supports the outer ends of the axles.
- D: Posts to join and space the two chassis plates.

Moving Parts:

1. Stationary end of Bourdon tube. This communicates with the inlet pipe through the receiver block.
2. Moving end of Bourdon tube. This end is sealed.

3. Pivot and pivot pin.
4. Link joining pivot pin to lever (5) with pins to allow joint rotation.
5. Lever. This an extension of the sector gear (7).
6. Sector gear axle pin.
7. Sector gear.
8. Indicator needle axle. This has a spur gear that engages the sector gear (7) and extends through the face to drive the indicator needle. Due to the short distance between the lever arm link boss and the pivot pin and the difference between the effective radius of the sector gear and that of the spur gear, any motion of the Bourdon tube is greatly amplified. A small motion of the tube results in a large motion of the indicator needle.
9. Hair spring to preload the gear train to eliminate gear lash and hysteresis.

Diaphragm

A pile of pressure capsules with corrugated diaphragms in an aneroid barograph.

A second type of aneroid gauge uses the deflection of a flexible membrane that separates regions of different pressure. The amount of deflection is repeatable for known pressures so the pressure can be determined by using calibration. The deformation of a thin diaphragm is dependent on the difference in pressure between its two faces. The reference face can be open to atmosphere to measure gauge pressure, open to a second port to measure differential pressure, or can be sealed against a vacuum or other fixed reference pressure to measure absolute pressure. The deformation can be measured using mechanical, optical or capacitive techniques. Ceramic and metallic diaphragms are used.

Useful range: above 10^{-2} Torr (roughly 1 Pa)

For absolute measurements, welded pressure capsules with diaphragms on either side are often used.

Shape:

- Flat
- corrugated
- flattened tube
- capsule

Bellows

In gauges intended to sense small pressures or pressure differences, or require that an absolute pressure be measured, the gear train and needle may be driven by an enclosed and sealed bellows chamber, called an **aneroid**, which means "without liquid". (Early barometers used a column of liquid such as water or the liquid metal mercury suspended by a vacuum.) This bellows configuration is used in aneroid barometers (barometers with an indicating needle and dial card), altimeters, altitude recording barographs, and the altitude telemetry instruments used in weather balloon radiosondes. These devices use the sealed chamber as a reference pressure and are driven by the external pressure. Other sensitive aircraft instruments such as air speed indicators and rate of climb indicators (variometers) have connections both to the internal part of the aneroid chamber and to an external enclosing chamber.

Electronic pressure sensors

- ***Piezoresistive Strain Gage***

  Uses the piezoresistive effect of bonded or formed strain gauges to detect strain due to applied pressure.

- ***Capacitive***

  Uses a diaphragm and pressure cavity to create a variable capacitor to detect strain due to applied pressure.

- ***Magnetic***

  Measures the displacement of a diaphragm by means of changes in inductance (reluctance), LVDT, Hall Effect, or by eddy current principal.

- ***Piezoelectric***

  Uses the piezoelectric effect in certain materials such as quartz to measure the strain upon the sensing mechanism due to pressure.

- ***Optical***

  Uses the physical change of an optical fiber to detect strain due applied pressure.

- ***Potentiometric***

Uses the motion of a wiper along a resistive mechanism to detect the strain caused by applied pressure.

- ***Resonant***

  Uses the changes in resonant frequency in a sensing mechanism to measure stress, or changes in gas density, caused by applied pressure.

Thermal conductivity

Generally, as a real gas increases in density -which may indicate an increase in pressure- its ability to conduct heat increases. In this type of gauge, a wire filament is heated by running current through it. A thermocouple or Resistance Temperature Detector (RTD) can then be used to measure the temperature of the filament. This temperature is dependent on the rate at which the filament loses heat to the surrounding gas, and therefore on the thermal conductivity. A common variant is the Pirani gauge which uses a single platinum filament as both the heated element and RTD. These gauges are accurate from 10 Torr to 10^{-3} Torr, but they are sensitive to the chemical composition of the gases being measured.

Two wire

One wire coil is used as a heater, and the other is used to measure nearby temperature due to convection.

Pirani (one wire)

A Pirani gauge consists of a metal wire open to the pressure being measured. The wire is heated by a current flowing through it and cooled by the gas surrounding it. If the gas pressure is reduced, the cooling effect will decrease, hence the equilibrium temperature of the wire will increase. The resistance of the wire is a function of its temperature: by measuring the voltage across the wire and the current flowing through it, the resistance (and so the gas pressure) can be determined. This type of gauge was invented by Marcello Pirani.

Thermocouple gauges and **thermistor gauges** work in a similar manner, except a thermocouple or thermistor is used to measure the temperature of the wire.

Useful range: 10^{-3} - 10 Torr (roughly 10^{-1} - 1000 Pa)

Ionization gauge

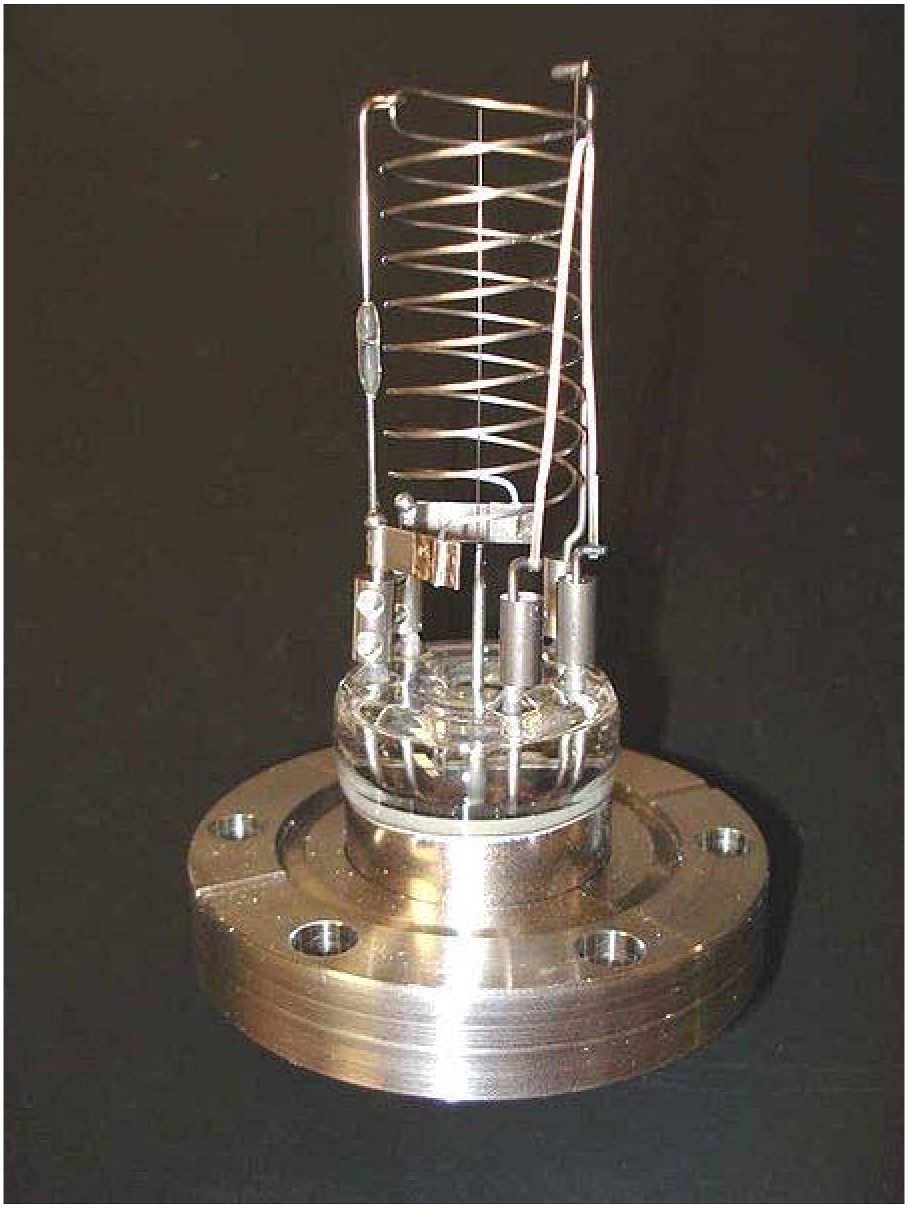
Ionization gauges are the most sensitive gauges for very low pressures (also referred to as hard or high vacuum). They sense pressure indirectly by measuring the electrical ions produced when the gas is bombarded with electrons. Fewer ions will be produced by lower density gases. The calibration of an ion gauge is unstable and dependent on the nature of the gases being measured, which is not always known. They can be calibrated against a McLeod gauge which is much more stable and independent of gas chemistry.

Thermionic emission generate electrons, which collide with gas atoms and generate positive ions. The ions are attracted to a suitably biased electrode known as the collector. The current in the collector is proportional to the rate of ionization, which is a function of the pressure in the system. Hence, measuring the collector current gives the gas pressure. There are several sub-types of ionization gauge.

Useful range: 10^{-10} - 10^{-3} torr (roughly 10^{-8} - 10^{-1} Pa)

Most ion gauges come in two types: hot cathode and cold cathode, a third type exists which is more sensitive and expensive known as a spinning rotor gauge, but is not discussed here. In the hot cathode version an electrically heated filament produces an electron beam. The electrons travel through the gauge and ionize gas molecules around them. The resulting ions are collected at a negative electrode. The current depends on the number of ions, which depends on the pressure in the gauge. Hot cathode gauges are accurate from 10^{-3} Torr to 10^{-10} Torr. The principle behind cold cathode version is the same, except that electrons are produced in the discharge of a high voltage. Cold Cathode gauges are accurate from 10^{-2} Torr to 10^{-9} Torr. Ionization gauge calibration is very sensitive to construction geometry, chemical composition of gases being measured, corrosion and surface deposits. Their calibration can be invalidated by activation at atmospheric pressure or low vacuum. The composition of gases at high vacuums will usually be unpredictable, so a mass spectrometer must be used in conjunction with the ionization gauge for accurate measurement.

Hot cathode



Bayard-Alpert hot cathode ionization gauge

A hot cathode ionization gauge is mainly composed of three electrodes acting together as a triode, where the cathode is the filament. The three electrodes are a collector or plate, a filament, and a grid. The collector current is measured in picoamps by an electrometer. The filament voltage to ground is usually at a potential of 30 volts while the grid voltage at 180–210 volts DC, unless there is an optional electron bombardment feature, by heating the grid which may have a high potential of approximately 565 volts. The most common ion gauge is the hot cathode **Bayard-Alpert gauge**, with a small ion collector inside the grid. A glass envelope with an opening to the vacuum can surround the electrodes, but usually the **Nude Gauge** is inserted in the vacuum chamber directly, the pins being fed through a ceramic plate in the wall of the chamber. Hot cathode gauges can be damaged or lose their calibration if they are exposed to atmospheric pressure or even low vacuum while hot. The measurements of a hot cathode ionization gauge are always logarithmic.

Electrons emitted from the filament move several times in back and forth movements around the grid before finally entering the grid. During these movements, some electrons collide with a gaseous molecule to form a pair of an ion and an electron (Electron ionization). The number of these ions is proportional to the gaseous molecule density multiplied by the electron current emitted from the filament, and these ions pour into the collector to form an ion current. Since the gaseous molecule density is proportional to the pressure, the pressure is estimated by measuring the ion current.

The low pressure sensitivity of hot cathode gauges is limited by the photoelectric effect. Electrons hitting the grid produce x-rays that produce photoelectric noise in the ion collector. This limits the range of older hot cathode gauges to 10^{-8} Torr and the Bayard-Alpert to about 10^{-10} Torr. Additional wires at cathode potential in the line of sight between the ion collector and the grid prevent this effect. In the extraction type the ions are not attracted by a wire, but by an open cone. As the ions cannot decide which part of the cone to hit, they pass through the hole and form an ion beam. This ion beam can be passed on to a

- Faraday cup
- Microchannel plate detector with Faraday cup
- Quadrupole mass analyzer with Faraday cup
- Quadrupole mass analyzer with Microchannel plate detector Faraday cup
- ion lens and acceleration voltage and directed at a target to form a sputter gun. In this case a valve lets gas into the grid-cage.

Cold cathode

There are two subtypes of cold cathode ionization gauges: the **Penning gauge** (invented by Frans Michel Penning), and the **Inverted magnetron**, also called a **Redhead gauge**. The major difference between the two is the position of the anode with respect to the cathode. Neither has a filament, and each may require a DC potential of about 4 kV for operation. Inverted magnetrons can measure down to 1×10^{-12} Torr.

Such gauges cannot operate if the ions generated by the cathode recombine before reaching the anodes. If the mean-free path of the gas within the gauge is smaller than the gauge's dimensions, then the electrode current will essentially vanish. A practical upper-bound to the detectable pressure is, for a Penning gauge, of the order of 10^{-3} Torr.

Similarly, cold cathode gauges may be reluctant to start at very low pressures, in that the near-absence of a gas makes it difficult to establish an electrode current - particularly in Penning gauges which use an axially symmetric magnetic field to create path lengths for ions which are of the order of metres. In ambient air suitable ion-pairs are ubiquitously formed by cosmic radiation; in a Penning gauge design features are used to ease the set-up of a discharge path. For example, the electrode of a Penning gauge is usually finely tapered to facilitate the field emission of electrons.

Maintenance cycles of cold cathode gauges are generally measured in years, depending on the gas type and pressure that they are operated in. Using a cold cathode gauge in gases with substantial organic components, such as pump oil fractions, can result in the growth of delicate carbon films and shards within the gauge which eventually either short-circuit the electrodes of the gauge, or impede the generation of a discharge path.

Calibration

Pressure gauges are either direct- or indirect-reading. Hydrostatic and elastic gauges measure pressure are directly influenced by force exerted on the surface by incident particle flux, and are called direct reading gauges. Thermal and ionization gauges read pressure indirectly by measuring a gas property that changes in a predictable manner with gas density. Indirect measurements are susceptible to more errors than direct measurements.

- Dead weight tester
- McLeod
- mass spec + ionization

Dynamic transients

When fluid flows are not in equilibrium, local pressures may be higher or lower than the average pressure in a medium. These disturbances propagate from their source as longitudinal pressure variations along the path of propagation. This is also called sound. Sound pressure is the instantaneous local pressure deviation from the average pressure caused by a sound wave. Sound pressure can be measured using a microphone in air and a hydrophone in water. The effective sound pressure is the root mean square of the instantaneous sound pressure over a given interval of time. Sound pressures are normally small and are often expressed in units of microbar.

- frequency response of pressure sensors
- resonance

History

European (CEN) Standard

- EN 472 : Pressure gauge - Vocabulary.
- EN 837-1 : Pressure gauges. Bourdon tube pressure gauges. Dimensions, metrology, requirements and testing.
- EN 837-2 : Pressure gauges. Selection and installation recommendations for pressure gauges.

- EN 837-3 : Pressure gauges. Diaphragm and capsule pressure gauges. Dimensions, metrology, requirements and testing..

Chapter 4

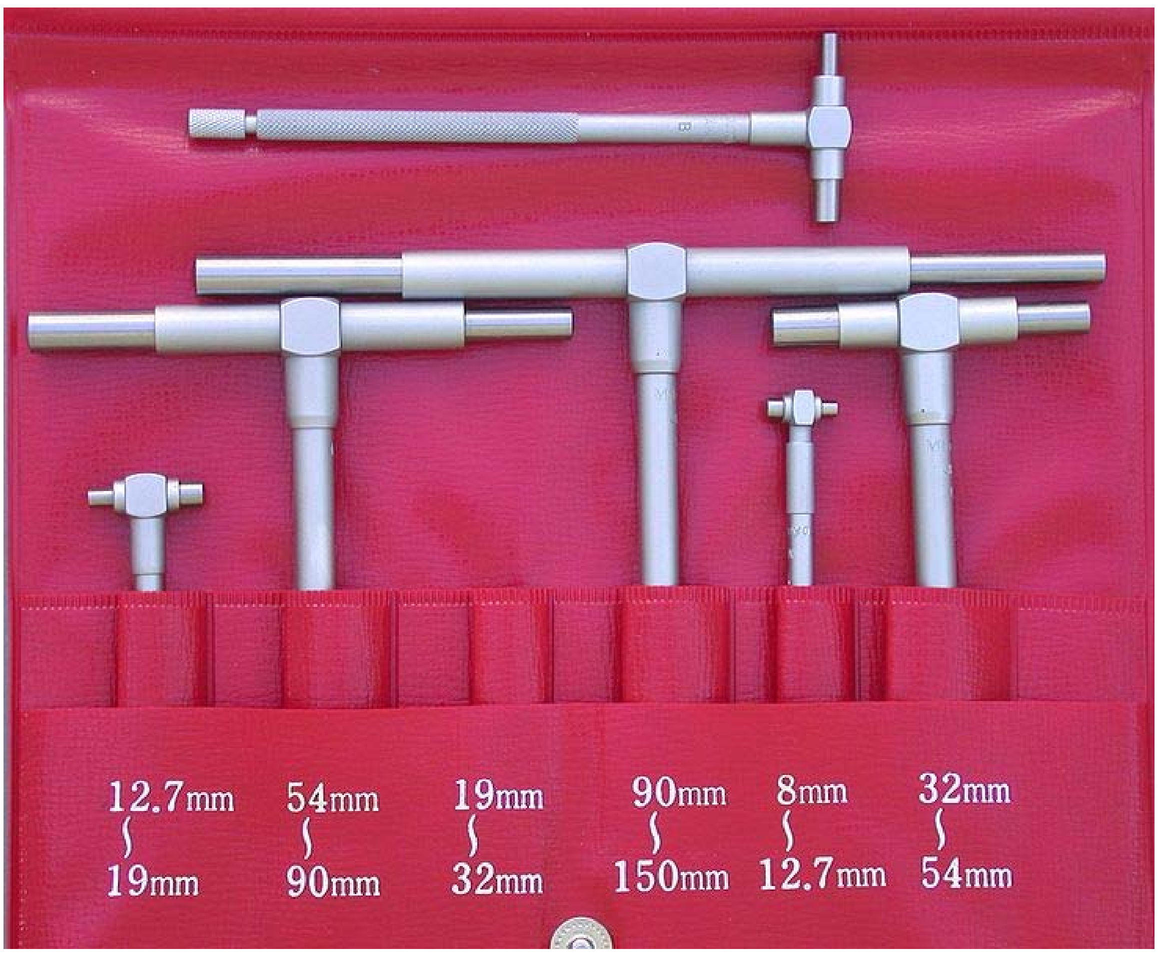
Bore Gauge, Center Gauge and Dial Indicator

Bore gauge

A **bore gauge** is a convenient term for the measuring or transfer tools that are used in the process of accurately measuring holes.

Transfer gauges

Telescopic gauges



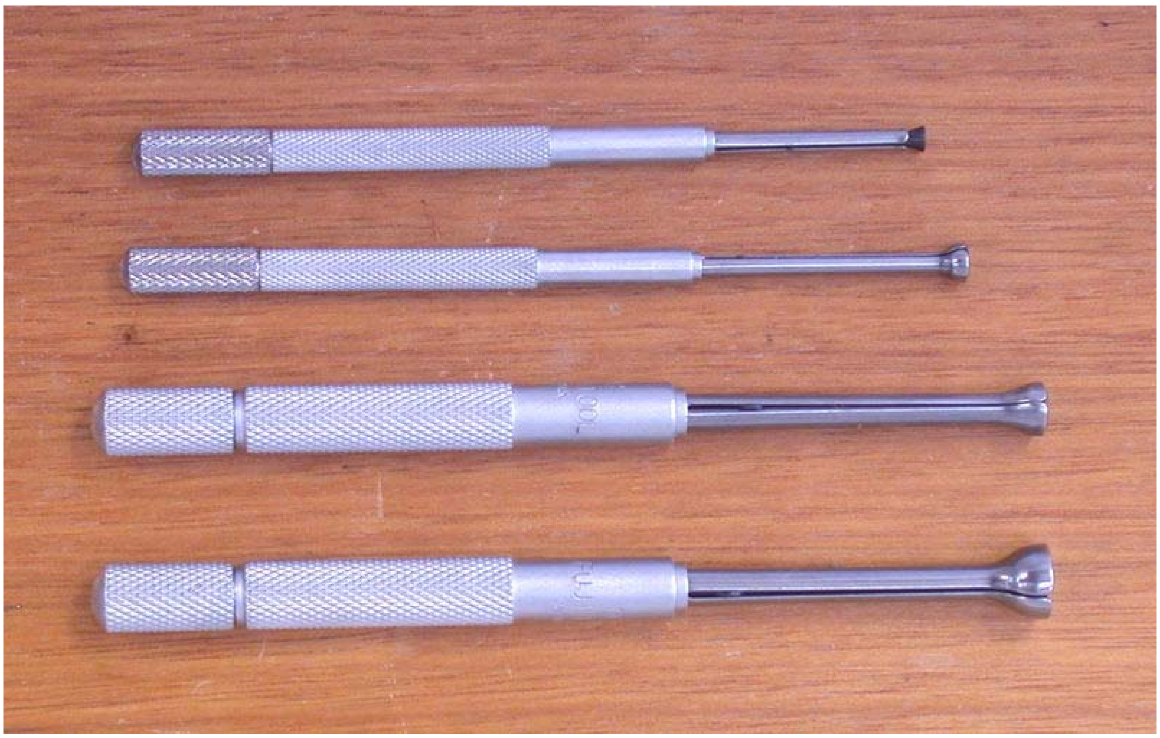
Telescopic gauge set

These are a range of gauges that are used to measure a bore's size, by transferring the internal dimension to a remote measuring tool. They are a direct equivalent of inside calipers and require the operator to develop the correct *feel* to obtain repeatable results.

The gauges are *locked* by twisting the knurled end of the handles, this action is performed to exert a small amount of friction on the telescopic portions of the gauge (the smaller diameter rods found at the **T** head of the gauge). Once gently locked to a size slightly larger than the bore, the gauges are inserted at an angle to the bore and slowly brought to align themselves radially, across the hole. This action compresses the two anvils where they remain locked at the bores dimension after being withdrawn.

The gauge is then removed and measured with the aid of a micrometer or caliper.

Small hole gauges



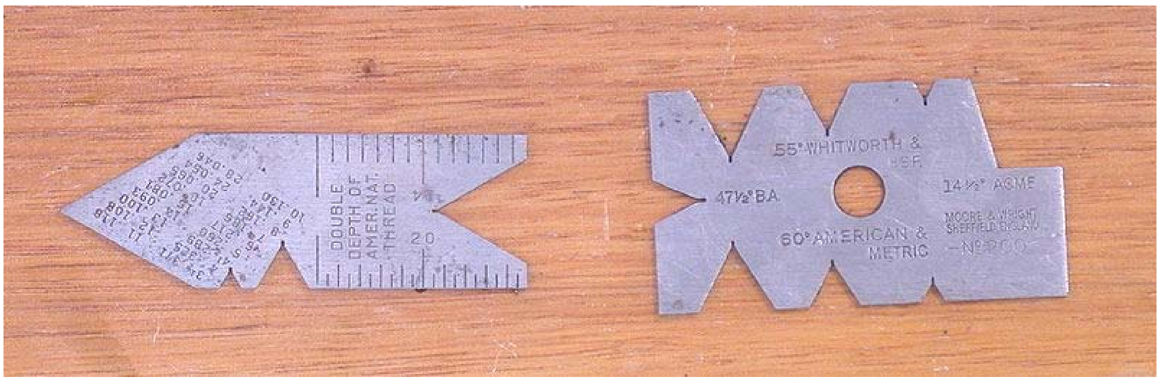
Small hole gauge set. Sizes from top to bottom:
3 to 5 mm (0.118 to 0.197 in)
5 to 7.5 mm (0.197 to 0.295 in)
7.5 to 10 mm (0.295 to 0.394 in)
10 to 13 mm (0.394 to 0.512 in)

Small hole gauges require a slightly different technique to the telescopic gauges, the small hole gauge is initially set smaller than the bore to be measured. It is then inserted into the bore and adjusted by rotating the knurled knob at the base, until light pressure is felt when the gauge is slightly moved in the bore. The gauge is then removed and measured with a caliper or micrometer.

Dial bore gauge

A dial or vernier bore gauge measures a bore directly. The gauge has three symmetrical anvils that protrude from the gauge body that are connected to the dial or micrometer mechanism. As the knob is rotated it moves the anvils in or out with respect to the measurements. The knob usually has a slipping mechanism to take the feel out of the device and increase reliability between measurements. The measurement given is the mean diameter of the three anvils, and is usually good to 0.001 mm (3.9×10^{-5} in).

Center gauge



Two different thread setting gauges

Center gauges and **fishtail gauges** are gauges used in lathe work for checking the angles when grinding the profiles of single-point screw-cutting tool bits and centers. In the image, the gauge on the left is called a **fishtail gauge** or **center gauge**, and the one on the right is another style of **center gauge**.

These gauges are most commonly used when hand-grinding threading tool bits on a bench grinder, although they may be used with tool and cutter grinders.

When the tool bit has been ground to the correct angle, they may then be used to set the tool perpendicular to the workpiece.

They can incorporate a range of sizes and types on the one gauge, the two most common being metric or UNS at 60°, and BSW at 55°. Gauges also exist for the Acme thread form.

Dial indicator

Dial indicators, also known as **dial gauges** and **probe indicators**, are instruments used to accurately measure small linear distances, and are frequently used in industrial and mechanical processes. They are named so because the measurement results are displayed in a magnified way by means of a dial.

A special variety of the dial indicator is the **dial test indicator** (DTI) which is primarily used in machine setups. The DTI measures displacement at an angle of a lever or plunger perpendicular to the axis of the indicator. A regular dial indicator measures linear displacement along that axis.

Dial indicators may be used to check the variation in tolerance during the inspection process of a machined part, measure the deflection of a beam or ring under laboratory conditions, as well as many other situations where a small measurement needs to be registered or indicated. Dial indicators typically measure ranges from 0.25 mm to 300 mm (0.015 in to 12.0 in), with graduations of 0.001 mm to 0.01 mm (metric) or 0.00005 in to 0.001 in (imperial).

General classification

There are several variables in dial indicators:

- Analog versus digital/electronic readout (most are analog)
- Dial size. Typically referred to be American Gage Design Specification (AGD):

AGD	Diameter range (in)	Diameter range (mm)
0	1–1 3/8	25–35
1	1 3/8–2	35–50
2	2–2 3/8	50–60
3	2 3/8–3	60–75
4	3–3 3/4	76–95

- Accuracy
- Range of travel
- Number of dial revolutions
- Dial style: balanced (e.g., -15 to 0 to +15) or continuous (e.g., 0 to 30)
- Graduation style: positive numbers (clockwise) or negative numbers (counterclockwise)
- Revolution counters, which show the number of revolutions of the principal needle.

Applications

- To check for runout when fitting a new disc to an automotive disc brake. Runout can rapidly ruin the disc if it exceeds the specified tolerance (typically 0.05 mm or less).
- In a quality environment to check for consistency and accuracy in the manufacturing process.
- On the *workshop floor* to initially set up or calibrate a machine, prior to a production run.
- By toolmakers (moldmakers) in the process of manufacturing precision tooling.
- In metal engineering workshops, where a typical application is the centering of a lathe's workpiece in a four jaw chuck. The DTI is used to indicate the *run out* (the misalignment between the work piece's axis of rotational symmetry and the axis of rotation of the spindle) of the work piece, with the ultimate aim of reducing it to a suitably small range using small chuck jaw adjustments.
- In areas other than manufacturing where accurate measurements need to be recorded (e.g., physics).

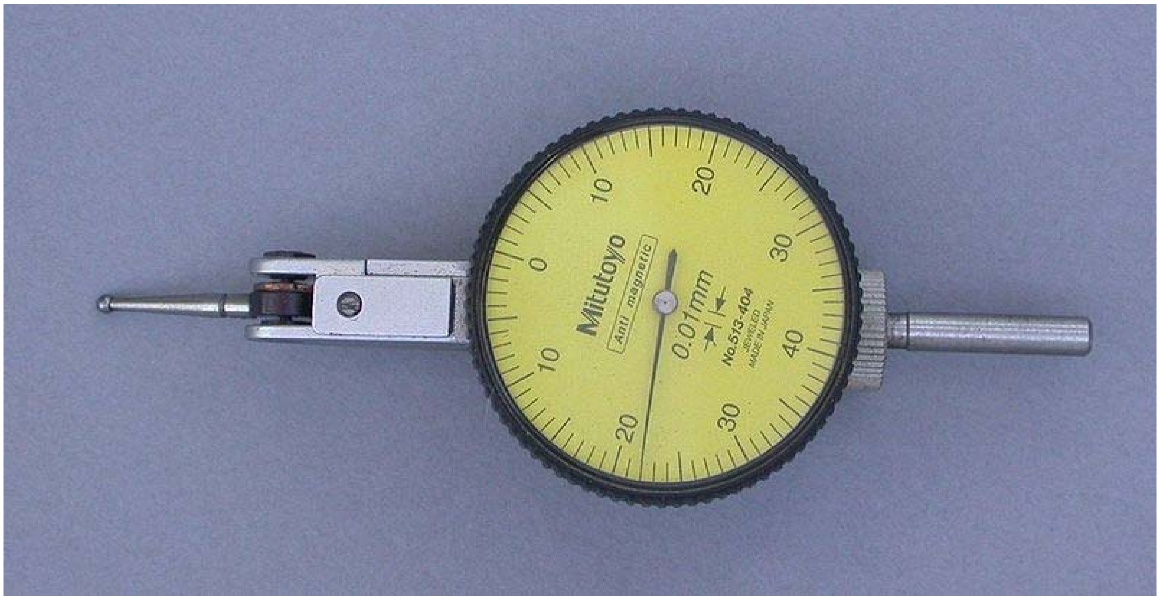
Probe indicator

0.1–20 mm dial indicator

Probe indicators typically consist of a graduated dial and needle (thus the *clock* terminology) to record the minor increments, with a smaller embedded clock face and needle to record the number of needle rotations on the main dial. The dial has fine gradations for precise measurement. The spring-loaded probe (or plunger) moves perpendicular to the object being tested by either retracting or extending from the indicator's body.

The dial face can be rotated to any position, this is used to orient the face towards the user as well as *set* the zero point, there will also be some means of incorporating limit indicators (the two metallic tabs visible in the right image, at 90 and 10 respectively), these limit tabs may be rotated around the dial face to any required position. There may also be a lever arm available that will allow the indicator's probe to be retracted easily.

Dial test indicator



Dial test indicator

A *dial test indicator*, also known as a *lever arm test indicator* or *finger indicator*, has a smaller measuring range than a standard dial indicator and therefore has the ability to measure in smaller increments. A test indicator measures the deflection of the arm, the probe does not retract but swings in an arc around its hinge point. The lever may be interchanged for length or ball diameter, and permits measurements to be taken in narrow grooves and small bores where the body of a probe type may not reach. The model shown is bidirectional, some types may have to be switched via a side lever to be able to measure in the opposite direction.

These indicators actually measure angular displacement and not linear displacement. If a force is perpendicular to the finger, the linear displacement error is acceptably small within the display range of the dial. However, this error starts to become noticeable when the force is as much as 10 degrees off the ideal 90.

Some cheaper models of test indicators may come with a pear-shaped contact point in an attempt to compensate for cosine error.

Contact points of higher end test indicators come with a standard carbide sphere at 1, 2, or 3 mm diameter. More usable materials are available for contact points such as ruby, teflon and PVC. These are more expensive and not available OEM, but, are extremely useful in applications where surfaces are easily scratched or damaged.

Digital indicator

With the advent of electronics and LCDs the clock face and analog display has been replaced with digital displays, these have the added advantage of sometimes being able to record and transmit the data electronically to a computer. This process is known as statistical process control (SPC) and involves a computer recording and interpreting the results, this also reduces the risk of the operator introducing recording errors. Digital indicators can also be switched between imperial and metric units with the press of a button, thereby increasing the DTI's versatility.

Contact point (tip) types

The tip of the probe may be interchanged with a range of shapes and sizes depending on the application. However if the contact point is not the same length as the one that is designed for the indicator, an offset is required for a proper measurement reading. The shape is usually chosen to give *point* contact, the shape of a small sphere allows for consistent measurements as the tip moves through an arc, while the size may be changed to allow the tip to enter a small hole. The tip may also be cylindrical or flat as the need arises. The contact angle of the tip is 90 degrees in relation to the surface that is being measured. If the angle is not 90 degrees, an offset (multiplier or correction factor) must be applied to achieve a correct non-zero measurement.

Chapter 5

Feeler Gauge and Load Cell

Feeler gauge

Feeler gauge set. Notice how it has both metric and imperial measurements recorded on each blade

A **feeler gauge** is a simple tool used to measure gap widths. Feeler gauges are mostly used in engineering to measure the clearance between two parts.

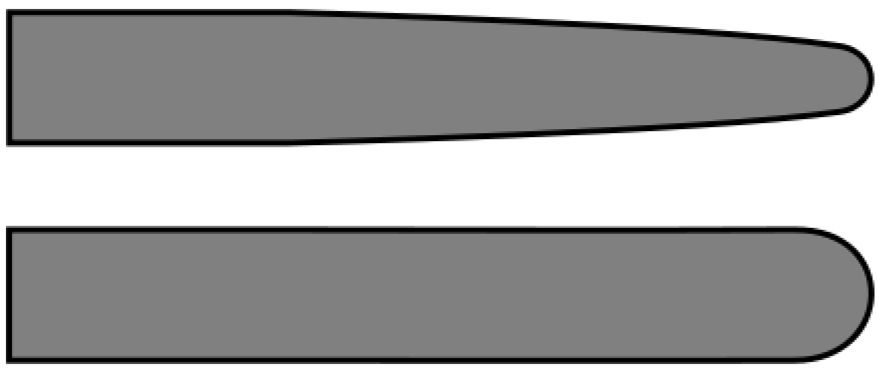
They consist of a number of small lengths of steel of different thicknesses with measurements marked on each piece. They are flexible enough that, even if they are all on the same hinge, several can be stacked together to gauge intermediate values. It is common to have two sets for imperial units (typically measured in thousandths of an inch) and metric (typically measured in hundredths of a millimetre) measurements.

A similar device with wires of specific diameter instead of flat blades is used to set the gap in spark plugs to the correct size; this is done by increasing or decreasing the gap until the gauge of the correct size just fits inside the gap.

The lengths of steel are sometimes called *blades*, although they have no sharp edge.

Types of feeler gauges

Taper feeler gauge



tapered (upper) and parallel (lower) feeler gauges

A taper feeler gauge is a feeler gauge of tapered, as opposed to parallel, shape. The blade of the gauge is of a constant thickness, and the two types of gauge are used in a similar way.

Load cell

A **load cell** is a transducer that is used to convert a force into electrical signal. This conversion is indirect and happens in two stages. Through a mechanical arrangement, the force being sensed deforms a strain gauge. The strain gauge converts the deformation (strain) to electrical signals. A load cell usually consists of four strain gauges in a Wheatstone bridge configuration. Load cells of one strain gauge (quarter bridge) or two strain gauges (half bridge) are also available. The electrical signal output is typically in the order of a few millivolts and requires amplification by an instrumentation amplifier before it can be used. The output of the transducer is plugged into an algorithm to calculate the force applied to the transducer.

Although strain gauge load cells are the most common, there are other types of load cells as well. In industrial applications, hydraulic (or hydrostatic) is probably the second most common, and these are utilized to eliminate some problems with strain gauge load cell devices. As an example, a hydraulic load cell is immune to transient voltages (lightning) so might be a more effective device in outdoor environments.

Other types include piezoelectric load cells (useful for dynamic measurements of force), and vibrating wire load cells, which are useful in geomechanical applications due to low amounts of drift.

Every load cell is subject to "ringing" when subjected to abrupt load changes. This stems from the spring-like behavior of load cells. In order to measure the loads, they have to deform. As such, a load cell of finite stiffness must have spring-like behavior, exhibiting vibrations at its natural frequency. An oscillating data pattern can be the result of ringing. Ringing can be suppressed in a limited fashion by passive means. Alternatively, a control system can use an actuator to actively damp out the ringing of a load cell. This method offers better performance at a cost of significant increase in complexity.

Load Cell types based on working principle

- Cantilever or bending beam
- Compression
- Tensile
- Universal
- Shear
- Torque
- Hollow

Load Cell types based on construction

- Bending beam
- Parallel beam or Binocular Beam
- Canister
- Shear beam
- Single column
- Multi-column
- Pancake
- Load button
- Single ended shear beam
- Double ended shear beam
- "S" type
- Inline rod end
- Digital ElectroMotive Force

- Diaphragm/membrane
- Torsion ring
- Bending ring
- Proving ring
- Load Pin

Load Cell types based on electrical properties

- Resistive
- Piezoelectric
- Capacitance
- Analog
- Digital
- Wireless

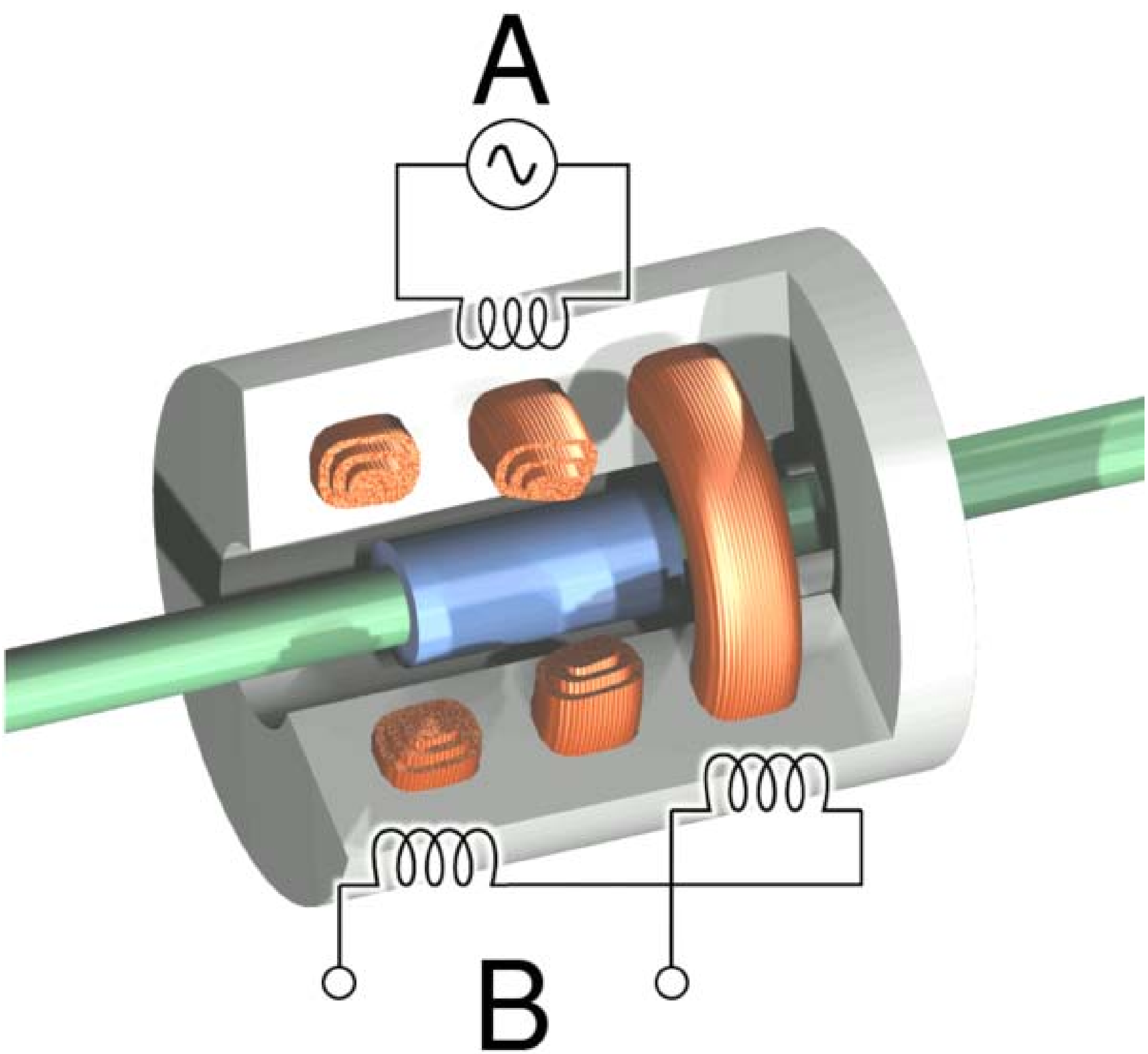
Applications

- Force measurement
- Portable weigh scales
- Platform scales
- Electronic weighbridge or truck weighing
- Electronic crane scales
- Hopper/Tank/Silo weighing
- Finding Center of gravity
- Onboard weighing
- Railcar weighing
- Structural health monitoring
- In-motion dynamic weighing check weigher
- Batch weighing
- Monitor inventory
- Feedback control
- Impact measurement
- Force gauge

Chapter 6

Linear Variable Differential Transformer and Profile Gauge

Linear variable differential transformer



Cutaway view of an LVDT. Current is driven through the primary coil at *A*, causing an induction current to be generated through the secondary coils at *B*.

The **linear variable differential transformer** (LVDT) is a type of electrical transformer used for measuring linear displacement. The transformer has three solenoidal coils placed end-to-end around a tube. The center coil is the primary, and the two outer coils are the secondaries. A cylindrical ferromagnetic core, attached to the object whose position is to be measured, slides along the axis of the tube.

An alternating current is driven through the primary, causing a voltage to be induced in each secondary proportional to its mutual inductance with the primary. The frequency is usually in the range 1 to 10 kHz.

As the core moves, these mutual inductances change, causing the voltages induced in the secondaries to change. The coils are connected in reverse series, so that the output voltage is the difference (hence "differential") between the two secondary voltages. When the core is in its central position, equidistant between the two secondaries, equal but opposite voltages are induced in these two coils, so the output voltage is zero.

When the core is displaced in one direction, the voltage in one coil increases as the other decreases, causing the output voltage to increase from zero to a maximum. This voltage is in phase with the primary voltage. When the core moves in the other direction, the output voltage also increases from zero to a maximum, but its phase is opposite to that of the primary. The magnitude of the output voltage is proportional to the distance moved by the core (up to its limit of travel), which is why the device is described as "linear". The phase of the voltage indicates the direction of the displacement.

Because the sliding core does not touch the inside of the tube, it can move without friction, making the LVDT a highly reliable device. The absence of any sliding or rotating contacts allows the LVDT to be completely sealed against the environment.

LVDTs are commonly used for position feedback in servomechanisms, and for automated measurement in machine tools and many other industrial and scientific applications.

Profile gauge

A contour gauge set to the profile of a little pot

A contour gauge

A **profile gauge** or **contour gauge** is a tool for recording the cross-sectional shape of a surface.

Contour gauges consist of a set of steel or plastic pins that are set tightly against one another in a frame which keeps them in the same plane and parallel while allowing them to move independently, perpendicularly to the frame. When pressed against an object, the pins conform to the object. The gauge can then be used to draw the profile or to copy it on to another surface.

Profile gauges are used widely in engineering and woodworking. In archaeological illustration, they are typically used to record the profile of pots, and are thus named **pottery gauges**; but in ceramics, a pottery gauge is a template used in making pots.

Chapter 7

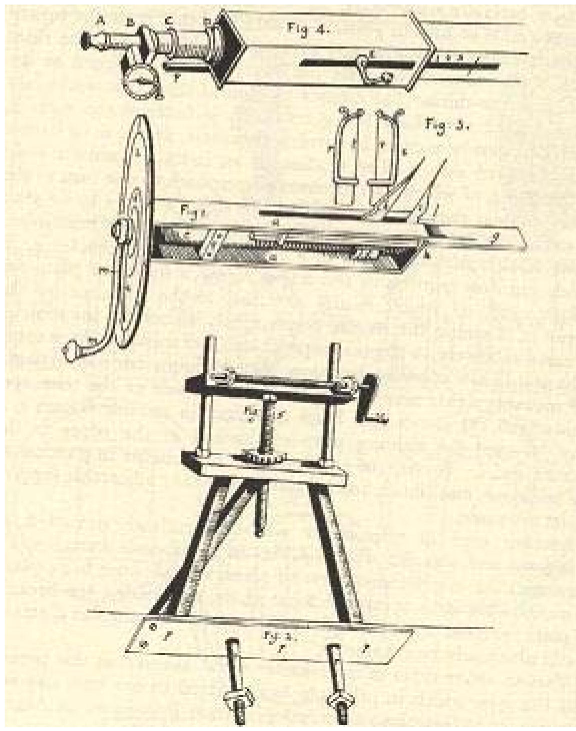
Micrometer

Outside, inside, and depth micrometers

A **micrometer** is a device incorporating a calibrated screw used widely for precise measurement of small distances in mechanical engineering and machining as well as most mechanical trades, along with other metrological instruments such as dial, vernier, and digital calipers. Micrometers are often, but not always, in the form of calipers.

Colloquially the word *micrometer* is often shortened to **mike** (US dict: mīk′).

History of the device and its name



Gascoigne's Micrometer as drawn by Robert Hooke

The word *micrometer* is a neoclassical coinage from Greek *micros*, "small", and *metron*, "measure". The *Merriam-Webster Collegiate Dictionary* says that English got it from French and that its first known appearance in English writing was in 1670. Neither the metre nor the micrometre nor the micrometer (device) as we know them today existed at that time. However, humans of that time did have much need for, and interest in, the ability to measure small things, and small differences; the word no doubt was coined in reference to this endeavor, even if it did not refer specifically to its present-day senses.

The first ever micrometric screw was invented by William Gascoigne in the 17th century, as an enhancement of the vernier; it was used in a telescope to measure angular distances between stars. Its adaptation for the precise measurement of handheld objects was made by Jean Laurent Palmer of Paris in 1848; the device is therefore often called *palmer* in French, and *tornillo de Palmer* ("Palmer screw") in Spanish. (Those languages also use the *micrometer* cognates: *micromètre, micrómetro*.) The micrometer caliper was introduced to the mass market in anglophone countries by Brown & Sharpe in 1867, allowing the penetration of the instrument's use into the average machine shop. Brown & Sharpe were inspired by several earlier devices, one of them being Palmer's design. In 1888 Edward Williams Morley added to the precision of micrometric measurements and proved their accuracy in a complex series of experiments.

Types

Basic types

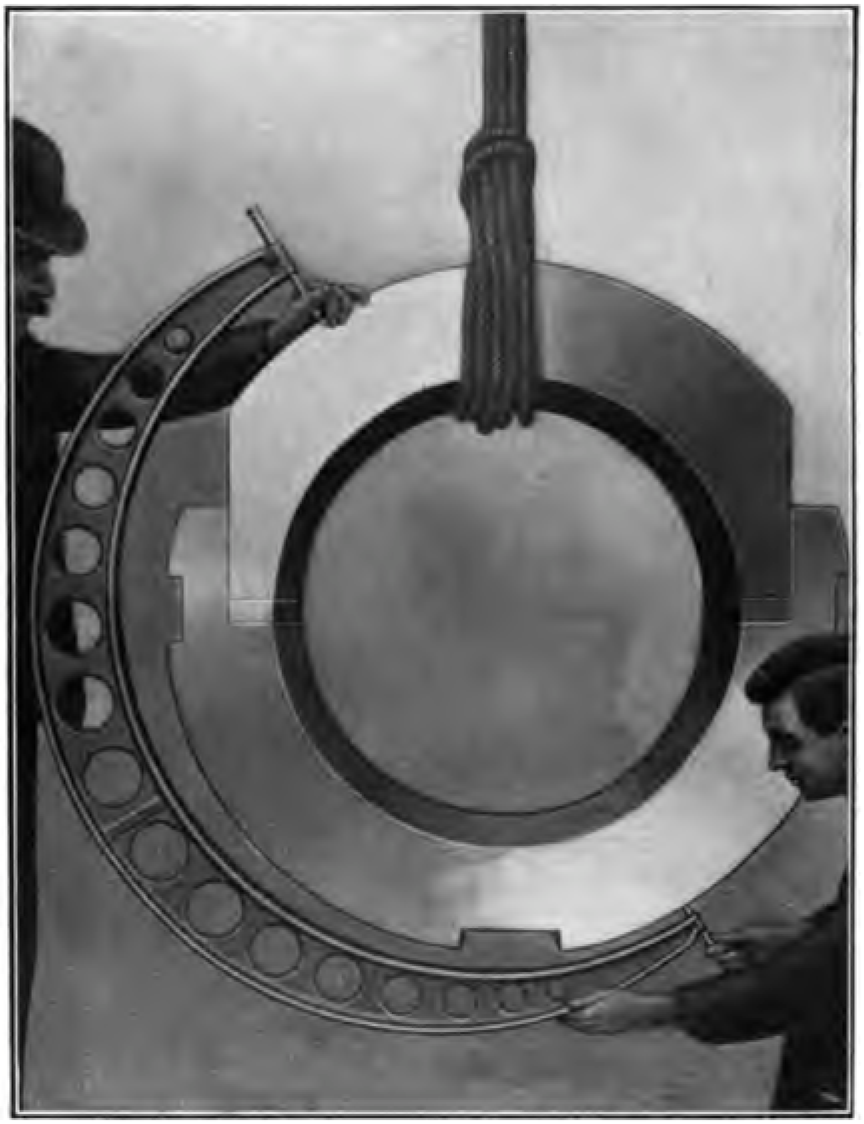


FIG. 221. — Large Micrometer.

Large micrometer caliper.

Another large micrometer in use.

The topmost image shows the three most common types of micrometer; the names are based on their application:

- **Outside micrometer** (aka micrometer caliper), typically used to measure wires, spheres, shafts and blocks.
- **Inside micrometer**, used to measure the diameter of holes.
- **Depth micrometer**, measures depths of slots and steps.

Specialized types

Each type of micrometer caliper can be fitted with specialized anvils and spindle tips for particular measuring tasks. For example, the anvil may be shaped in the form of a segment of screw thread, in the form of a v-block, or in the form of a large disc.

- **Universal micrometer sets** come with interchangeable anvils, such as flat, spherical, spline, disk, blade, point, and knife-edge. The term **universal micrometer** may also refer to a type of micrometer whose frame has modular components, allowing one micrometer to function as outside mic, depth mic, step mic, etc. (often known by the brand names Mul-T-Anvil and Uni-Mike).

- **Blade micrometers** have a matching set of narrow tips (blades). They allow, for example, the measuring of a narrow o-ring groove.
- **Pitch-diameter micrometers** have a matching set of thread-shaped tips for measuring the pitch diameter of screw threads.
- **Limit mics** have two anvils and two spindles, and are used like a snap gauge. The part being checked must pass through the first gap and must stop at the second gap in order to be within specification.
- **Bore micrometer**, typically a three-anvil head on a micrometer base used to accurately measure inside diameters.
- **Tube micrometers** have a cylindrical anvil positioned perpendicularly to a spindle and is used to measure the thickness of tubes.
- **Micrometer stops** are essentially inside mics that are mounted on the table of a manual milling machine, bedways of a lathe, or other machine tool, in place of simple stops. They help the operator to position the table or carriage precisely. Stops can also be used to actuate kickout mechanisms or limit switches to halt an automatic feed system.
- **Ball micrometers** have ball-shaped (spherical) anvils. They may have one flat and one ball anvil, in which case they are used for measuring tube wall thickness, distance of a hole to an edge, and other distances where one anvil must be placed against a rounded surface. They differ in application from tube micrometers in that they may be used to measure against rounded surfaces which are not tubes, but the ball anvil may also not be able to fit into smaller tubes as easily as a tube micrometer. Ball micrometers with a pair of balls can be used when single-tangential-point contact is desired on both sides. The most common example is in measuring the pitch diameter of screw threads (which is also done with conical anvils or the 3-wire method, the latter of which uses similar geometry as the pair-of-balls approach).

Operating principles

Micrometers use the principle of a screw to amplify small distances that are too small to measure directly into large rotations of the screw that are big enough to read from a scale. The accuracy of a micrometer derives from the accuracy of the threadform that is at its heart. The basic operating principles of a micrometer are as follows:

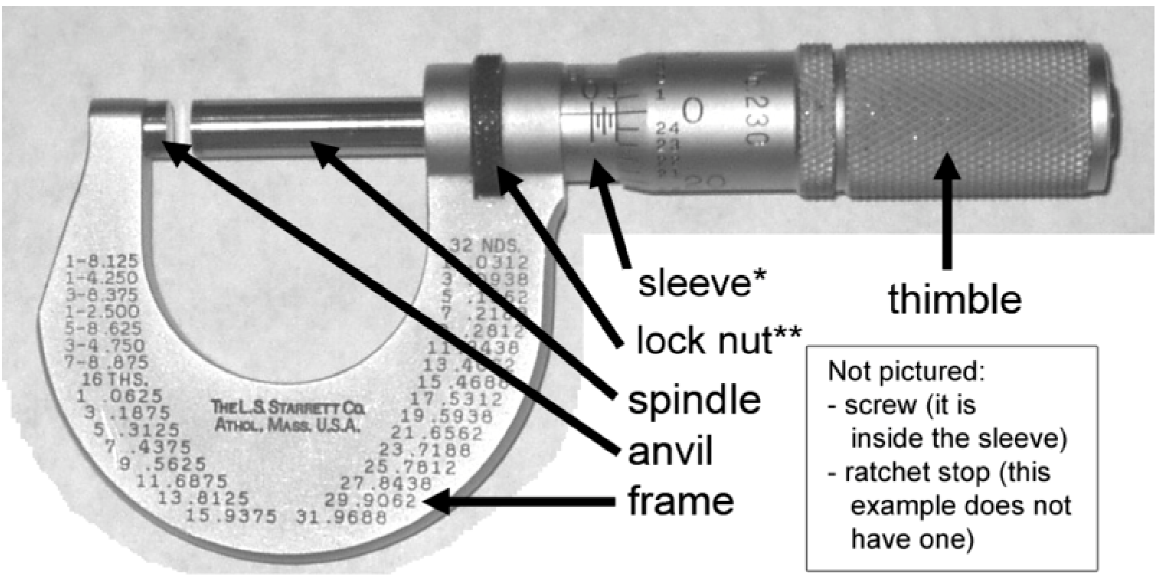
1. The amount of rotation of an accurately made screw can be directly and precisely correlated to a certain amount of axial movement (and vice versa), through the constant known as the screw's *lead* (/ˈliː d/). A screw's *lead* is the distance it moves forward axially with one complete turn (360°). (In most threads [that is, in all single-start threads], *lead* and *pitch* refer to essentially the same concept.)
2. With an appropriate lead and major diameter of the screw, a given amount of axial movement will be *amplified* in the resulting circumferential movement.

For example, if the lead of a screw is 1 mm, but the major diameter (here, outer diameter) is 10 mm, then the circumference of the screw is 10π, or about 31.4 mm. Therefore, an axial movement of 1 mm is amplified (magnified) to a circumferential movement of

31.4 mm. This amplification allows a small difference in the sizes of two similar measured objects to correlate to a larger difference in the position of a micrometer's thimble.

In older micrometers the position of the thimble is read directly from scale markings on the thimble and shaft. A vernier scale is usually included, which allows the position to be read to a fraction of the smallest scale mark. In newer digital micrometers, an electronic readout displays the length digitally on an LCD display on the instrument.

Parts



**Sleeve* is the most prevalent name. May also be called the *barrel* or *stock*.
**Aka *lock-ring*. Some mics have a *lock lever* instead.

The parts of a micrometer caliper, labeled. (Notice also that there is a handy decimal-fraction equivalents chart printed right on the frame of this inch-reading micrometer.)

A micrometer is composed of:

Frame

> The C-shaped body that holds the anvil and barrel in constant relation to each other. It is thick because it needs to minimize flexion, expansion, and contraction, which would distort the measurement.
> The frame is heavy and consequently has a high thermal mass, to prevent substantial heating up by the holding hand/fingers. It is often covered by insulating plastic plates which further reduce heat transference.
> Explanation: if you hold the frame long enough so that it heats up by 10°C, then the increase in length of any 10 cm linear piece of steel is of magnitude 1/100 mm. For micrometers this is their typical accuracy range.
> Micrometers typically have a temperature specified, at which the measurement is correct.

Anvil

The shiny part that the spindle moves toward, and that the sample rests against.

Sleeve / barrel / stock

The stationary round part with the linear scale on it. Sometimes vernier markings.

Lock nut / lock-ring / thimble lock

The knurled part (or lever) that one can tighten to hold the spindle stationary, such as when momentarily holding a measurement.

Screw

(not seen) The heart of the micrometer, as explained under "Operating principles". It is inside the barrel. (No wonder that the usual name for the device in German is *Messschraube*, literally "measuring screw".)

Spindle

The shiny cylindrical part that the thimble causes to move toward the anvil.

Thimble

The part that one's thumb turns. Graduated markings.

Ratchet stop

(not shown in illustration) Device on end of handle that limits applied pressure by slipping at a calibrated torque.

Reading

Inch system

Micrometer thimble showing 0.276 inch

The spindle of an inch-system micrometer has 40 threads per inch, so that one turn moves the spindle axially 0.025 inch (1 ÷ 40 = 0.025), equal to the distance between two graduations on the frame. The 25 graduations on the thimble allow the 0.025 inch to be further divided, so that turning the thimble through one division moves the spindle axially 0.001 inch (0.025 ÷ 25 = 0.001). Thus, the reading is given by the number of whole divisions that are visible on the scale of the frame, multiplied by 25 (the number of thousandths of an inch that each division represents), plus the number of that division on the thimble which coincides with the axial zero line on the frame. The result will be the diameter expressed in thousandths of an inch. As the numbers 1, 2, 3, etc., appear below every fourth sub-division on the frame, indicating hundreds of thousandths, the reading can easily be taken mentally.

Suppose the thimble were screwed out so that graduation 2, and three additional sub-divisions, were visible (as shown in the image), and that graduation 1 on the thimble coincided with the axial line on the frame. The reading then would be 0.2000 + 0.075 + 0.001, or .276 inch.

Metric system

Micrometer thimble reading 5.78mm

The spindle of an ordinary metric micrometer has 2 threads per millimetre, and thus one complete revolution moves the spindle through a distance of 0.5 millimetre. The longitudinal line on the frame is graduated with 1 millimetre divisions and 0.5 millimetre subdivisions. The thimble has 50 graduations, each being 0.01 millimetre (one-hundredth of a millimetre). Thus, the reading is given by the number of millimetre divisions visible on the scale of the sleeve plus the particular division on the thimble which coincides with the axial line on the sleeve.

Suppose that the thimble were screwed out so that graduation 5, and one additional 0.5 subdivision were visible (as shown in the image), and that graduation 28 on the thimble coincided with the axial line on the sleeve. The reading then would be 5.00 + 0.5 + 0.28 = 5.78 mm.

Vernier

Micrometer sleeve (with vernier) reading 5.783mm

Some micrometers are provided with a vernier scale on the sleeve in addition to the regular graduations. These permit measurements within 0.001 millimetre to be made on metric micrometers, or 0.0001 inches on inch-system micrometers.

The additional digit of these micrometers is obtained by finding the line on the sleeve vernier scale which exactly coincides with one on the thimble. The number of this coinciding vernier line represents the additional digit.

Thus, the reading for metric micrometers of this type is the number of whole millimetres (if any) and the number of hundredths of a millimetre, as with an ordinary micrometer, and the number of thousandths of a millimetre given by the coinciding vernier line on the sleeve vernier scale.

For example, a measurement of 5.783 millimetres would be obtained by reading 5.5 millimetres on the sleeve, and then adding 0.28 millimetre as determined by the thimble. The vernier would then be used to read the 0.003 (as shown in the image).

Inch micrometers are read in a similar fashion.

Note: 0.01 millimetre = 0.000393 inch, and 0.002 millimetre = 0.000078 inch (78 millionths) or alternately, 0.0001 inch = 0.00254 millimetres. Therefore, metric micrometers provide smaller measuring increments than comparable inch unit micrometers—the smallest graduation of an ordinary inch reading micrometer is 0.001 inch; the vernier type has graduations down to 0.0001 inch (0.00254 mm). When using either a metric or inch micrometer, without a vernier, smaller readings than those graduated may of course be obtained by visual interpolation between graduations.

Torque repeatability via torque-limiting ratchets or sleeves

An additional feature of many micrometers is the inclusion of a torque-limiting device on the thimble—either a spring-loaded ratchet or a friction sleeve. Without this device, workers may overtighten the micrometer on the work, causing the mechanical advantage of the screw to squeeze the material or tighten the screw threads, giving an inaccurate measurement. However, with a thimble that will ratchet or friction slip at a certain torque, the micrometer will not continue to advance once sufficient resistance is encountered. This results in greater accuracy and repeatability of measurements—most especially for low-skilled or semi-skilled workers, who may not have developed the light, consistent touch of a skilled user.

Testing and calibration

A standard ordinary one-inch micrometer has readout divisions of .001 inch and a rated accuracy of +/- .0001 inch. Both the measuring instrument and the object being measured should be at room temperature for an accurate measurement; dirt, abuse, and operator skill are the main sources of error.

The accuracy of micrometers is checked by using them to measure gauge blocks, rods, or similar standards whose lengths are precisely and accurately known. If the gauge block is known to be 0.7500" (± .00005"), then the micrometer should measure it as 0.7500". If the micrometer measures 0.7516", then it is out of calibration.

The accuracy of the gauge blocks themselves is traceable through a chain of comparisons back to a master standard, such as are maintained in measurement standards laboratories.

Chapter 8

Ring Gauge, Thread Pitch Gauge and Radius Gauge

Ring gauge

A **ring gauge**, or **ring gage**, is a cylindrical ring of steel whose inside diameter is finished to gauge tolerance and is used for checking the external diameter of a cylindrical object.

Ring gauges are used for comparative gauging as well as for checking, calibrating, or setting of gauges or other standards. Individual ring gauges or ring gauge sets are made to variety of tolerance grades in metric and English dimensions for master, setting, or working applications.

"Go" spline ring gage

There are three main types of ring gauges: go, no go, and master or setting ring gauges.

Go ring gauges provide a precision tool for production comparative gauging based on a fixed limit. Go gauges consist of a fixed limit gauge with a gauging limit based on the plus or minus tolerances of the inspected part. A go ring gauge's dimensions are based on the maximum OD tolerance of the round bar or part being gauged. A go plug gauge's dimensions are based on the minimum ID tolerance of the hole or part being gauged. The go plug (ID) gauge should be specified to a plus gaugemakers' tolerance from the minimum part tolerance. The go ring (OD) gauge should be specified to a minus gaugemakers' tolerance from the maximum part tolerance.

No-go or not-go gauges provide a precision tool for production comparative gauging based on a fixed limit. No-go gauges consist of a fixed limit gauge with a gauging limit based on the minimum or maximum tolerances of the inspected part. A no-go ring gauge's dimensions are based on the minimum OD tolerance of the round bar or part being gauged. The no go ring (OD) gauge should be specified to a plus gaugemakers' tolerance from the minimum part tolerance.

Master and setting ring gauges includes gauge blocks, master or setting discs, and setting rings are types of master gauges used to calibrate or set micrometers, optical comparators, or other gauging systems. Working gauges are used in the shop for dimensional inspection and periodically checked against a master gauge.

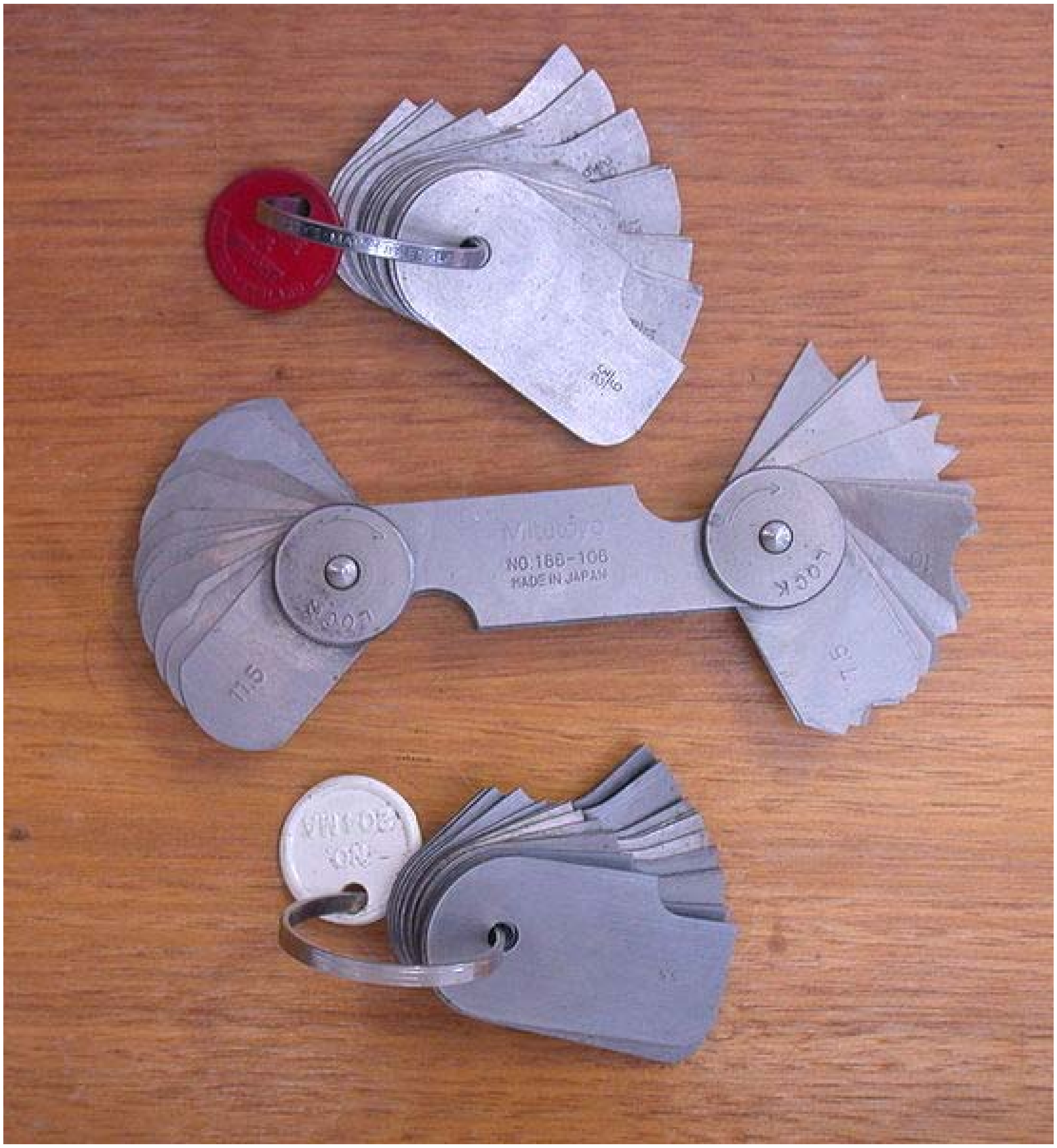
Thread pitch gauge

Three different sets of threading gauges

A **thread pitch gauge**, also known as a **screw pitch gauge** or **pitch gauge**, is used to measure the pitch or lead of a screw thread. The uppermost gauge in the image is an ISO metric pitch gauge, the larger gauge in the center is for measuring the Acme thread form, and the lower gauge is for Whitworth screws.

Thread pitch gauges are used as a reference tool in determining the pitch of a thread that is on a screw or in a tapped hole. This tool is not used as a precision measuring instrument. This device allows the user to determine the profile of the given thread and quickly categorize the thread by shape and pitch. This device also saves time, in that it removes the need for the user to measure and calculate the thread pitch of the threaded item.

Radius gauge



Two types of radius gauges

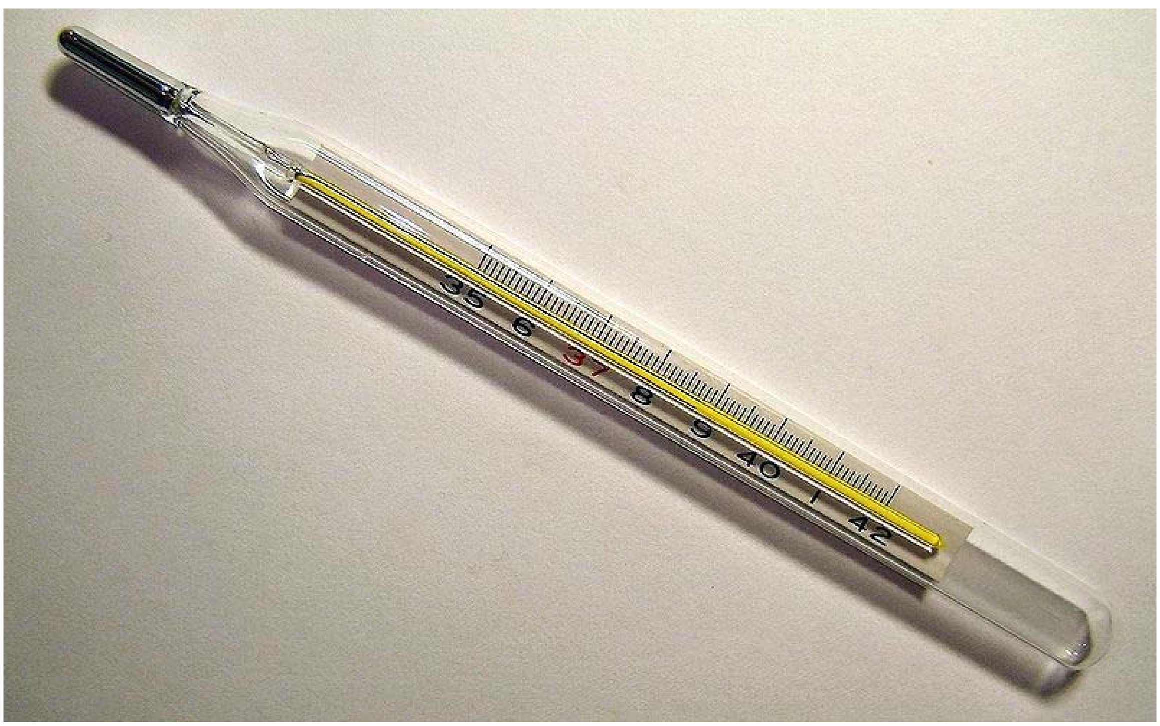
A **radius gauge**, also known as a **fillet gauge**, is a tool used to measure the radius of an object.

Radius gauges require a bright light behind the object to be measured. The gauge is placed against the edge to be checked and any light leakage between the blade and edge indicates a mismatch that requires correction.

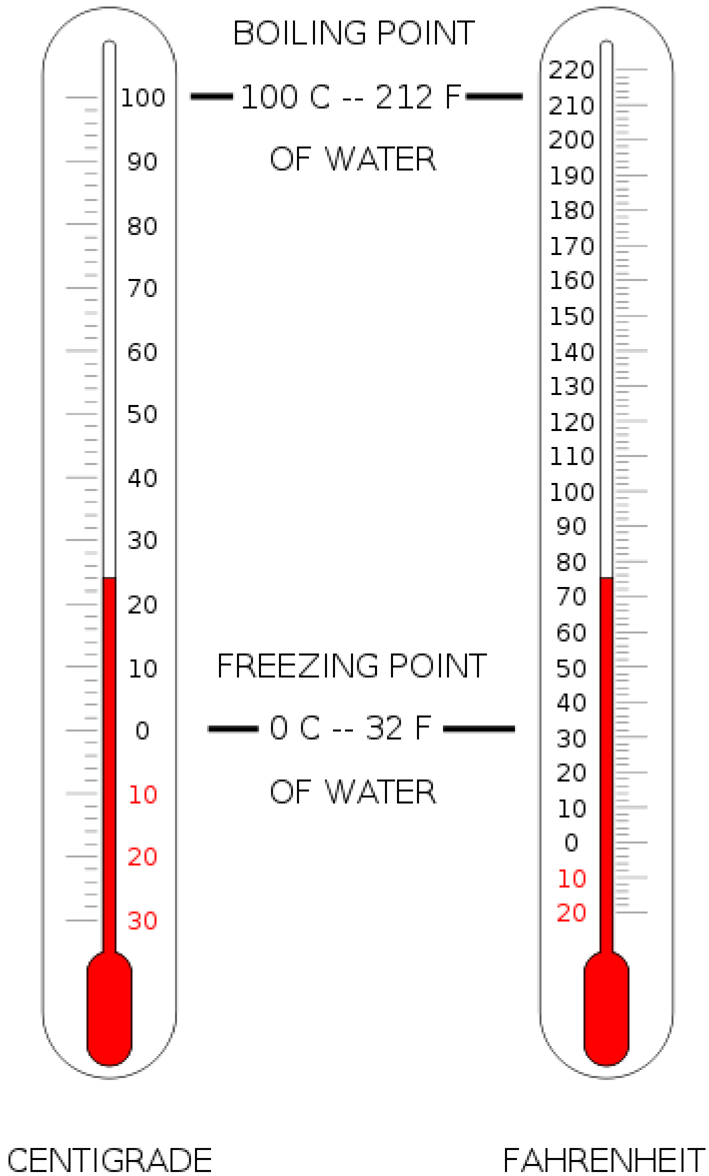
A good set of gauges will offer both convex and concave sections, and allow for their application in awkward locations.

Chapter 9

Thermometer



A clinical mercury-in-glass thermometer



Thermometer

A **thermometer** (from the Greek *θερμός* (*thermo*) meaning "warm" and *meter*, "to measure") is a device that measures temperature or temperature gradient using a variety of different principles. A thermometer has two important elements: the temperature sensor (e.g. the bulb on a mercury thermometer) in which some physical change occurs with temperature, plus some means of converting this physical change into a value (e.g. the scale on a mercury thermometer). Thermometers increasingly use electronic means to provide a digital display or input to a computer.

Primary and secondary thermometers

Thermometers can be divided into two separate groups according to the level of knowledge about the physical basis of the underlying thermodynamic laws and quantities. For **primary thermometers** the measured property of matter is known so well that temperature can be calculated without any unknown quantities. Examples of these are thermometers based on the equation of state of a gas, on the velocity of sound in a gas, on the thermal noise voltage or current of an electrical resistor, and on the angular anisotropy of gamma ray emission of certain radioactive nuclei in a magnetic field. Primary thermometers are relatively complex.

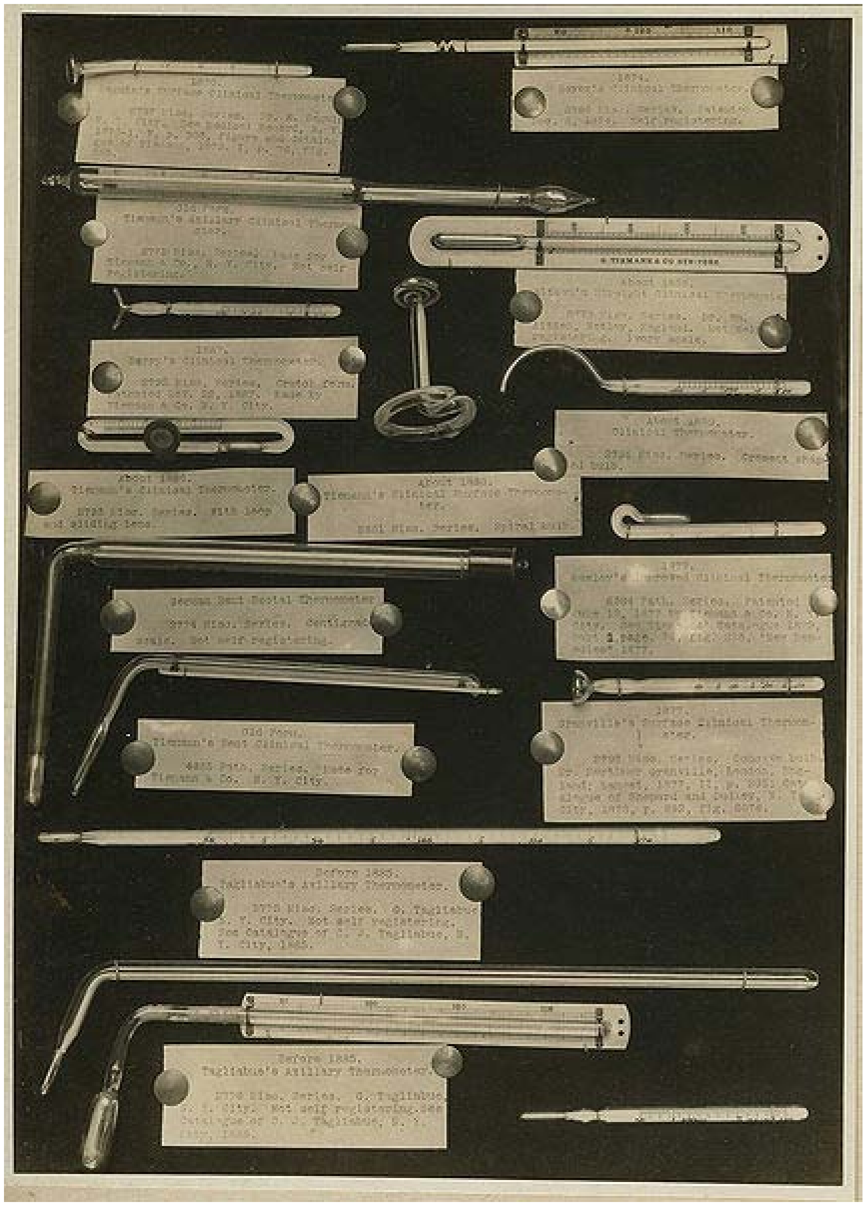
Secondary thermometers are most widely used because of their convenience. Also, they are often much more sensitive than primary ones. For secondary thermometers knowledge of the measured property is not sufficient to allow direct calculation of temperature. They have to be calibrated against a primary thermometer at least at one temperature or at a number of fixed temperatures. Such fixed points, for example, triple points and superconducting transitions, occur reproducibly at the same temperature.

Temperature

While an individual thermometer is able to measure degrees of hotness, the readings on two thermometers cannot be compared unless they conform to an agreed scale. There is today an absolute thermodynamic temperature scale. Internationally agreed temperature scales are designed to approximate this closely, based on fixed points and interpolating thermometers. The most recent official temperature scale is the International Temperature Scale of 1990. It extends from 0.65 K (−272.5 °C; −458.5 °F) to approximately 1,358 K (1,085 °C; 1,985 °F).

Development

Galileo thermometer



Various thermometers from the 19th century.

Various authors have credited the invention of the thermometer to Cornelius Drebbel, Robert Fludd, Galileo Galilei or Santorio Santorio. The thermometer was not a single invention, however, but a development.

Philo of Byzantium and Hero of Alexandria knew of the principle that certain substances, notably air, expand and contract and described a demonstration in which a closed tube partially filled with air had its end in a container of water. The expansion and contraction of the air caused the position of the water/air interface to move along the tube.

Such a mechanism was later used to show the hotness and coldness of the air with a tube in which the water level is controlled by the expansion and contraction of the air. These devices were developed by several European scientists in the 16th and 17th centuries, notably Galileo Galilei. As a result, devices were shown to produce this effect reliably, and the term *thermoscope* was adopted because it reflected the changes in sensible heat (the concept of temperature was yet to arise). The difference between a thermoscope and a thermometer is that the latter has a scale. Though Galileo is often said to be the inventor of the thermometer, what he produced were thermoscopes.

Galileo Galilei also discovered that objects (glass spheres filled with aqueous alcohol) of slightly different densities would rise and fall, which is nowadays the principle of the Galileo thermometer (shown). Today such thermometers are calibrated to a temperature scale.

The first clear diagram of a thermoscope was published in 1617 by Giuseppe Biancani: the first showing a scale and thus constituting a thermometer was by Robert Fludd in 1638. This was a vertical tube, with a bulb at the top and the end immersed in water. The water level in the tube is controlled by the expansion and contraction of the air, so it is what we would now call an air thermometer.

The first person to put a scale on a thermoscope is variously said to be Francesco Sagredo or Santorio Santorio in about 1611 to 1613.

The word thermometer (in its French form) first appeared in 1624 in *La Récréation Mathématique* by J. Leurechon, who describes one with a scale of 8 degrees.

The above instruments suffered from the disadvantage that they were also barometers, i.e. sensitive to air pressure. In about 1654 Ferdinando II de' Medici, Grand Duke of Tuscany, made sealed tubes part filled with alcohol, with a bulb and stem, the first modern-style thermometer, depending on the expansion of a liquid, and independent of air pressure. Many other scientists experimented with various liquids and designs of thermometer.

However, each inventor and each thermometer was unique—there was no standard scale. In 1665 Christiaan Huygens suggested using the melting and boiling points of water as standards, and in 1694 Carlo Renaldini proposed using them as fixed points on a universal scale. In 1701 Isaac Newton proposed a scale of 12 degrees between the melting point of ice and body temperature. Finally in 1724 Daniel Gabriel Fahrenheit produced a temperature scale which now (slightly adjusted) bears his name. He could do this because he manufactured thermometers, using mercury (which has a high coefficient of expansion) for the first time and the quality of his production could provide a finer scale and greater reproducibility, leading to its general adoption. In 1742 Anders Celsius proposed a scale with zero at the boiling point and 100 degrees at the melting point of water, though the scale which now bears his name has them the other way around.

In 1866 Sir Thomas Clifford Allbutt invented a clinical thermometer that produced a body temperature reading in five minutes as opposed to twenty. In 1999 Dr. Francesco Pompei of the Exergen Corporation introduced the world's first temporal artery thermometer, a non-invasive temperature sensor which scans the forehead in about 2 seconds and provides a medically accurate body temperature.

Old thermometers were all **non-registering thermometers**. That is, the thermometer did not hold the temperature after it was moved to a place with a different temperature. Determining the temperature of a pot of hot liquid required the user to leave the thermometer in the hot liquid until after reading it. If the non-registering thermometer was removed from the hot liquid, then the temperature indicated on the thermometer would immediately begin changing to reflect the temperature of its new conditions (in this case, the air temperature). **Registering thermometers** are designed to hold the temperature indefinitely, so that the thermometer can be removed and read at a later time or in a more convenient place. Mechanical registering thermometers hold either the highest or lowest temperature recorded, until manually re-set, e.g., by shaking down a mercury-in-glass thermometer, or until an even more extreme temperature is experienced. Electronic registering thermometers may be designed to remember the highest or lowest temperature, or to remember whatever temperature was present at a specified point in time.

Calibration

Mercury-in-glass thermometer

Thermometers can be calibrated either by comparing them with other calibrated thermometers or by checking them against known fixed points on the temperature scale. The best known of these fixed points are the melting and boiling points of pure water. (Note that the boiling point of water varies with pressure, so this must be controlled.)

The traditional method of putting a scale on a liquid-in-glass or liquid-in-metal thermometer was in three stages:

1. Immerse the sensing portion in a stirred mixture of pure ice and water at 1 Standard atmosphere (101.325 kPa ; 760.0 mmHg) and mark the point indicated when it had come to thermal equilibrium.
2. Immerse the sensing portion in a steam bath at 1 Standard atmosphere (101.325 kPa ; 760.0 mmHg) and again mark the point indicated.
3. Divide the distance between these marks into equal portions according to the temperature scale being used.

Other fixed points were used in the past are the body temperature (of a healthy adult male) which was originally used by Fahrenheit as his upper fixed point (96 °F (36 °C) to be a number divisible by 12) and the lowest temperature given by a mixture of salt and ice, which was originally the definition of 0 °F (−18 °C). (This is an example of a Frigorific mixture). As body temperature varies, the Fahrenheit scale was later changed to use an upper fixed point of boiling water at 212 °F (100 °C).

These have now been replaced by the defining points in the International Temperature Scale of 1990, though in practice the melting point of water is more commonly used than its triple point, the latter being more difficult to manage and thus restricted to critical standard measurement. Nowadays manufacturers will often use a thermostat bath or solid block where the temperature is held constant relative to a calibrated thermometer. Other thermometers to be calibrated are put into the same bath or block and allowed to come to equilibrium, then the scale marked, or any deviation from the instrument scale recorded. For many modern devices calibration will be stating some value to be used in processing an electronic signal to convert it to a temperature.

Precision, accuracy, and reproducibility

The "*Boyce MotoMeter*" radiator cap on a 1913 Car-Nation automobile, used to measure temperature of vapor in 1910s and 1920s cars.

The **precision** or **resolution** of a thermometer is simply to what fraction of a degree it is possible to make a reading. For high temperature work it may only be possible to measure to the nearest 10°C or more. Clinical thermometers and many electronic thermometers are usually readable to 0.1°C. Special instruments can give readings to one thousandth of a degree. However, this precision does not mean the reading is true or accurate.

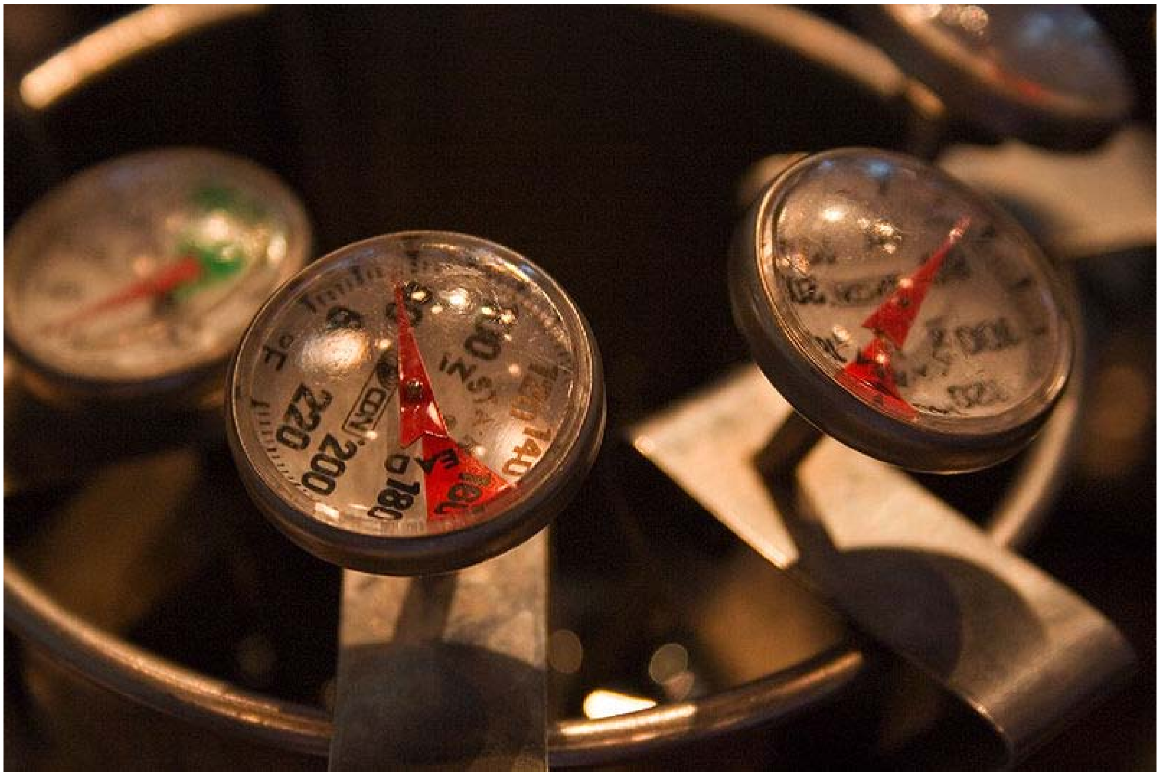
Thermometers which are calibrated to known fixed points (e.g. 0 and 100°C) will be **accurate** (i.e. will give a true reading) at those points. Most thermometers are originally calibrated to a constant-volume gas thermometer. In between a process of interpolation is used, generally a linear one. This may give significant differences between different types of thermometer at points far away from the fixed points. For example the expansion of mercury in a glass thermometer is slightly different from the change in resistance of a platinum resistance of the thermometer, so these will disagree slightly at around 50°C. There may be other causes due to imperfections in the instrument, e.g. in a liquid-in-glass thermometer if the capillary varies in diameter.

For many purposes **reproducibility** is important. That is, does the same thermometer give the same reading for the same temperature (or do replacement or multiple thermometers give the same reading)? Reproducible temperature measurement means that comparisons are valid in scientific experiments and industrial processes are consistent. Thus if the same type of thermometer is calibrated in the same way its readings will be valid even if it is slightly inaccurate compared to the absolute scale.

An example of a reference thermometer used to check others to industrial standards would be a platinum resistance thermometer with a digital display to 0.1°C (its precision) which has been calibrated at 5 points against national standards (-18, 0, 40, 70, 100°C) and which is certified to an accuracy of ±0.2°C.

According to a British Standard, correctly calibrated, used and maintained liquid-in-glass thermometers can achieve a measurement uncertainty of ±0.01°C in the range 0 to 100°C, and a larger uncertainty outside this range: ±0.05°C up to 200 or down to -40°C, ±0.2°C up to 450 or down to -80°C.

Uses



Bi-metallic stem thermometers used to measure the temperature of steamed milk

There are a number of uses for thermometers. Thermometers have been built which utilize a range of physical effects to measure temperature. Temperature sensors are used in a wide variety of scientific and engineering applications, especially measurement systems. Temperature systems are primarily either electrical or mechanical, occasionally inseparable from the system which they control (as in the case of a mercury-in-glass thermometer). Alcohol thermometers, [[infrared thermometer]]s, mercury-in-glass thermometers, recording thermometers, thermistors, and Six's thermometers are used outside in areas which are well-exposed to the elements at various levels of the Earth's atmosphere and within the Earth's oceans is necessary within the fields of meteorology and climatology. Airplanes use thermometers and hygrometers to determine if atmospheric icing conditions exist along their flight path, and these measurements are used to initialize weather forecast models. Thermometers are used within roadways in cold weather climates to help determine if icing conditions exist. Indoors, thermistors are used in climate control systems such as air conditioners, freezers, heaters, refrigerators, and water heaters. Galileo thermometers are used to measure indoor air temperature, due to their limited measurement range.

Bi-metallic stemmed thermometers, thermocouples, infrared thermometers, and thermisters are handy during cooking in order to know if meat has been properly cooked. Temperature of food is important because if it sits within environments with a temperature between 5 °C (41 °F) and 57 °C (135 °F) for four hours or more, bacteria can multiply leading to foodborne illnesses. Thermometers are used in the production of candy. Medical thermometers such as mercury-in-glass thermometers, infrared thermometers, pill thermometers, and liquid crystal thermometers are used within health care to determine if individuals have a fever or are hypothermic. Liquid crystal thermometers can also be used to measure the temperature of water in fish tanks. Fiber Bragg grating temperature sensors are used within nuclear power facilities to monitor reactor core temperatures and avoid the possibility of nuclear meltdowns.

Other types of thermometers

- Beckmann differential thermometer
- Bi-metal mechanical thermometer
- Coulomb blockade thermometer
- Galileo thermometer
- Resistance thermometer
- Reversing thermometer
- Silicon bandgap temperature sensor
- Phosphor thermometry

*[[Alcohol thermometer]]

Chapter 10

Go/no Go Gauge

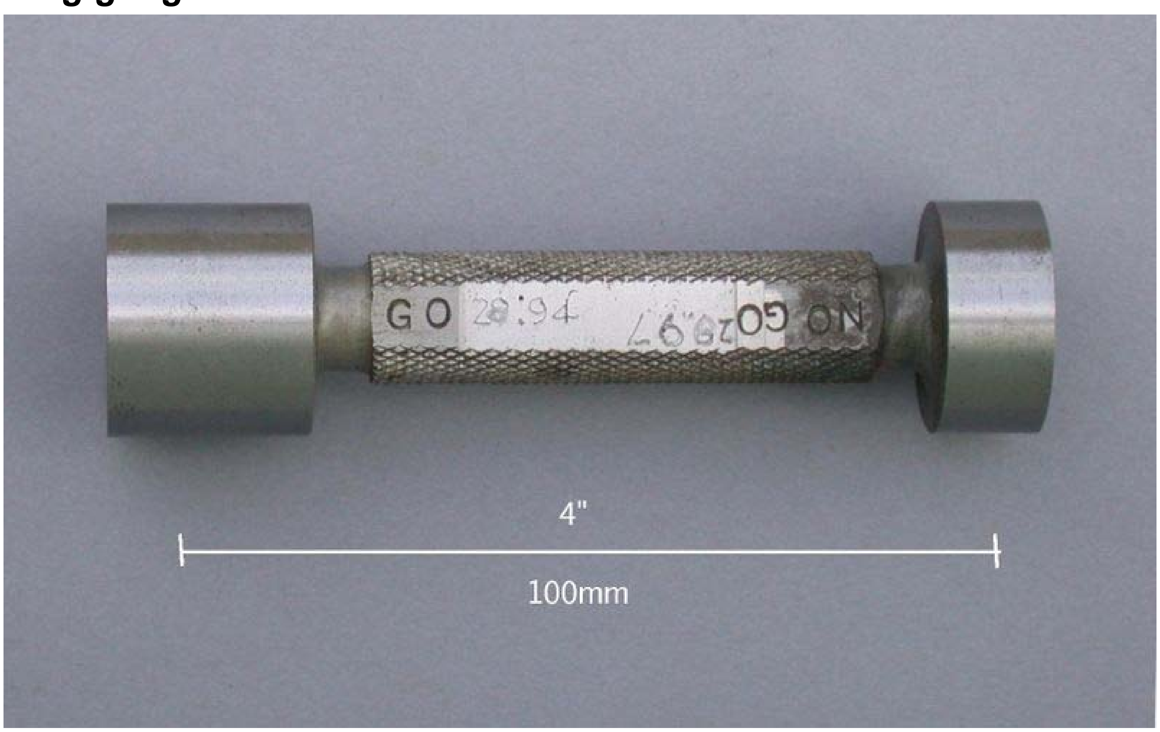
A **Go-NoGo gauge** (or **Go/no go**) refers to an inspection tool used to check a workpiece against its allowed tolerances. Its name derives from its use: the gauge has two tests; the check involves the workpiece having to **pass** one test (*Go*) and **fail** the other (*No Go*).

It is an integral part of the quality process that is used in the manufacturing industry to ensure interchangeability of parts between processes, or even between different manufacturers.

A Go NoGo gauge is a measuring tool that does not return a *size* in the conventional sense, but instead returns a *state*. The *state* is either acceptable (the part is within tolerance and may be used) or it is unacceptable (and must be rejected).

They are well suited for use in the production area of the factory as they require little skill or interpretation to use effectively and have few, if any, moving parts to be damaged in the often hostile production environment.

Plug gauge



Hardened and ground plug gauge

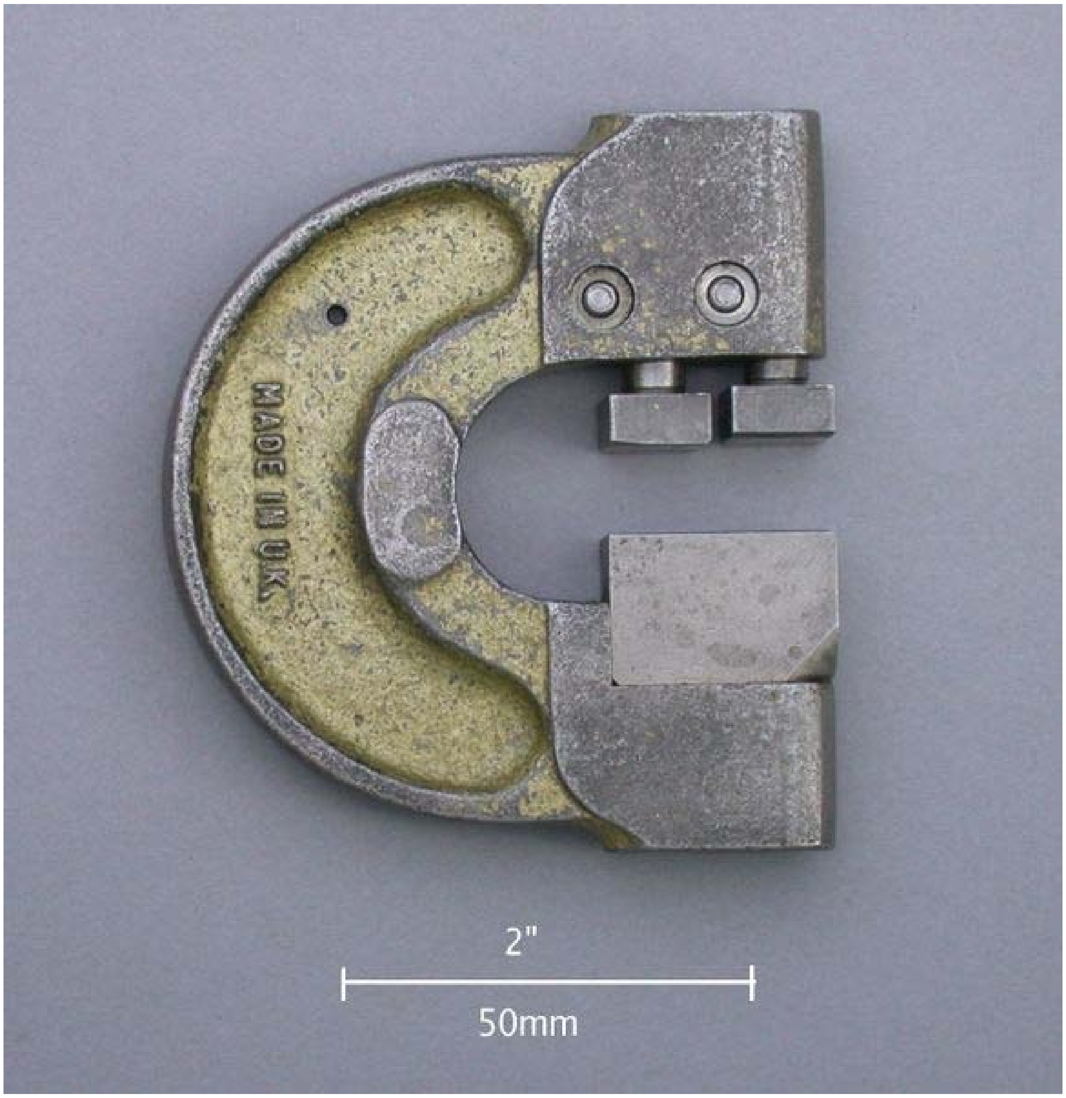
Replaceable thread and plug gauges

These gauges are referred to as plug gauges; they are used in the manner of a plug. They are generally assembled from standard parts where the gauge portion is interchangeable with other gauge pieces (obtained from a set of pin type gauge blocks) and a body that uses the collet principle to hold the gauges firmly. To use this style of gauge, one end is inserted into the part first and depending on the result of that test, the other end is tried.

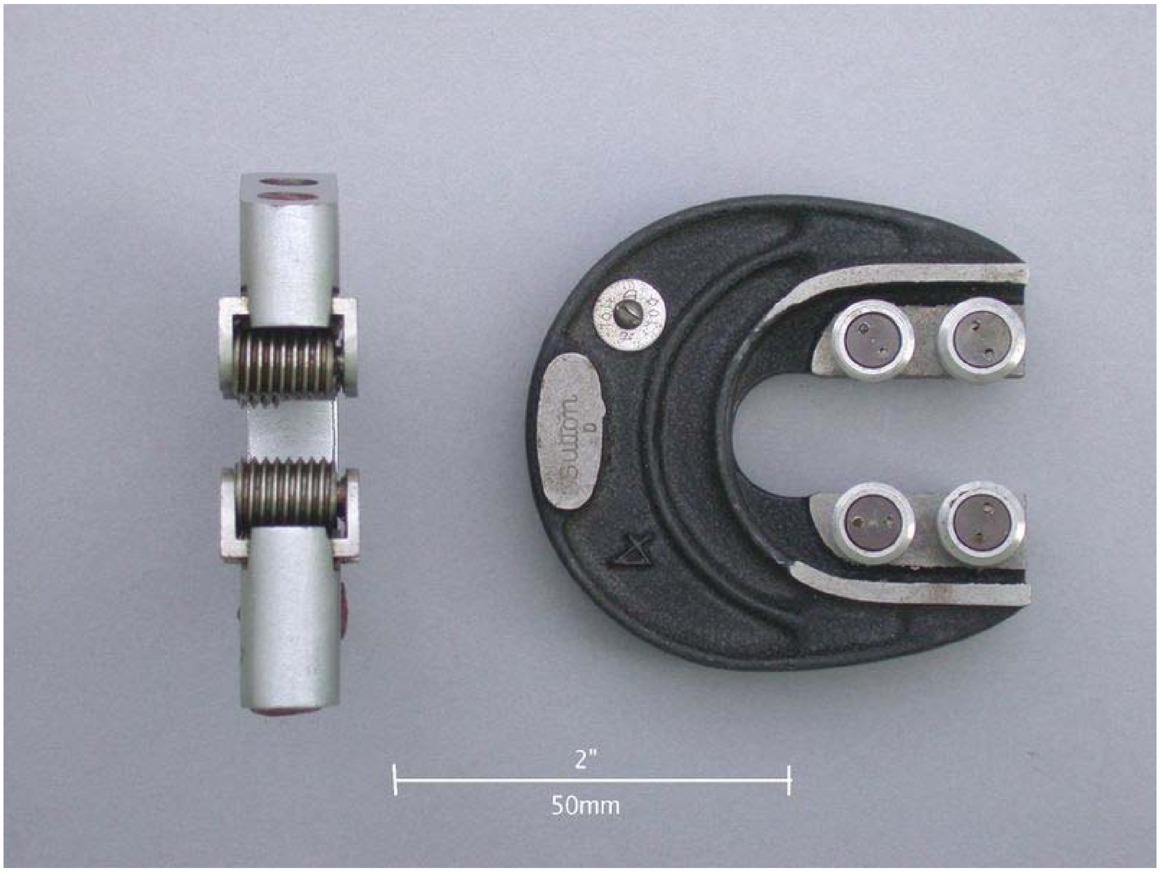
In the right hand image, the top gauge is a thread gauge that is screwed into the part to be tested, the labeled *GO* end will enter into the part fully, the *NOT GO* end should not. The lower image is a plain plug gauge used to check the size of a hole, the green end is the *GO*, red is the *NO GO*. The tolerance of the part this gauge checks is 0.30mm where the lower size of the hole is 12.60mm and the upper size is 12.90mm, every size outside this range is *out of tolerance*. This may be initially expressed on the parts drawing in a number of styles, three possibilities may be:

- 12.75mm +/- 0.15mm
- 12.60mm +0.30 -0.00
- 12.90mm +0.00 -0.30

Snap gauge



Snap go/no go gauge for the OD of a cylindrical workpiece



Thread snap gauge

Snap gauges (or snap gage) are oftentimes used when a large quantity of workpieces must be inspected. The snap gauge has four *anvils* or *jaws*, the first one or pair (outermost) are set using the upper limit (tolerance) of the part and the inner set adjusted to the lower limit of the part. A correctly machined part will pass the first set of jaws and stop at the second — end of test. In this manner a part may be checked in one action, unlike the plug gauge that needs to be used twice and flipped to access the second gauge.

Other styles

Once the concept is understood, the principle of operation can lead to all manner of designs where internal grooves, keyways, splines etc. may be measured in a simple yet effective manner. These will often be made to order by the toolmakers, or a related skilled tradesman.

Chapter 11

Height Gauge

The left height gauge has the vernier scale, while the right one is an electronic height gauge with a digital readout.

A **height gauge** is a measuring device used either for determining the height of something, or for repetitious marking of items to be worked on. The former type of height gauge is often used in doctor's surgeries to find the height of people.

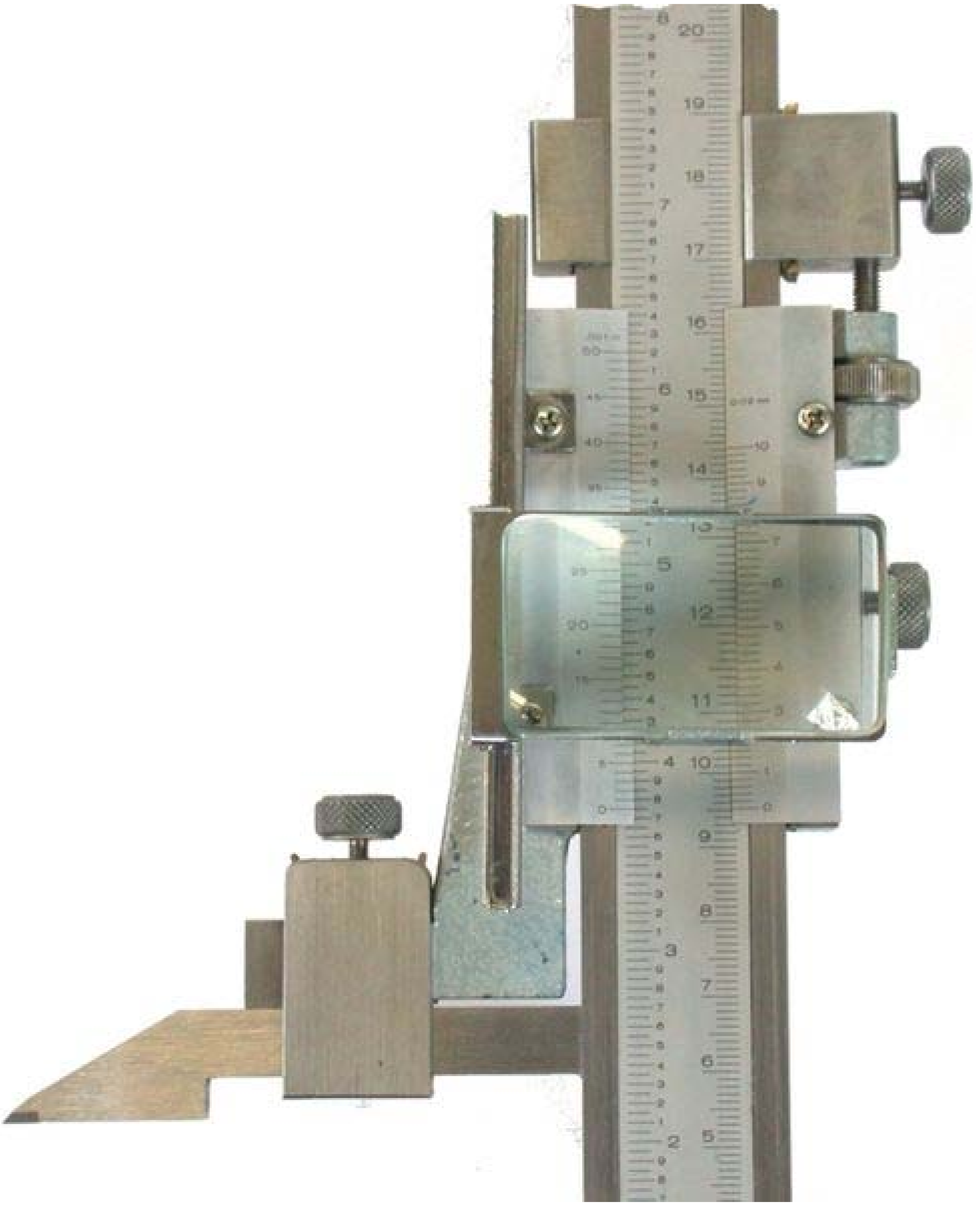
These measuring tools are used in metalworking or metrology to either set or measure vertical distances; the pointer is sharpened to allow it to act as a scriber and assist in marking out work pieces.

They may also be used to measure the height of an object by using the underside of the scriber as the datum. The datum may be permanently fixed or the height gauge may have provision to adjust the scale, this is done by sliding the scale vertically along the body of the height gauge by turning a fine feed screw at the top of the gauge; then with the scriber set to the same level as the base, the scale can be matched to it. This adjustment allows different scribers or probes to be used, as well as adjusting for any errors in a damaged or resharpened probe.

Types

There are two types of height gauges: *Vernier height gauges* and *electronic height gauges*. The vernier height gauge has the additional refinement of a vernier scale for greater accuracy in reading or setting the tool. The electronic height gauge has a digital readout that gives the height.

Vernier height gauge adjusters, close up view



Vernier height gauge, close up view

Electronic height gauge, close up view

Chapter 12

Stubs Iron Wire Gauge and Sight Glass

Stubs Iron Wire Gauge

The **Stubs Iron Wire Gauge** system (also known as the **Birmingham Wire Gauge**) is used used to specify thickness or diameter of metal wire, strip, and tube products. The Stubs system was the first wire gauge recognized as a standard by any country when Great Britain adopted it in 1884.

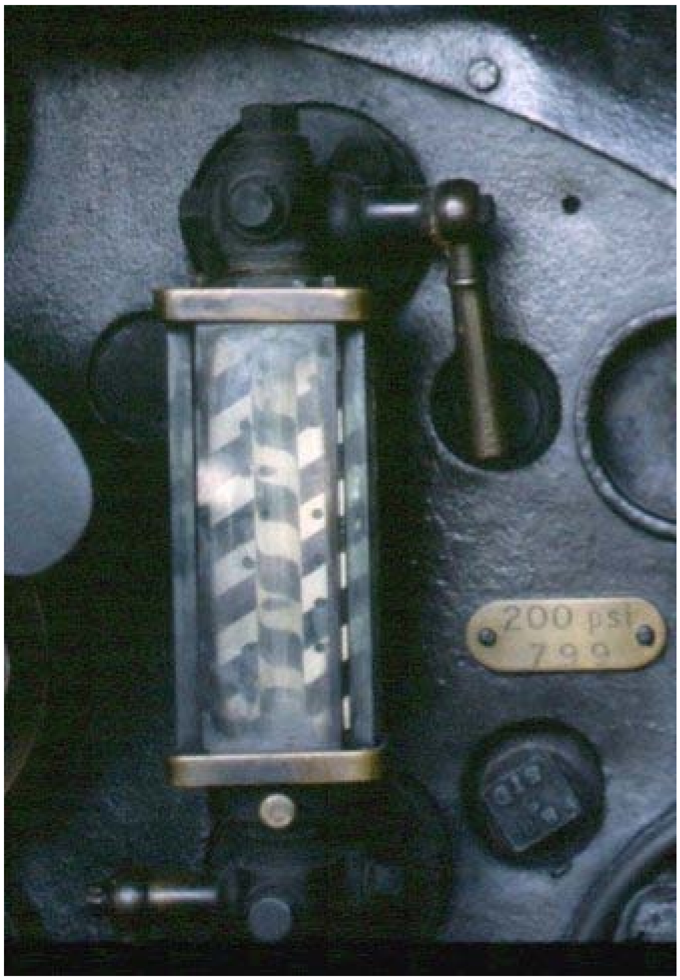
The gauge starts at the lowest gauge number of 5Ø or 00000, corresponding to the largest size of 0.500" (12.7mm) to the highest gauge number of 26, corresponding to the smallest size of 0.018" (0.46mm). Size steps between gauges range from .002" between high gauge numbers to .046" between low gauge numbers and do not correspond to a particular mathematical pattern, although for the most part the steps get smaller as the gauge number goes up. Concerning wire and fine tubing, the gauge number is used to specify the outside diameter of the product, whereas for larger mechanical tubing the gauge number specifies the wall thickness independent of the overall size of the tube.

In medicine, the Stubs system specifies the outside diameter of hypodermic needles, catheters, and suture wires. It was originally developed in early 19th-century England for use in wire manufacture, and it began appearing in a medical setting in the early 20th century.

Another common needle gauge system is the French catheter scale.

A common approximation used for medical needles is diameter (in inches) is equal to the reciprocal of the gauge. In other words, a 23g is really 1/23 of an inch (in lumen diameter of the needle).

Sight glass



Water gauge on a steam locomotive. Here the water is at the “top nut”, the maximum working level. Note the patterned backplate to help reading and toughened glass shroud.

A **sight glass** or **water gauge** is a transparent tube through which the operator of a tank or boiler can observe the level of liquid contained within.

Liquid in tanks

Simple sight glasses may be just a plastic or glass tube connected to the bottom of the tank at one end and the top of the tank at the other. The level of liquid in the sight glass will be the same as the level of liquid in the tank. Today, however, sophisticated float switches have replaced sight glasses in many such applications.

Steam boilers

If the liquid is hazardous or under pressure, more sophisticated arrangements must be made. In the case of a boiler, the pressure of the water below and the steam above is equal, so any change in the water level will be seen in the gauge. The transparent tube (the “glass” itself) may be mostly enclosed within a metal or toughened glass shroud to prevent it from being damaged through scratching or impact and offering protection to the operators in the case of breakage. This usually has a patterned backplate to make the magnifying effect of the water in the tube more obvious and so allow for easier reading. In some locomotives where the boiler operated at very high pressures, the tube itself would be made of metal-reinforced toughened glass. It is important to keep the water at the specified level, otherwise the top of the firebox will be exposed, creating an overheat hazard and causing damage and possibly catastrophic failure.

To check that the device is offering a correct reading and the connecting pipes to the boiler are not blocked by scale, the water level needs to be “bobbed” by quickly opening the taps in turn and allowing a brief spurt of water through the drain cock.

Failure

The gauge glass on a boiler needs to be inspected periodically and replaced if it is seen to have worn thin in the vicinity of the gland nuts, but a failure in service can still occur. Drivers are expected to carry two or three glass tubes, pre-cut to the required length, together with hemp or rubber seals, to replace the tubes on the road. Familiarity with this disquieting occurrence was considered so important that a glass would often be smashed deliberately while a trainee driver was on the footplate, to give them practice in fitting a new tube. Although automatic ball valves are fitted in the mounts to limit the release of steam and scalding water, these can fail through accumulation of limescale. It was standard procedure to hold the coal scoop in front of the face while the other hand, holding the cap for protection, reached to turn off the valves at both ends of the glass.

Repair of a broken glass

The following is the generally accepted procedure of safely fitting a new tubular glass on a steam boiler in industrial applications. Leather work gloves and a full face shield should be worn while working with the glass; this to prevent burns, cuts, and protect the operator's eyesight.

1. Shut both the valves and open the glass drain cock
2. Loosen and remove both gland nuts
3. Remove any broken glass or other debris from glass valve body
4. Place gland nuts and new seals on the precut glass

5. Install glass in upper valve first and loosely tighten the nut. Pull glass down to bottom so that the gap in upper and lower valve body is even (this allows for expansion of the glass)
6. Hand tighten both nuts, and then using a wrench, give each nut an additional quarter turn.
7. Crack open steam side valve and allow the steam to lightly blow through to warm the glass. This prevents the glass from being subject to sudden thermal shock. (Should the glass be subject to thermal shock the effects may not be noticed immediately. However, the glass may then be much more brittle and even a slight bump might shatter it.)
8. Close drain valve and crack open valve on water side of glass
9. Observe gland for leakage and tighten as required
10. Open both valves fully.

Reflex Gauges

A reflex gauge is more complex in construction but can give a clearer distinction between gas (steam) and liquid (water). Instead of containing the media in a glass tube, the gauge consists of a vertically-oriented slotted metal body with a strong glass plate mounted on the open side of the slot facing the operator. The rear of the glass, in contact with the media, has grooves moulded into its surface, running vertically. The grooves form a zig-zag pattern with 90° angles. Incident light entering the glass is refracted at the rear surface in contact with the media. In the region that is contact with the gas, most of the light is reflected from the surface of one groove to the next and back towards the operator, appearing silvery white. In the region that is in contact with the liquid, most of the light is refracted into the liquid causing this region to appear almost black to the operator. Well-known makes of reflex gauge are Penberthy, Jerguson, Klinger, and Cesare-Bonetti. Due to the caustic nature of boiler anti-scaling treatments ("water softeners"), reflex gauges tend to become relatively rapidly etched by the water and lose their effectivess at displaying the liquid level. Therefore, bi-colour gauges are recommended for certain types of boiler, particularly those operating at pressure above 60 bar.

Bi-Colour Gauges

A bi-colour gauge is generally preferred for caustic media in order to afford protection to the glass. The gauge consists of a vertically-oriented slotted metal body with a strong plain glass to the front and the rear. The front and rear body surfaces are in non-parallel vertical planes. Behind the gauge body are light sources with two quite different wavelengths, typically red and green. Due to the different refraction of the red and green light, the liquid region appears green to the operator, while the gas region appears red. Unlike the reflex gauge, the glass has a plane surface which it does not need to be in direct contact with the media and can be protected with a layer of a caustic-resistant transparent material such as silica.

Magnetic Gauges

In a magnetic gauge a float on the surface of the liquid contains a permanent magnet. The liquid is contained in a chamber of strong, non-magnetic material avoiding the use of glass. The level indicator consists of a number of pivoting magnetic vanes arranged one above the other and placed close to the chamber containing the float. The two faces of the vanes are differently coloured. As the magnet passes up and down behind the vanes it cause them to rotate, displaying one colour for the region containing the liquid and another for the region containing gas. Magnetic gauges are stated in various manufacturers' literature to be most suitable for very high pressure and / or temperature and for aggressive liquids.

History

The first locomotive to be fitted with the device was built in 1829 by John Rastrick at his Stourbridge works.

Modern Industrial Sight Glass

A Fused-glass Sight Glass

Industrial observational instruments have changed with industry itself. More structurally sophisticated than the water gauge, the contemporary sight glass — also called the sight window or sight port — can be found on the media vessel at chemical plants and in other industrial settings, including pharmaceutical, food, beverage and bio gas plants. Sight glasses enable operators to visually observe processes inside tanks, pipes, reactors and vessels. The modern industrial sight glass is a glass disk held between two metal frames, which are secured by bolts and gaskets, or the glass disc is fused to the metal frame during manufacture. The glass used for this purpose is either soda lime glass or borosilicate glass, and the metal, usually a type of stainless steel, is chosen for desired properties of strength. Borosilicate glass is superior to other formulations in terms of chemical corrosion resistance and temperature tolerance, as well as transparency. Fused sight glasses are also called mechanically prestressed glass, because the glass is strengthened by compression of the metal ring. Heat is applied to a glass disc and its surrounding steel ring, causing a fusion of the materials. As the steel cools, it contracts, compressing the glass and making it resistant to tension. Because glass typically breaks under tension, mechanically prestressed glass is unlikely to break and endanger workers. The strongest sight glasses are made with borosilicate glass, because of the greater difference in its coefficient of expansion.

Chapter 13

ANOVA Gauge R&R and Air Core Gauge

ANOVA Gauge R&R

ANOVA Gauge R&R (or ANOVA Gauge Repeatability & Reproducibility) is a Measurement Systems Analysis technique which uses Analysis of Variance (ANOVA) random effects model to assess a measurement system.

The evaluation of a measurement system is *not* limited to gauges (or gages) but to all types of measuring instruments, test methods, and other measurement systems.

Purpose

ANOVA Gauge R&R measures the amount of variability induced in measurements by the measurement system itself, and compares it to the total variability observed to determine the viability of the measurement system. There are several factors affecting a measurement system, including:

- **Measuring instruments**, the gauge or instrument itself and all mounting blocks, supports, fixtures, load cells, etc. The machine's ease of use, sloppiness among mating parts, and, "zero" blocks are examples of sources of variation in the measurement system. In systems making electrical measurements, sources of variation include electrical noise and analog-to-digital converter resolution.

- **Operators (people)**, the ability and/or discipline of a person to follow the written or verbal instructions.

- **Test methods**, how the devices are set up, the test fixtures, how the data is recorded, etc.

- **Specification**, the measurement is reported against a specification or a reference value. The range or the engineering tolerance does not affect the measurement, but is an important factor in evaluating the viability of the measurement system.

- **Parts** or specimens (what is being measured), some items are easier to be measured than others. A measurement system may be good for measuring steel block length but not for measuring rubber pieces, for example.

There are two important aspects of a Gauge R&R:

- **Repeatability**: The variation in measurements taken by a single person or instrument on the same item and under the same conditions.
- **Reproducibility**: The variability induced by the operators. It is the variation induced when different operators (or different laboratories) measure the same part.

It is important to understand the difference between accuracy and precision to understand the purpose of Gauge R&R. Gauge R&R addresses only the precision of a measurement system. It is common to examine the **P/T ratio** which is the ratio of the precision of a measurement system to the (total) tolerance of the manufacturing process of which it is a part. If the P/T ratio is low, the impact on product quality of variation due to the measurement system is small. If the P/T ratio is larger, it means the measurement system is "eating up" a large fraction of the tolerance, in that the parts that do not have sufficient tolerance may be measured as acceptable by the measurement system. Generally, a P/T ratio less than 0.1 indicates that the measurement system can reliably determine whether any given part meets the tolerance specification. A P/T ratio greater than 0.3 suggests that unacceptable parts will be measured as acceptable (or vice-versa) by the measurement system, making the system inappropriate for the process for which it is being used.

Anova Gauge R&R is an important tool within the Six Sigma methodology, and it is also a requirement for a Production Part Approval Process (PPAP) documentation package.

How to perform a Gauge R&R

The Gauge R&R (GRR) is performed by measuring parts using the established measurement system. The goal is to capture as many sources of measurement variation as possible, so they can be assessed and understood. Please note that the objective is not for the parts to "pass". A small variation (a favorable result) might result from a GRR study because an important source of error was missed in the process.

To capture reproducibility errors, multiple operators are needed. Some (ASTM E691 Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method) call for at least ten operators (or laboratories) but others use only two or three to measure the same parts.

To capture repeatability errors, the same part is usually measured several times by each operator. Each measurement cycle on an individual part must include the full set of operations required if the operator were testing multiple different parts, including the complete handling, loading, and unloading of the part from the measurement system.

To capture interactions of operators with parts (e.g. one part may be more difficult to measure than another), usually between five and ten parts are measured.

There is not a universal criterion of minimum sample requirements for the GRR matrix, it being a matter for the Quality Engineer to assess risks depending on how critical the measurement is and how costly they are. The "10x2x2" (ten parts, two operators, two repetitions) is an acceptable sampling for some studies, although it has very few degrees of freedom for the operator component. Several methods of determining the sample size and degree of replication are used.

Air core gauge

An auto tachometer has a sweep of about 240-250 degrees and typically uses an air core gauge.

An **air core gauge** is a specific type of rotary actuator in an analog display gauge that allows an indicator to rotate a full 360 degrees. It is used in gauges and displays, most commonly automotive instrument clusters.

A typical automotive application is shown at the right. The air core gauge is a type of "air-core motor". It may be considered a "gauge movement" or "pointer indication device".

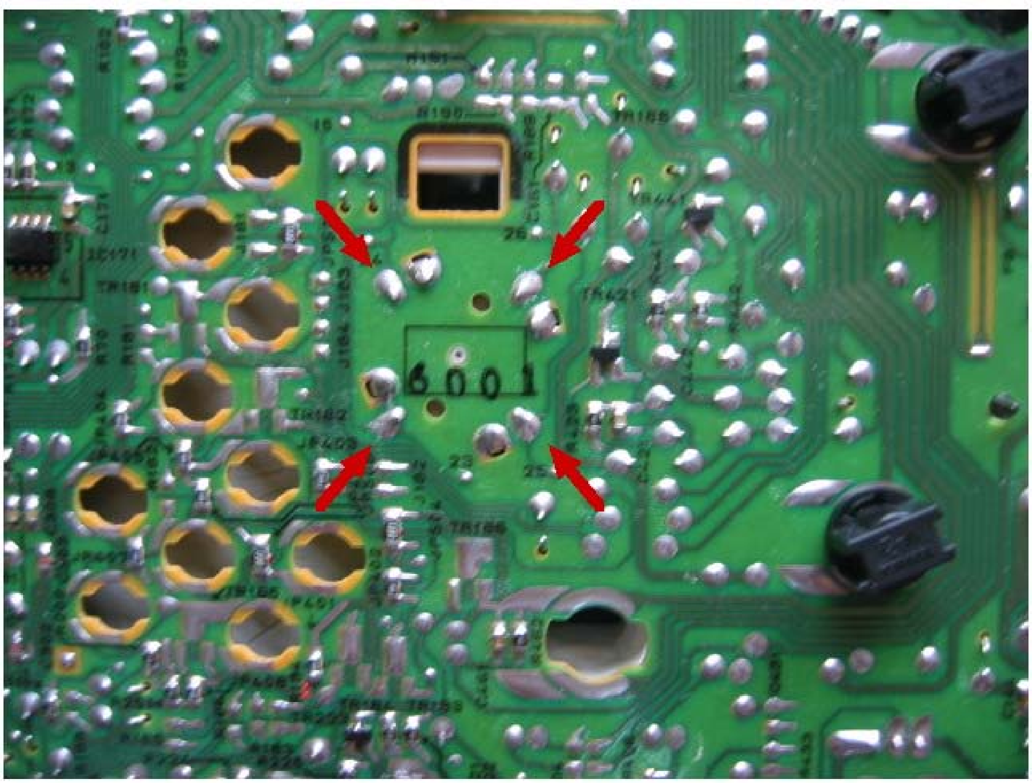
Background

There are four common types of rotary actuators :

- Physical gauges, in which the needle is attached directly to the value being measured; for example, a mechanical pressure gauge
- Analog volt meters or d'Arsonval movements, which consist of a coil and a permanent magnet
- Stepper motors, which move in one-notch increments or steps
- Air-core motors, as described below.

Construction and operation

The air core gauge consists of two independent, perpendicular coils surrounding a hollow chamber. A needle shaft protrudes into the chamber, where a permanent magnet is affixed to the shaft. When current flows through the perpendicular coils, their magnetic fields superimpose and the magnet is free to align with the combined fields.



Back side of an auto instrument cluster showing four mounting terminals for an air core gauge.

A typical air core gauge has four terminals, two for each coil, as shown. The two coils are identified as the sine coil and the cosine coil.

Theory

The direction θ of the overall magnetic field is approximately:

$$\theta = \arctan\left(\frac{y}{x}\right)$$

Where *x* and *y* are the coils' respective currents. The permanent magnet aligns itself with that field, eventually settling near θ. In this way, by proportioning the current through each coil, the needle can reach all 360° of rotation.

Example

If the sin coil current is 50 mA and the cos current is 29 mA:

The coil current ratio is 0.58, and arctan 0.58 = 30 degrees.

Drivers

Air core gauges require special electronics to properly drive the coils. Driver integrated circuits typically have a serial input data port and two pair of output lines. One pair of the output lines drives the sin coil and one pair drives the cos coil.

The input data defines:

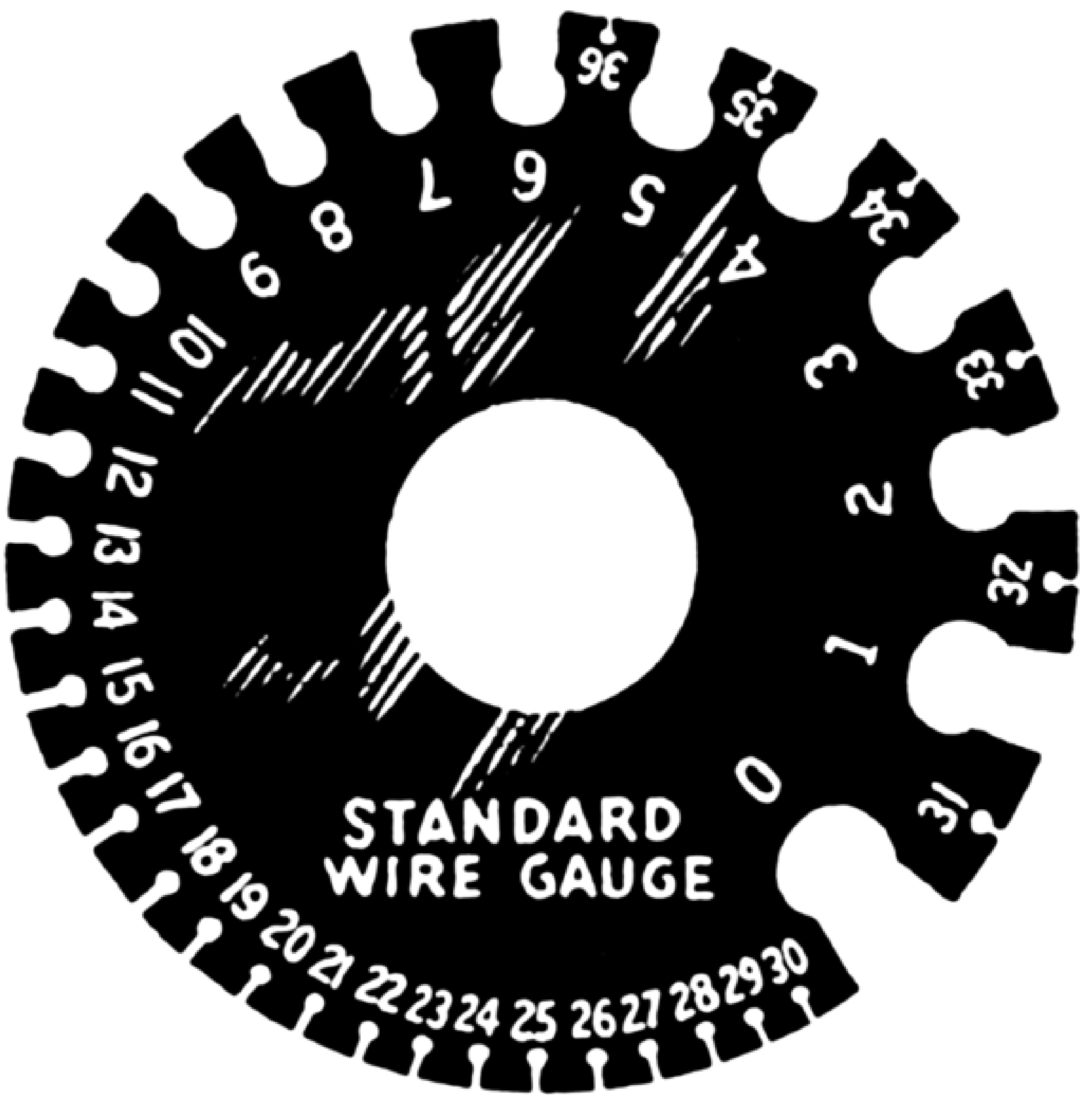
- The quadrant to which the actuator will point. This defines the polarity of the voltage to the sin coil and the cos coil.
- The desired number of degrees within the quadrant.

Some typical driver ICs include:

- On Semiconductor CS4172 16 pin dual inline package
- On Semiconductor CS4192 surface mount package
- Melexis MLX10407
- Melexis MLX10420

Chapter 14

American Wire Gauge



A standard wire gauge.

American wire gauge (**AWG**), also known as the **Brown & Sharpe wire gauge**, is a standardized wire gauge system used since 1857 predominantly in the United States and Canada for the diameters of round, solid, nonferrous, electrically conducting wire. The cross-sectional area of each gauge is an important factor for determining its current-carrying capacity.

The steel industry uses different wire gauges (for example, W&M Wire Gauge or US Steel Wire Gauge, or Music Wire Gauge). The table below does not apply to steel wire.

Increasing gauge numbers give decreasing wire diameters, which is similar to many other non-metric gauging systems. This gauge system originated in the number of drawing operations used to produce a given gauge of wire. Very fine wire (for example, 30 gauge) requires more passes through the drawing dies than does 0 gauge wire. Manufacturers of wire formerly had proprietary wire gauge systems; the development of standardized wire gauges rationalized selection of wire for a particular purpose.

The AWG tables are for a single, solid, round conductor. The AWG of a stranded wire is determined by the total cross-sectional area of the conductor, which determines its current-carrying capacity and electrical resistance. Because there are also small gaps between the strands, a stranded wire will always have a slightly larger overall diameter than a solid wire with the same AWG.

AWG is also commonly used to specify body piercing jewelry sizes, especially smaller sizes.

Formula

By definition, No. 36 AWG is 0.0050 inches in diameter, and No. 0000 is 0.4600 inches in diameter. The ratio of these diameters is 92, and there are 40 gauge sizes from No. 36 to No. 0000, or 39 steps. Using this common ratio, wire gauge sizes vary geometrically according to the following formula: The diameter of a No. *n* AWG wire is

$$d_n = 0.005 \text{ inch} \times 92^{\frac{36-n}{39}} = 0.127 \text{ mm} \times 92^{\frac{36-n}{39}}$$

or equivalently

$$d_n = e^{-1.12436-0.11594n} \text{ inch} = e^{2.1104-0.11594n} \text{ mm}$$

The gauge can be calculated from the diameter using

$$n = -39\log_{92}\left(\frac{d_n}{0.005 \text{ inch}}\right) + 36 = -39\log_{92}\left(\frac{d_n}{0.127 \text{ mm}}\right) + 36$$

and the cross-section area is

$$A_n = \frac{\pi}{4} d_n^2 = 0.000019635\ \text{inch}^2 \times 92^{\frac{36-n}{19.5}} = 0.012668\ \text{mm}^2 \times 92^{\frac{36-n}{19.5}},$$

The ASTM B 258-02 standard defines the ratio between successive sizes to be the 39th root of 92, or approximately 1.1229322. ASTM B 258-02 also dictates that wire diameters should be tabulated with no more than 4 significant figures, with a resolution of no more than 0.0001 inches (0.1 mils) for wires larger than No. 44 AWG, and 0.00001 inches (0.01 mils) for wires No. 45 AWG and smaller.

Sizes with multiple zeros are successively larger than No. 0 and can be denoted using "*number of zeros*/0", for example 4/0 for 0000. For an *m*/0 AWG wire, use $n = -(m-1) = 1-m$ in the above formulas. For instance, for No. 0000 or 4/0, use n = −3.

Rules of thumb

The sixth power of this ratio is very close to 2, which leads to the following rules of thumb:

- When the *diameter* of a wire is doubled, the AWG will decrease by 6. (e.g., No. 2 AWG is about twice the diameter of No. 8 AWG.)
- When the *cross-sectional area* of a wire is doubled, the AWG will decrease by 3. (e.g., Two No. 14 AWG wires have about the same cross-sectional area as a single No. 11 AWG wire.)

Additionally, a decrease of ten gauge numbers, for example from No. 10 to 1/0, multiplies the area and weight by approximately 10 and reduces the resistance by a factor of approximately 10.

Table of AWG wire sizes

The table below shows various data including both the resistance of the various wire gauges and the allowable current (ampacity) based on plastic insulation. The diameter information in the table applies to *solid* wires. Stranded wires are calculated by calculating the equivalent cross sectional copper area. Fusing Current (melting wire) is estimated based on 25°C. The table below assumes DC, or AC frequencies equal to or less than 60 Hz, and **does not** take skin effect into account. Turns of wire is on a best-case scenario when winding tightly packed coils with no insulation.

AWG	Diameter		Turns of wire		Area		Copper resistance		NEC copper wire ampacity with 60/75	Approximate stranded metric equiv	Fusing Current (copper)		
	(inch)	(mm)	(per inch)	(per cm)	(kcmil)	(mm²)	(Ω/km)	(Ω/kFT)			Preece (~10s)	Onderdonk (1s)	Onderdonk (32ms)

									/ 90°C insulation (A)	alents			
0000 (4/0)	0.4600	11.684	2.17	0.856	212	107	0.1608	0.04901	195 / 230 / 260			31KA	173KA
000 (3/0)	0.4096	10.404	2.44	0.961	168	85.0	0.2028	0.06180	165 / 200 / 225			24.5KA	137KA
00 (2/0)	0.3648	9.266	2.74	1.08	133	67.4	0.2557	0.07793	145 / 175 / 195			19.5KA	109KA
0 (1/0)	0.3249	8.252	3.08	1.21	106	53.5	0.3224	0.09827	125 / 150 / 170		1.9KA	15.5KA	87KA
1	0.2893	7.348	3.46	1.36	83.7	42.4	0.4066	0.1239	110 / 130 / 150		1.6KA	12KA	68KA
2	0.2576	6.544	3.88	1.53	66.4	33.6	0.5127	0.1563	95 / 115 / 130		1.3KA	9.7KA	54KA
3	0.2294	5.827	4.36	1.72	52.6	26.7	0.6465	0.1970	85 / 100 / 110	196/0.4	1.1KA	7.7KA	43KA
4	0.2043	5.189	4.89	1.93	41.7	21.2	0.8152	0.2485	70 / 85 / 95		946A	6.1KA	34KA
5	0.1819	4.621	5.50	2.16	33.1	16.8	1.028	0.3133		126/0.4	795A	4.8KA	27KA
6	0.1620	4.115	6.17	2.43	26.3	13.3	1.296	0.3951	55 / 65 / 75		668A	3.8KA	21KA
7	0.1443	3.665	6.93	2.73	20.8	10.5	1.634	0.4982		80/0.4	561A	3KA	17KA
8	0.1285	3.264	7.78	3.06	16.5	8.37	2.061	0.6282	40 / 50 / 55		472A	2.4KA	13.5KA
9	0.1144	2.906	8.74	3.44	13.1	6.63	2.599	0.7921			396A	1.9KA	10.7KA
10	0.1019	2.588	9.81	3.86	10.4	5.26	3.277	0.9989	30 / 35 / 40	84/0.3	333A	1.5KA	8.5KA
11	0.09	2.30	11.	4.34	8.23	4.17	4.13	1.260		56/0.3	280A	1.2K	6.7KA

	07	5	0				2					A	
12	0.0808	2.053	12.4	4.87	6.53	3.31	5.211	1.588	25 / 25 / 30		235A	955A	5.3KA
13	0.0720	1.828	13.9	5.47	5.18	2.62	6.571	2.003		50/0.25	198A	758A	4.2KA
14	0.0641	1.628	15.6	6.14	4.11	2.08	8.286	2.525	20 / 20 / 25		166A	601A	3.3KA
15	0.0571	1.450	17.5	6.90	3.26	1.65	10.45	3.184			140A	477A	2.7KA
16	0.0508	1.291	19.7	7.75	2.58	1.31	13.17	4.016	— / — / 18	30/0.25	117A	377A	2.1KA
17	0.0453	1.150	22.1	8.70	2.05	1.04	16.61	5.064		32/0.2	99A	300A	1.7KA
18	0.0403	1.024	24.8	9.77	1.62	0.823	20.95	6.385	— / — / 14	24/0.2	83A	237A	1.3KA
19	0.0359	0.912	27.9	11.0	1.29	0.653	26.42	8.051			70A	189A	1KA
20	0.0320	0.812	31.3	12.3	1.02	0.518	33.31	10.15		16/0.2	58.5A	149A	834A
21	0.0285	0.723	35.1	13.8	0.810	0.410	42.00	12.80		13/0.2	49A	119A	662A
22	0.0253	0.644	39.5	15.5	0.642	0.326	52.96	16.14		7/0.25	41A	94A	525A
23	0.0226	0.573	44.3	17.4	0.509	0.258	66.79	20.36			35A	74A	416A
24	0.0201	0.511	49.7	19.6	0.404	0.205	84.22	25.67		1/0.5, 7/0.2, 30/0.1	29A	59A	330A
25	0.0179	0.455	55.9	22.0	0.320	0.162	106.2	32.37			24A	47A	262A
26	0.0159	0.405	62.7	24.7	0.254	0.129	133.9	40.81		7/0.15	20A	37A	208A
27	0.0142	0.361	70.4	27.7	0.202	0.102	168.9	51.47					
28	0.0126	0.321	79.1	31.1	0.160	0.0810	212.9	64.90					
29	0.0113	0.286	88.8	35.0	0.127	0.0642	268.5	81.84					
30	0.0100	0.255	99.7	39.3	0.101	0.0509	338.6	103.2		1/0.25, 7/0.1			

31	0.00893	0.227	112	44.1	0.0797	0.0404	426.9	130.1		
32	0.00795	0.202	126	49.5	0.0632	0.0320	538.3	164.1		1/0.2, 7/0.08
33	0.00708	0.180	141	55.6	0.0501	0.0254	678.8	206.9		
34	0.00630	0.160	159	62.4	0.0398	0.0201	856.0	260.9		
35	0.00561	0.143	178	70.1	0.0315	0.0160	1079	329.0		
36	0.00500	0.127	200	78.7	0.0250	0.0127	1361	414.8		
37	0.00445	0.113	225	88.4	0.0198	0.0100	1716	523.1		
38	0.00397	0.101	252	99.3	0.0157	0.00797	2164	659.6		
39	0.00353	0.0897	283	111	0.0125	0.00632	2729	831.8		
40	0.00314	0.0799	318	125	0.00989	0.00501	3441	1049		

The "Approximate stranded metric equivalents" column lists commonly available cables in the format "number of strands / diameter of individual strand (mm)" which is the common nomenclature describing cable construction within an overall cross-sectional area. Some common metric cables are midway between two AWG sizes. Cables sold in Europe are normally labeled according to the combined cross section of all strands in mm², which can be compared directly with the *Area* column.

In the North American electrical industry, conductors larger than 4/0 AWG are generally identified by the area in thousands of circular mils (**kcmil**), where 1 kcmil = 0.5067 mm². A *circular mil* is the area of a wire one mil in diameter. One million circular mils is the area of a circle with 1000 mil = 1 inch diameter. An older abbreviation for one thousand circular mils is *MCM*.

Outside North America, wire sizes for electrical power installation purposes are usually given as the cross sectional area in square millimeters. International standard manufacturing sizes for conductors in electrical cables are defined in IEC 60228.

Nomenclature and abbreviations in electrical distribution

Alternate ways are commonly used in the electrical industry to specify wire sizes as AWG.

- **4 AWG** (proper)

    - **#4** (the pound sign is used as an abbreviation for "number")
    - **No. 4** (No. is used as an abbreviation for "number")
    - **No. 4 AWG**
    - **4 ga.** (abbreviation for "gauge")

- **000 AWG** (proper for large sizes)

    - **3/0** (common for large sizes)
    - **3/0 AWG**
    - **#000**

Any of these may be followed by the type or composition of the wire, such as:

- Copper or Cu
- Aluminum or Al
- Solid
- Stranded

The industry also bundles common wire for use in electrical distribution in homes and businesses, identifying a bundle's wire size followed by the number of wires in the bundle, e.g.:

- #12/2 with ground is a nonmetallic sheathed bundle of three solid AWG 12 wires.
- #14/3 with ground is a nonmetallic sheathed bundle of four solid AWG 14 wires.