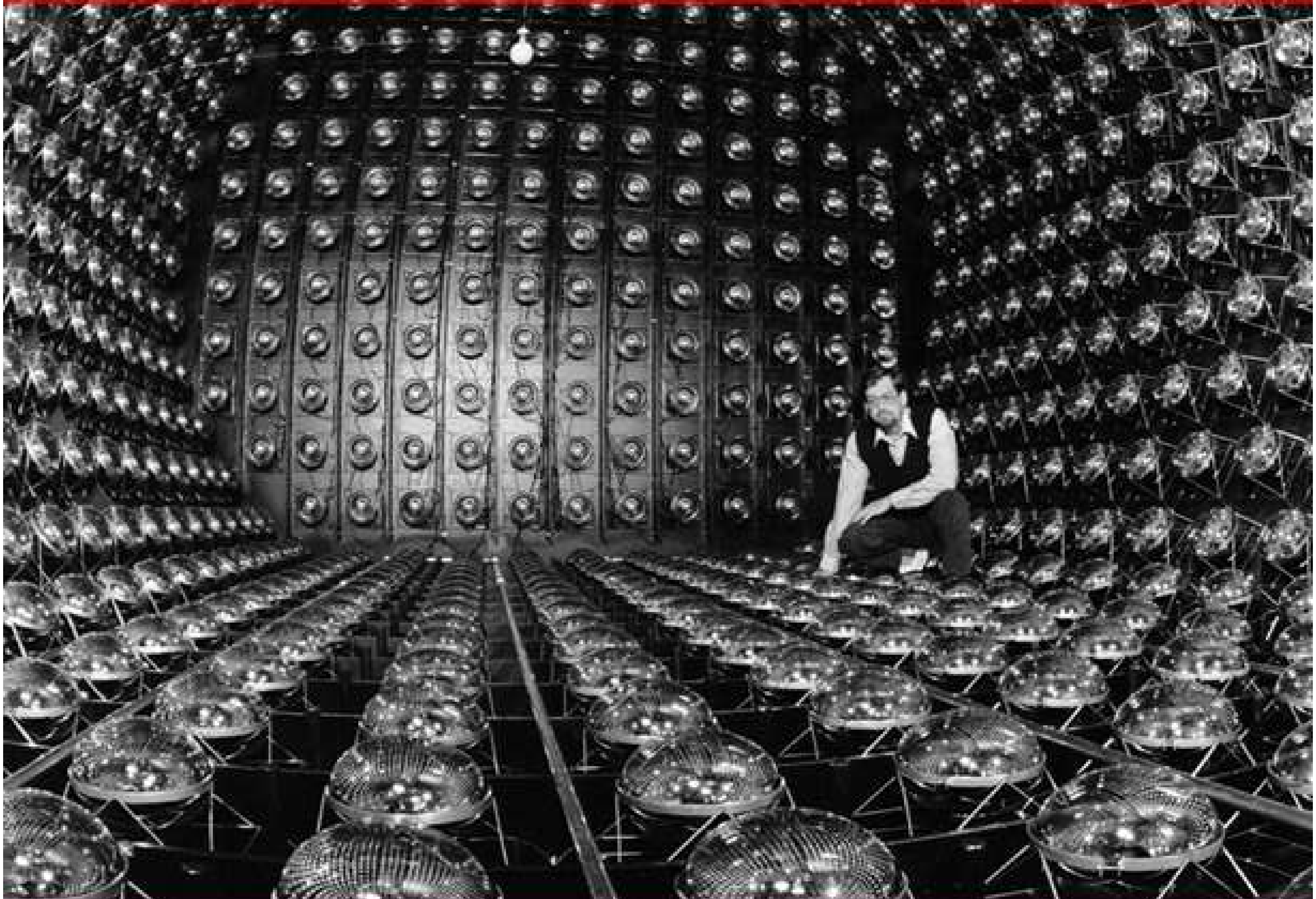
Detectors and Sensors

(Devices and Instruments)



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Metal Detector

A U.S. Army soldier uses a metal detector to search for weapons and ammunition in Iraq

A **metal detector** is a device which responds to metal that may not be readily apparent.

The simplest form of a metal detector consists of an oscillator producing an alternating current that passes through a coil producing an alternating magnetic field. If a piece of electrically conductive metal is close to the coil, eddy currents will be induced in the metal, and this produces an alternating magnetic field of its own. If another coil is used to measure the magnetic field (acting as a magnetometer), the change in the magnetic field due to the metallic object can be detected.

The first industrial metal detectors were developed in the 1960s and were used extensively for mining and other industrial applications. Uses include de-mining (the detection of land mines), the detection of weapons such as knives and guns, especially in airport security, geophysical prospecting, archaeology and treasure hunting. Metal detectors are also used to detect foreign bodies in food, and in the construction industry to detect steel reinforcing bars in concrete and pipes and wires buried in walls and floors.

History and development

Toward the end of the 19th century, many scientists and engineers used their growing knowledge of electrical theory in an attempt to devise a machine which would pinpoint metal. The use of such a device to find ore-bearing rocks would give a huge advantage to any miner who employed it. The German physicist Heinrich Wilhelm Dove invented the induction balance system, which was incorporated into metal detectors a hundred years later. Early machines were crude, used a lot of battery power, and worked only to a very limited degree. Alexander Graham Bell used such a device to attempt to locate a bullet lodged in the chest of American President James Garfield in 1881; the attempt was unsuccessful because the metal coil spring bed Garfield was lying on confused the detector.

Modern developments

The modern development of the metal detector began in the 1930s. Gerhard Fisher had developed a system of radio direction-finding, which was to be used for accurate navigation. The system worked extremely well, but Fisher noticed that there were anomalies in areas where the terrain contained ore-bearing rocks. He reasoned that if a radio beam could be distorted by metal, then it should be possible to design a machine which would detect metal using a search coil resonating at a radio frequency. In 1937 he applied for, and was granted, the first patent for a metal detector. However, it was one Lieutenant Jozef Stanislaw Kosacki, a Polish officer attached to a unit stationed in St Andrews, Fife, Scotland, during the early years of World War II, who refined the design into a practical Polish mine detector. They were heavy, ran on vacuum tubes, and needed separate battery packs.

The design invented by Kosacki was used extensively during the clearance of the German mine fields during the Second Battle of El Alamein when 500 units were shipped to Field Marshal Montgomery to clear the minefields of the retreating Germans, and later used during the Allied invasion of Sicily, the Allied invasion of Italy and the Invasion of Normandy. As it was a wartime research operation to create and refine the design of the detector, the knowledge that Kosacki created the first practical metal detector was kept secret for over 50 years.

After the war, there were plenty of surplus mine detectors on the market; they were bought up by relic hunters who used them for fun and profit. This helped to form metal detecting into a hobby.

Further refinements

Many manufacturers of these new devices brought their own ideas to the market. Whites Electronics of Oregon began in the '50s by building a machine called the Oremaster Geiger Counter. Another leader in detector technology was Charles Garrett, who pioneered the BFO (Beat Frequency Oscillator) machine. With the invention and development of the transistor in the '50s and '60s, metal detector manufacturers and designers made smaller lighter machines with improved circuitry, running on small battery packs. Companies sprang up all over the USA and Britain to supply the growing demand.

Modern top models are fully computerized, using integrated circuit technology to allow the user to set sensitivity, discrimination, track speed, threshold volume, notch filters, etc., and hold these parameters in memory for future use. Compared to just a decade ago, detectors are lighter, deeper-seeking, use less battery power, and discriminate better.

Larger portable metal detectors are used by archaeologists and treasure hunters to locate metallic items, such as jewelry, coins, bullets, and other various artifacts buried shallowly underground.

Discriminators

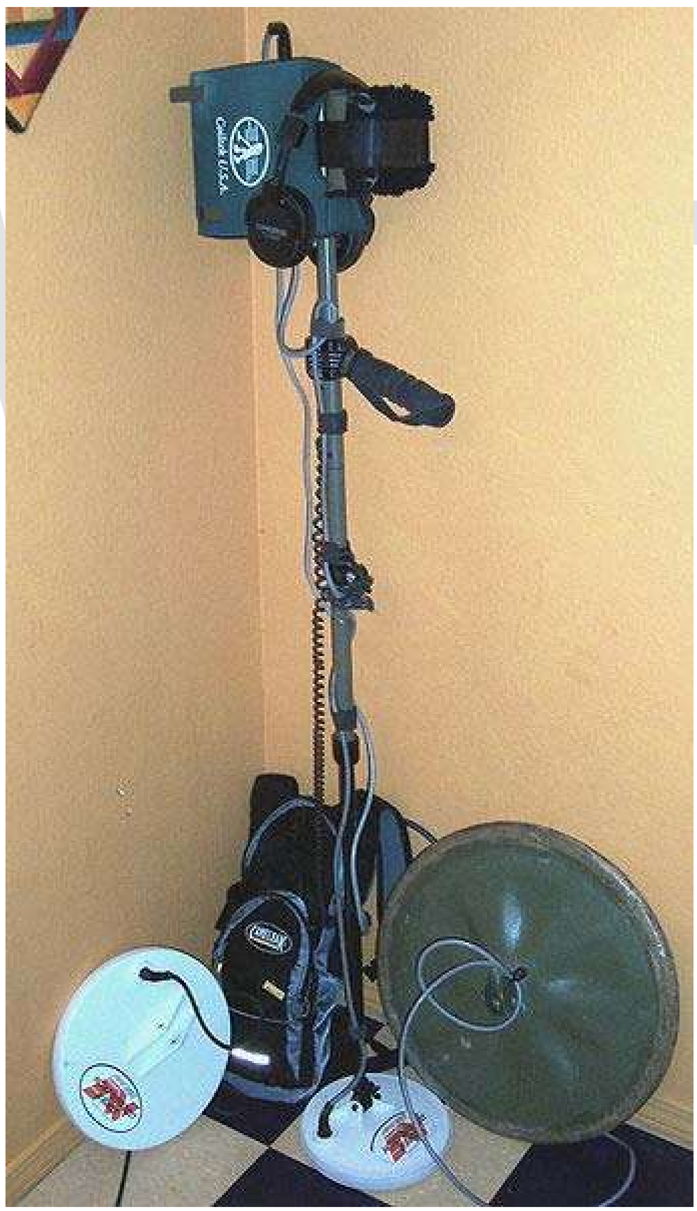
The biggest technical change in detectors was the development of the induction-balance system. This system involved two coils that were electrically balanced. When metal was introduced to their vicinity, they would become unbalanced. What allowed detectors to discriminate between metals was the fact that every metal has a different phase response when exposed to alternating current. Scientists had long known of this fact by the time detectors were developed that could selectively detect desirable metals, while ignoring undesirable ones.

Even with discriminators, it was still a challenge to avoid undesirable metals, because some of them have similar phase responses e.g. tinfoil and gold, particularly in alloy form. Thus, improperly tuning out certain metals increased the risk of passing over a valuable find. Another disadvantage of discriminators was that they reduced the sensitivity of the machines.

New coil designs

Coil designers also tried out innovative designs. The original induction balance coil system consisted of two identical coils placed on top of one another. Compass Electronics produced a new design: two coils in a D shape, mounted back-to-back to form a circle. This system was widely used in the 1970s, and both concentric and D type (or widescan as they became known) had their fans. Another development was the invention of detectors which could cancel out the effect of mineralization in the ground. This gave greater depth, but was a non-discriminate mode. It worked best at lower frequencies than those used before, and frequencies of 3 to 20 kHz were found to produce the best results. Many detectors in the 1970s had a switch which enabled the user to switch between the discriminate mode and the non-discriminate mode. Later developments switched electronically between both modes. The development of the induction balance detector would ultimately result in the motion detector, which constantly checked and balanced the background mineralization.

Pulse induction



A pulse induction metal detector with an array of coils

At the same time, developers were looking at using a different technique in metal detection called Pulse Induction. Unlike the Beat Frequency Oscillator or the Induction Balance machines which both used a uniform alternating current at a low frequency, the pulse induction machine simply fired a high-voltage pulse of signal into the ground. In the absence of metal, the 'spike' decayed at a uniform rate, and the time it took to fall to zero volts could be accurately measured. However, if metal was present when the machine fired, a small current would flow in the metal, and the time for the voltage to drop to zero would be increased. These time differences were minute, but the improvement in electronics made it possible to measure them accurately and identify the presence of metal at a reasonable distance. These new machines had one major advantage: they were completely impervious to the effects of mineralization, and rings and other jewelry could now be located even under highly-mineralized black sand.

Uses

Archaeology

In England and Wales metal detecting is legal provided that permission is granted by the landowner, and that the area is not a Scheduled Ancient Monument, a site of special scientific interest (SSSI), or covered by elements of the Countryside Stewardship Scheme. Items discovered which fall within the definition of treasure must be reported to the coroner or a place designated by the coroner for treasure. The voluntary reporting of finds which do not qualify as treasure to the Portable Antiquities Scheme or the UK Detector Finds Database is encouraged.

The situation in Scotland is very different. Under the Scots law principle of *bona vacantia*, the Crown has claim over any object of any material value where the original owner cannot be traced. There is also no 300 year limit to Scottish finds. Any artifact found, whether by metal detector survey or from an archaeological excavation, must be reported to the Crown through the Treasure Trove Advisory Panel at the National Museums of Scotland. The panel then determines what will happen to the artifacts. Reporting is not voluntary, and failure to report the discovery of historic artifacts is a criminal offence in Scotland.

As a hobby

This 156 ounce nugget was found by an individual prospector in the Southern California Desert using a metal detector

There are six major types of hobbyist activities involving metal detectors:

- Coin shooting is looking for coins after an event involving many people, like a baseball game, or simply looking for any old coins. Serious coin shooters will spend hours, days and months doing historical research to locate long lost sites that have the potential to give up historical and collectible coins.
- Prospecting is looking for valuable metals like gold and silver in their natural forms, such as nuggets or flakes.
- General metal detecting is very similar to coin shooting except that the metal detectorist is after any type of historical artifact. Metal detectorists may be dedicated to preserving historical artifacts, and often have considerable expertise. Coins, bullets, buttons, axe heads, and buckles are just a few of the items that are commonly found by relic hunters; in general the potential is far greater in Europe and Asia than many other parts of the world. More valuable finds in Britain alone

include the Staffordshire Hoard of Anglo-Saxon gold, sold for £3,285,000, the gold Celtic Newark Torc, the Ringlemere Cup, West Bagborough Hoard, Milton Keynes Hoard, Roman Crosby Garrett Helmet, Stirling Hoard, Collette Hoard and thousands of smaller finds.

- Beach combing is hunting for lost coins or jewelry on a beach. Beach hunting can be as simple or as complicated as one wishes to make it. Many dedicated beach hunters also familiarize themselves with tide movements and beach erosion. There are two main techniques for beach hunting. The first one is called "gridding", which is when you search in a pattern. For example, you start from the beach line, and work your way down to the shoreline, move to the side a little, and repeat the process. The next technique is called "Random searching". Random searching is when you walk around the beach in no particular pattern, hoping to cover more ground.
- Metal detecting clubs across the United States, United Kingdom and Canada exist for hobbyists to learn from others, show off finds from their hunts and to learn more about the hobby.

Security screening

Metal detectors at an airport

A series of aircraft hijackings led the Finnish company Outokumpu to adapt mining metal detectors, still housed in a large cylindrical pipe, to the purpose of screening airline passengers as they walked through. The development of these systems continued in a spin off company and systems branded as Metor Metal Detectors evolved in the form of the rectangular gantry now standard in airports. In common with the developments in other uses of metal detectors both alternating current and pulse systems are used, and the design of the coils and the electronics has moved forward to improve the discrimination of these systems. In 1995 systems such as the Metor 200 appeared with the ability to indicate the approximate height of the metal object above the ground, enabling security personnel to more rapidly locate the source of the signal. Smaller hand held metal detectors are also used to locate a metal object on a person more precisely.

Industrial metal detectors

Industrial metal detectors are used in the pharmaceutical, food, beverage, textile, garment, plastics, chemicals, lumber, and packaging industries.

Contamination of food by metal shards from broken processing machinery during the manufacturng process is a major safety issue in the food industry. Metal detectors for this purpose are widely used and integrated into the production line.

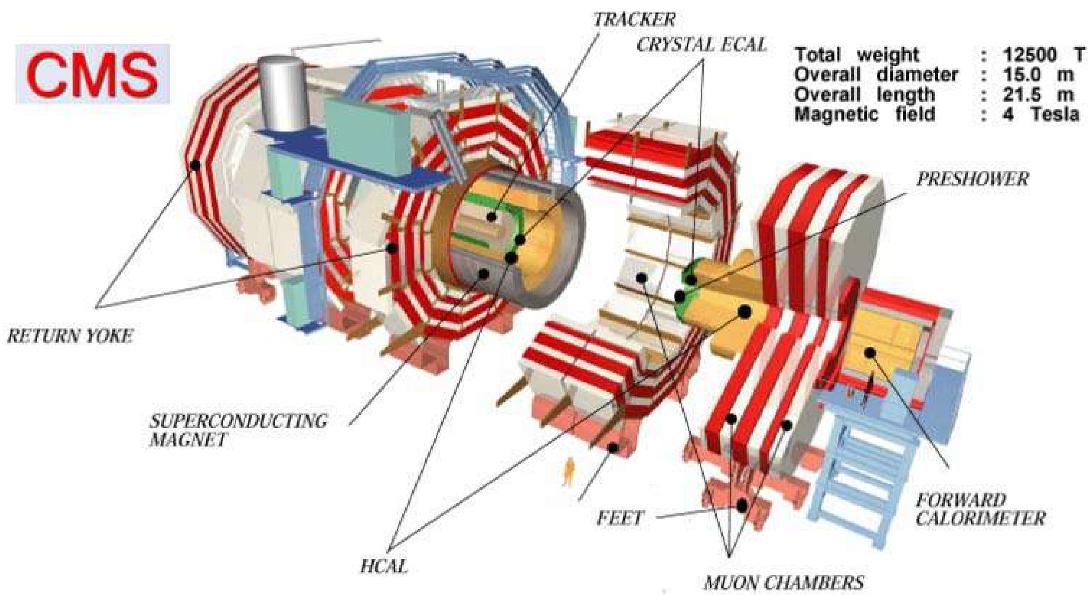
Current practice at garment or apparel industry plants is to apply metal detecting after the garments are completely sewn and before garments are packed to check whether there is any metal contamination (needle, broken needle, etc) in the garments. This needs to be done for safety reasons.

Civil engineering

In civil engineering special metal detectors (cover meters) are used to locate rebars. Rebar detectors are less sophisticated devices that can only locate metallic objects below the surface.

Chapter- 2

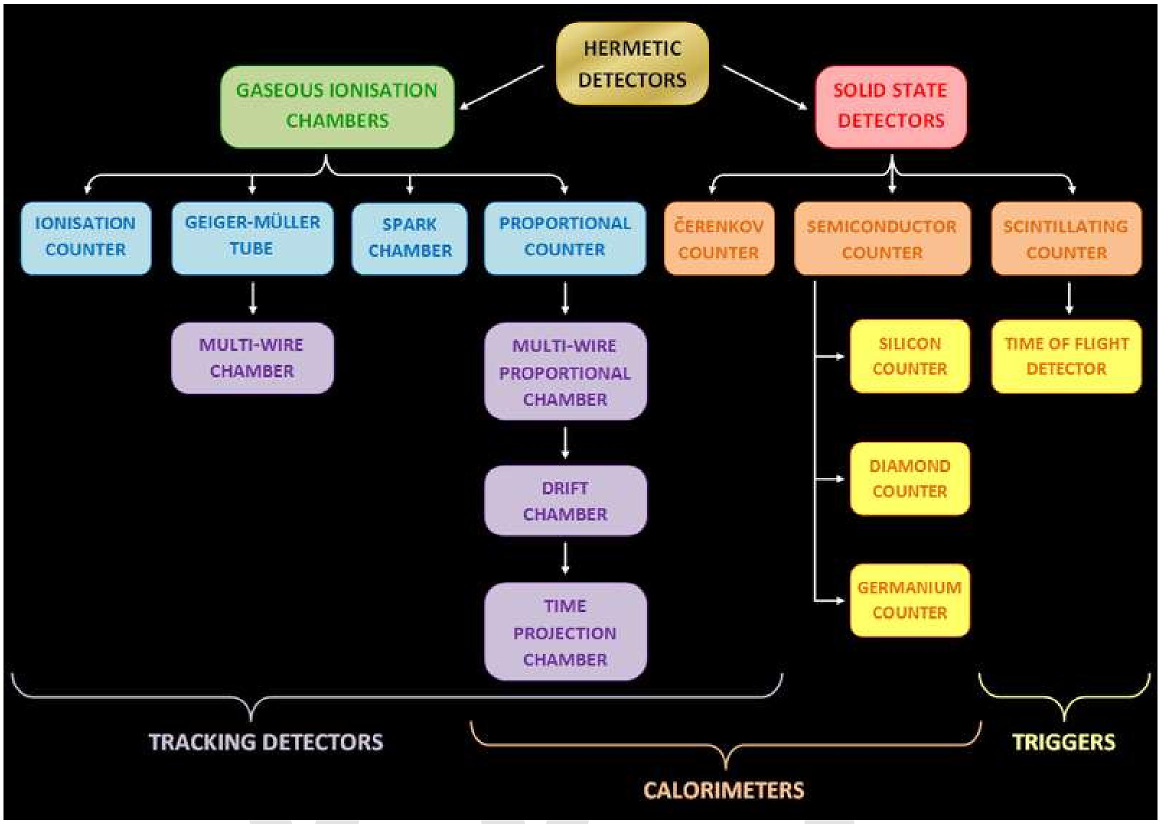
Particle Detector



The Compact Muon Solenoid (CMS) is an example of a large particle detector. Notice the person for scale.

In experimental and applied particle physics, nuclear physics, and nuclear engineering, a **particle detector**, also known as a **radiation detector**, is a device used to detect, track, and/or identify high-energy particles, such as those produced by nuclear decay, cosmic radiation, or reactions in a particle accelerator. Modern detectors are also used as calorimeters to measure the energy of the detected radiation. They may also be used to measure other attributes such as momentum, spin, charge etc. of the particles.

Description



Summary of Particle Detectors

Detectors designed for modern accelerators are huge, both in size and in cost. The term *counter* is often used instead of *detector*, when the detector counts the particles but does not resolve its energy or ionization. Particle detectors usually can also track ionizing radiation (high energy photons or even visible light). If their main purpose is radiation measurement, they are called *radiation detectors*, but as photons are also (massless) particles, the term *particle detector* is still correct.

Examples and types

Many of the detectors invented and used so far are ionization detectors (of which gaseous ionization detectors and semiconductor detectors are most typical) and scintillation detectors; but other, completely different principles have also been applied, like Čerenkov light and transition radiation.

Cloud chamber with visible tracks from ionizing radiation (short, thick: α-particles; long, thin: β-particles

Historical Examples

- Bubble chamber
- Wilson cloud chamber (diffusion chamber)
- Photographic plates

Detectors for Radiation Protection

- Dosimeter
- Electroscope (miniature electroscopes are used as portable dosimeters)

Commonly used detectors for Particle and Nuclear Physics

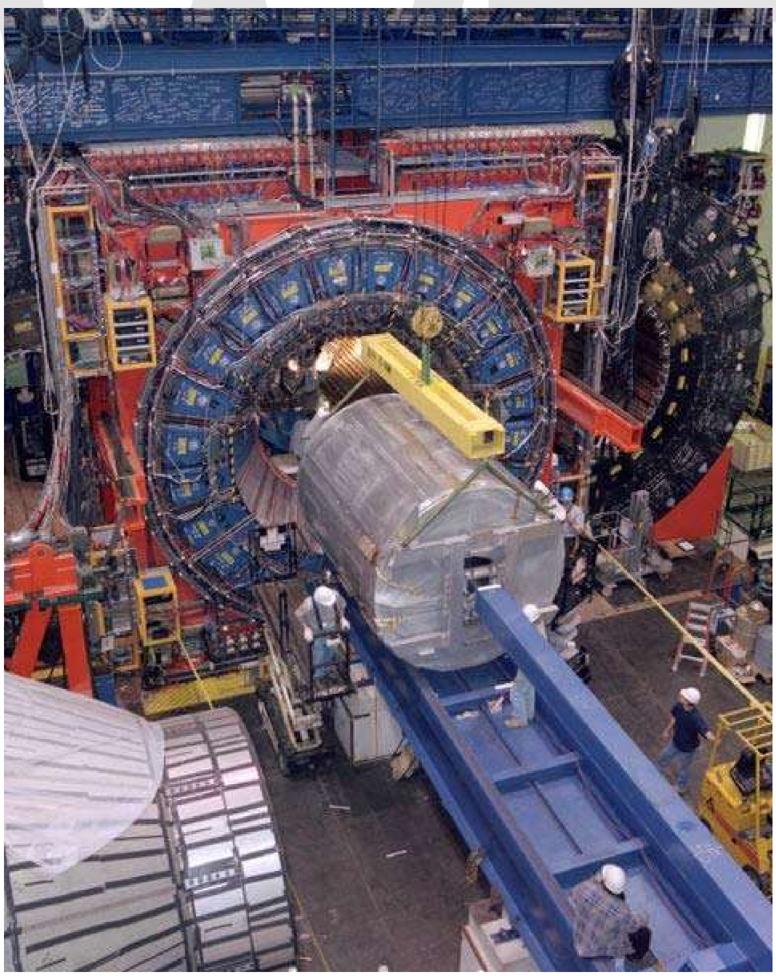
- Gaseous ionization detectors
    - Ionization chamber
    - Proportional counter
        - Multiwire Proportional Chamber
        - Drift chamber
        - Time projection chamber

- Geiger-Müller tube
- Spark chamber

- Solid-state detectors
    - Cherenkov detector
        - RICH (Ring Imaging Cherenkov Detector)
    - Scintillation counter and associated Photomultiplier or Photodiode / Avalanche photodiode
        - Lucas cell
        - Time of flight detector
    - Semiconductor detector
        - Silicon Vertex Detector
    - Transition radiation detector

- Calorimeters

Hermetic Detectors

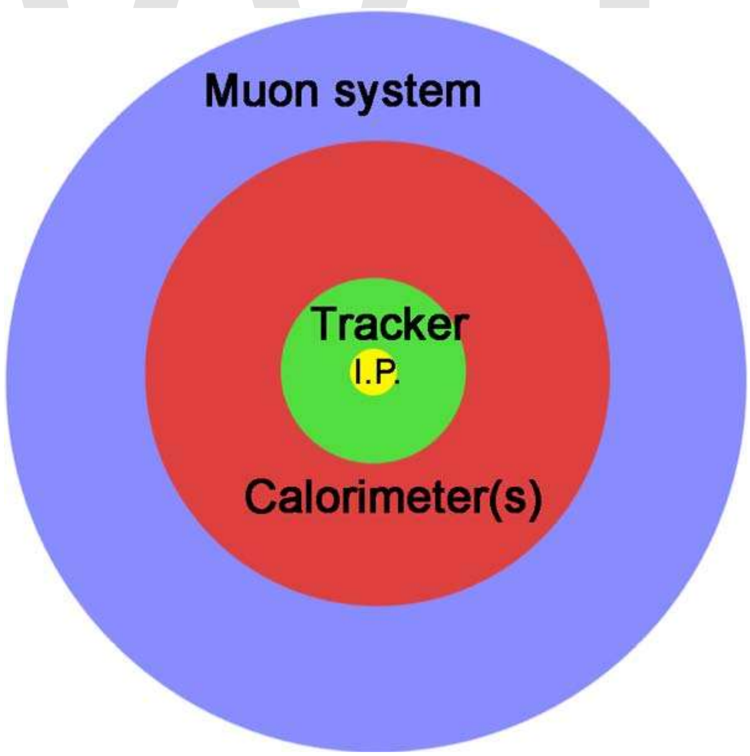


A currently-operating hermetic detector, the Collider Detector at Fermilab

In particle physics, a **hermetic detector** (also called a **4π detector**) is a particle detector designed to observe all possible decay products of an interaction between subatomic particles in a collider by covering as large an area around the interaction point as possible and incorporating multiple types of sub-detectors. They are typically roughly cylindrical, with different types of detectors wrapped around each other; each detector type specializes in particular particles so that almost any particle will be detected and identified. Such detectors are called "hermetic" because they are designed to let as few particles as possible escape; the name "4π detector" comes from the fact that such detectors are designed to cover nearly all of the 4π steradians of solid angle around the interaction point.

The first such detector was the Mark I at the Stanford Linear Accelerator Center, and the basic design has been used for all subsequent collider detectors. Prior to the building of the Mark I, it was thought that most particle decay products would have relatively low transverse momentum (i.e. momentum perpendicular to the beamline), so that detectors could cover this area only. However, it was learned at the Mark I and subsequent experiments that most fundamental particle interactions at colliders involve very large exchanges of energy and therefore large transverse momenta are not uncommon; for this reason, large angular coverage is critical for modern particle physics.

Components



A schematic of the basic components of a hermetic detector; I.P. refers to the region containing the interaction point for the colliding particles. This is a cross section of the typical cyllindrical design.

There are three main components of a hermetic detector. From the inside out, the first is a **tracker**, which measures the momentum of charged particles as they curve in a magnetic field. Next there are one or more **calorimeters**, which measure the energy of most charged and neutral particles by absorbing them in dense material, and a **muon system** which measures the one type of particle that is not stopped through the calorimeters and can still be detected. Each component may have several different specialized sub-components.

Trackers

The tracking system plots the helix traced by a charged particle that curves in a magnetic field by localizing it in space in finely-segmented layers of detecting material, usually silicon. The degree to which the particle curves is inversely proportional to its momentum perpendicular to the beam, while the degree to which it drifts in the direction of the beam axis gives its momentum in that direction.

Calorimeters

Calorimeters slow particles down and absorb their energy into a material, allowing that energy to be measured. They are often divided into two types: the electromagnetic calorimeter that specializes in absorbing particles that interact electromagnetically, and the hadronic calorimeter that can detect hadrons, which interact via the strong nuclear force. A hadronic detector is required in particular to detect heavy neutral particles.

Muon system

Of all the known stable particles, only muons and neutrinos pass through the calorimeter without losing most or all of their energy. Neutrinos are practically undetectable, and their existence must be inferred, but muons (which are charged) can be measured by an additional tracking system outside the calorimeters.

Particle identification

Most particles have unique combinations of signals left in each detector sub-system, allowing different particles to be identified. For example, an electron is charged and interacts electromagnetically, so it is tracked by the tracker and then deposits all of its energy in the (electromagnetic) calorimeter. By contrast, a photon is neutral and interacts electromagnetically, so it deposits its energy in the calorimeter without leaving a track.

Installations of particle detectors

At colliders

- At CERN
  - for the LHC

        - CMS
        - ATLAS
        - ALICE
        - LHCb
    - for the LEP
        - Aleph
        - Delphi
        - L3
        - Opal
    - for the SPS
        - The COMPASS Experiment
        - Gargamelle
        - NA49
- At Fermilab
    - for the Tevatron
        - CDF
        - D0
- At DESY
    - for HERA
        - H1
        - HERA-B
        - HERMES
        - ZEUS
- At BNL
    - for the RHIC
        - PHENIX
        - Phobos (physics)
        - STAR
- At SLAC
    - for the PeP-II
        - BaBar
    - for the SLC
        - SLD
- At Cornell
    - for CESR
        - CLEO
        - CUSB
- Others
    - MECO from UC Irvine

Under construction

- For ILC
    - CALICE

Without colliders

- Super-Kamiokande
- AMANDA
- CMDS

Chapter- 3

Smoke Detector

A **smoke detector** is a device that detects smoke, typically as an indicator of fire. Commercial, industrial, and mass residential devices issue a signal to a fire alarm system, while household detectors, known as smoke alarms, generally issue a local audible and/or visual alarm from the detector itself.

Smoke detectors are typically housed in a disk-shaped plastic enclosure about 150 millimetres (6 in) in diameter and 25 millimetres (1 in) thick, but the shape can vary by manufacturer or product line. Most smoke detectors work either by optical detection (photoelectric) or by physical process (ionization), while others use both detection methods to increase sensitivity to smoke. Sensitive alarms can be used to detect, and thus deter, smoking in areas where it is banned such as toilets and schools. Smoke detectors in large commercial, industrial, and residential buildings are usually powered by a central fire alarm system, which is powered by the building power with a battery backup. However, in many single family detached and smaller multiple family housings, a smoke alarm is often powered only by a single disposable battery.

History

The first automatic electric fire alarm was invented in 1890 by Francis Robbins Upton (U.S. patent no. 436,961). Upton was an associate of Thomas Edison, but there is no evidence that Edison contributed to this project.

In the late 1930s the Swiss physicist Walter Jaeger tried to invent a sensor for poison gas. He expected that gas entering the sensor would bind to ionized air molecules and thereby alter an electric current in a circuit in the instrument. His device failed: small concentrations of gas had no effect on the sensor's conductivity. Frustrated, Jaeger lit a cigarette—and was soon surprised to notice that a meter on the instrument had registered a drop in current. Smoke particles had apparently done what poison gas could not. Jaeger's experiment was one of the advances that paved the way for the modern smoke detector.

It was 30 years, however, before progress in nuclear chemistry and solid-state electronics made a cheap sensor possible. While home smoke detectors were available during most of the 1960s, the price of these devices was rather high. Before that, alarms were so expensive that only major businesses and theaters could afford them.

The first truly affordable home smoke detector was invented by Duane D. Pearsall in 1965, featuring an individual battery powered unit that could be easily installed and replaced. The first units for mass production came from Duane Pearsall’s company, Statitrol Corporation, in Lakewood, Colorado.

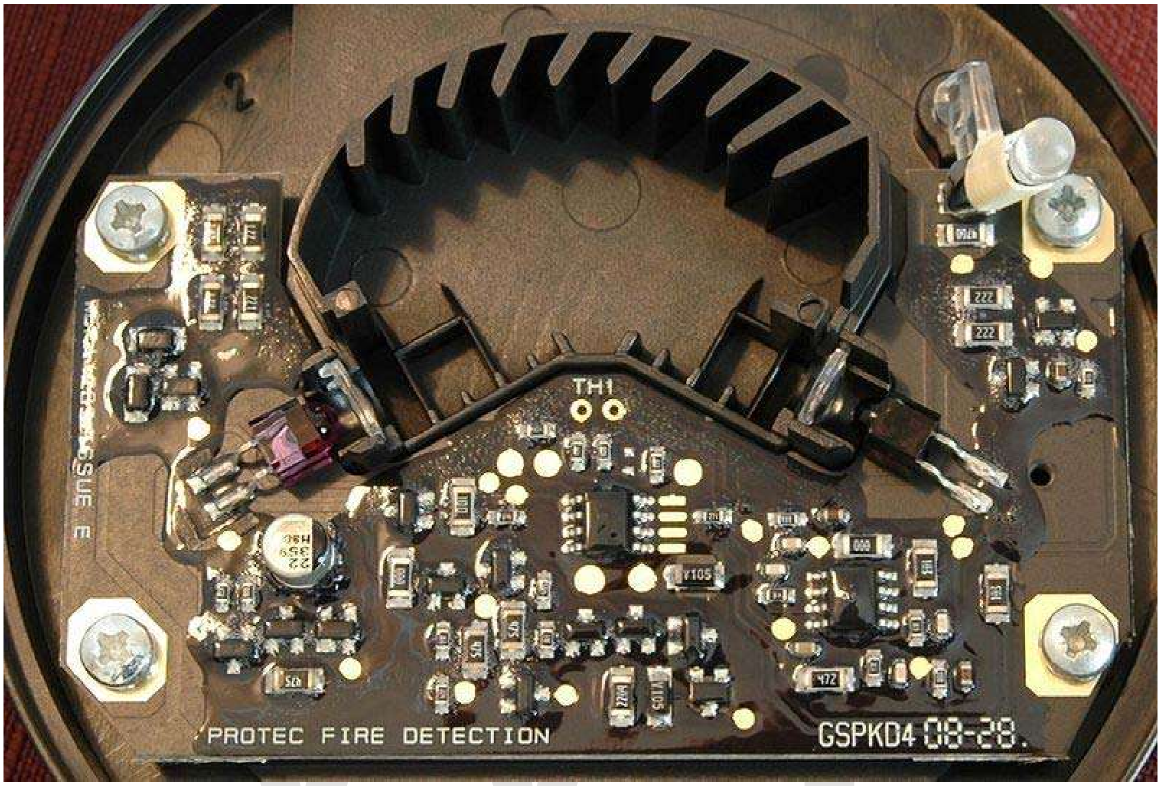
These first units were made from strong fire resistant steel and shaped much like a bee's hive. The battery was a rechargeable specialized unit created by Gates Energy. The need for a quick replace battery didn't take long to show itself and the rechargeable was replaced with a pair of AA batteries along with a plastic shell encasing the detector. The small assembly line sent close to 500 units per day before Statitrol sold its invention to Emerson Electric in 1980 and Sears’s retailers picked up full distribution of the 'now required in every home' smoke detector.

The first commercial smoke detectors came to market in 1969. Today they are installed in 93% of U.S. homes and 85% of UK homes. However it is estimated that any given time over 30% of these alarms don't work, as users remove the batteries, or forget to replace them.

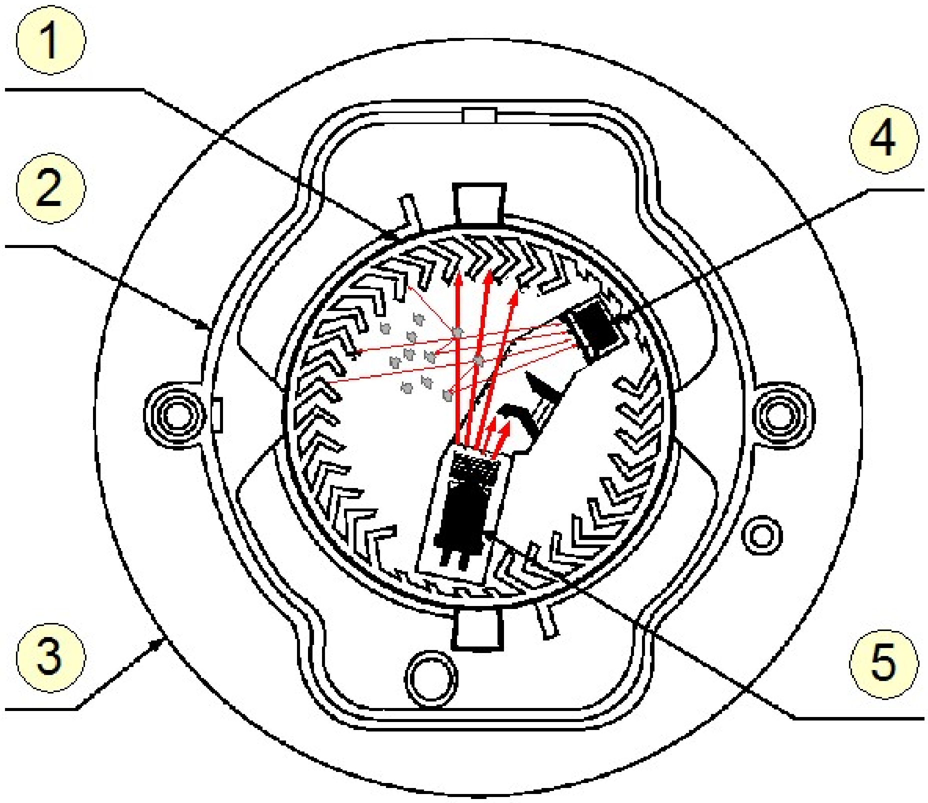
Although commonly attributed to NASA, smoke detectors were not invented as a result of the space program, though a variant with adjustable sensitivity was developed for Skylab.

Design

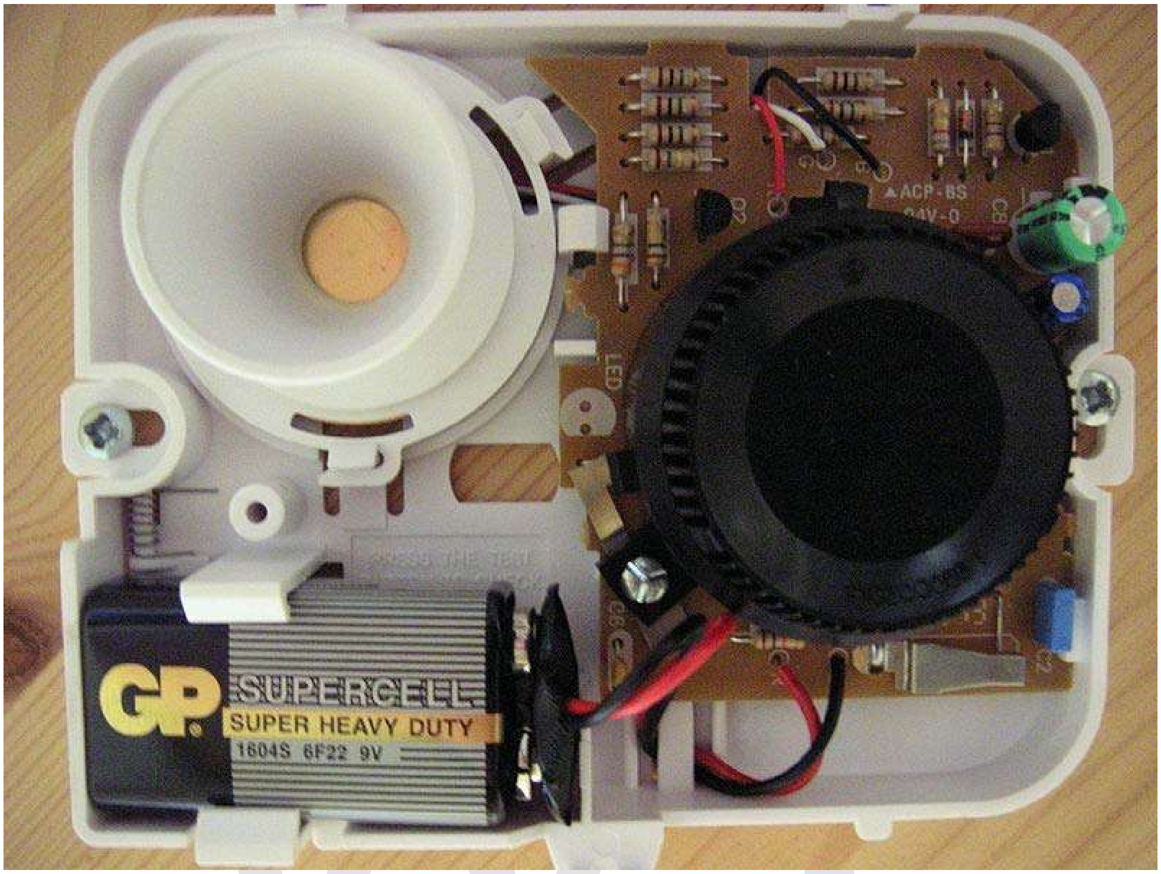
Optical



Optical Smoke Detector with the cover removed



Optical Smoke Detector
1: Optical chamber
2: Cover
3: Case moulding
4: Photodiode (detector)
5: Infrared LED



Inside a basic ionization smoke detector. The black, round structure at the right is the ionization chamber. The white, round structure at the upper left is the piezoelectric buzzer that produces the alarm sound.

An optical detector is a light sensor. When used as a smoke detector, it includes a light source (incandescent bulb or infrared LED), a lens to collimate the light into a beam, and a photodiode or other photoelectric sensor at an angle to the beam as a light detector. In the absence of smoke, the light passes in front of the detector in a straight line. When smoke enters the optical chamber across the path of the light beam, some light is scattered by the smoke particles, directing it at the sensor and thus triggering the alarm.

Also seen in large rooms, such as a gymnasium or an auditorium, are devices to detect a projected beam. A unit on the wall sends out a beam, which is either received by a receiver or reflected back via a mirror. When the beam is less visible to the "eye" of the sensor, it sends an alarm signal to the fire alarm control panel.

Optical smoke detectors are quick in detecting particulate (smoke) generated by smoldering (cool, smoky) fires. Many independent tests indicate that optical smoke detectors typically detect particulates (smoke) from hot, flaming fires approximately 30 seconds later than ionization smoke alarms.

They are less sensitive to false alarms from steam or cooking fumes generated in kitchen or steam from the bathroom than are ionization smoke alarms. For the aforementioned reason, they are often referred to as 'toast proof' smoke alarms.

Ionization

This type of detector is cheaper than the optical detector; however, it is sometimes rejected because it is more prone to false (nuisance) alarms than photoelectric smoke detectors. It can detect particles of smoke that are too small to be visible. It includes about 37 kBq or 1 μCi of radioactive americium-241 (^{241}Am), corresponding to about 0.3 μg of the isotope. The radiation passes through an ionization chamber, an air-filled space between two electrodes, and permits a small, constant current between the electrodes. Any smoke that enters the chamber absorbs the alpha particles, which reduces the ionization and interrupts this current, setting off the alarm.

^{241}Am, an alpha emitter, has a half-life of 432 years. This means that it does not have to be replaced during the useful life of the detector, and also makes it safe for people at home, since it is only slightly radioactive. Alpha radiation, as opposed to beta and gamma, is used for two additional reasons: Alpha particles have high ionization, so sufficient air particles will be ionized for the current to exist, and they have low penetrative power, meaning they will be stopped by the plastic of the smoke detector and/or the air. About one percent of the emitted radioactive energy of ^{241}Am is gamma radiation.

Air-sampling

An air-sampling smoke detector is capable of detecting microscopic particles of smoke. Most air-sampling detectors are aspirating smoke detectors, which work by actively drawing air through a network of small-bore pipes laid out above or below a ceiling in parallel runs covering a protected area. Small holes drilled into each pipe form a matrix of holes (sampling points), providing an even distribution across the pipe network. Air samples are drawn past a sensitive optical device, often a solid-state laser, tuned to detect the extremely small particles of combustion. Air-sampling detectors may be used to trigger an automatic fire response, such as a gaseous fire suppression system, in high-value or mission-critical areas, such as archives or computer server rooms.

Most air-sampling smoke detection systems are capable of a higher sensitivity than spot type smoke detectors and provide multiple levels of alarm threshold, such as Alert, Action, Fire 1 and Fire 2. Thresholds may be set at levels across a wide range of smoke levels. This provides earlier notification of a developing fire than spot type smoke detection, allowing manual intervention or activation of automatic suppression systems before a fire has developed beyond the smoldering stage, thereby increasing the time available for evacuation and minimizing fire damage.

Carbon monoxide and carbon dioxide detection

Some smoke alarms use a carbon dioxide sensor or carbon monoxide sensor in order to detect extremely dangerous products of combustion. However, not all smoke detectors that are advertised with such gas sensors are actually able to warn of poisonous levels of those gases in the absence of a fire.

Performance differences

Optical or "toast-proof" smoke detectors are generally quicker in detecting particulate (smoke) generated by smoldering (cool, smokey) fires. Ionization smoke detectors are generally quicker in detecting particulate (smoke) generated by flaming (hot) fires.

According to fire tests conformant to EN 54, normally the CO_2 cloud from smoke can be detected before particulate.

Obscuration is a unit of measurement that has become the standard definition of smoke detector [Sensitivity (electronics) [sensitivity]]. Obscuration is the effect that smoke has on reducing visibility. Higher concentrations of smoke result in higher obscuration levels, lowering visibility.

Typical smoke detector obscuration ratings

Type of Detector	Obscuration Level
Ionization	2.6–5.0% obs/m (0.8–1.5% obs/ft)
Photoelectric	6.5–13.0% obs/m (2–4% obs/ft)
Beam	3% obs/m (0.9% obs/ft)
Aspirating	0.005–20.5% obs/m (0.0015–6.25% obs/ft)
Laser	0.06–6.41% obs/m (0.02–2.0% obs/ft)

Commercial smoke detectors

An integrated locking mechanism for commercial building doors. Inside an enclosure are a locking device, smoke detector and power supply.

Commercial smoke detectors are either conventional or analog addressable, and are wired up to security monitoring systems or fire alarm control panels (FACP). These are the most common type of detector, and usually cost a lot more than a household smoke alarms. They exist in most commercial and industrial facilities, such as high rises, ships and trains. These detectors don't need to have built in alarms, as alarm systems can be controlled by the connected FACP, which will set off relevant alarms, and can also implement complex functions such as a staged evacuation.

Conventional

The word Conventional is slang used in to distinguish the method used to communicate with the control unit from that used by addressable detectors whose methods were unconventional at the time of their introduction. So called “Conventional Detectors” cannot be individually identified by the control unit and resemble an electrical switch in their information capacity. These detectors are connected in parallel to the signaling path or (initiating device circuit) so that the current flow is monitored to indicate a closure of the circuit path by any connected detector when smoke or other similar environmental stimulus sufficiently influences any detector. The resulting increase in current flow is interpreted and processed by the control unit as a confirmation of the presence of smoke and a fire alarm signal is generated.

Addressable

This type of installation gives each detector on a system an individual number, or address. Thus, addressable detectors allow an FACP, and therefore fire fighters, to know the exact location of an alarm where the address is indicated on a diagram.

Analog addressable detectors provide information about the amount of smoke in their detection area, so that the FACP can decide itself, if there is an alarm condition in that area (possibly considering day/night time and the readings of surrounding areas). These are usually more expensive than autonomous deciding detectors.

Standalone smoke alarms

The main function of a standalone smoke alarm is to alert persons at risk. Several methods are used and documented in industry specifications published by Underwriters Laboratories Alerting methods include:

- Audible tones
    - Usually around 3200 Hz due to component constraints
    - 85 dBA at 10 feet
- Spoken voice alert
- Visual strobe lights
    - 110 candela output
- Tactile stimulation, e.g., bed or pillow shaker (No standards exist as of 2008 for tactile stimulation alarm devices.)

Some models have a hush or temporary silence feature that allows silencing without removing the battery. This is especially useful in locations where false alarms can be relatively common (i.e. due to "toast burning") or users could remove the battery permanently to avoid the annoyance of false alarms, but removing the battery permanently is strongly discouraged.

While current technology is very effective at detecting smoke and fire conditions, the deaf and hard of hearing community has raised concerns about the effectiveness of the alerting function in awakening sleeping individuals in certain high risk groups such as the elderly, those with hearing loss and those who are intoxicated. Between 2005 and 2007, research sponsored by the United States' National Fire Protection Association (NFPA) has focused on understanding the cause of a higher number of deaths seen in such high risk groups. Initial research into the effectiveness of the various alerting methods is sparse. Research findings suggest that a low frequency (520 Hz) square wave output is significantly more effective at awakening high risk individuals. Wireless Wi-Safe smoke and carbon monoxide detectors linked to alert mechanisms such as vibrating pillow pads, strobes and remote warning handsets have been found to support the groups above.

Batteries

Photoelectric smoke detector equipped with strobe light for the hearing impaired

Most residential smoke detectors run on 9-volt alkaline or carbon-zinc batteries. When these batteries run down, the smoke detector becomes inactive. Most smoke detectors will signal a low-battery condition. The alarm may chirp at intervals if the battery is low, though if there is more than one unit within earshot, it can be hard to locate. It is common, however, for houses to have smoke detectors with dead batteries. It is estimated, in the UK, that over 30% of smoke alarms may have dead or removed batteries. As a result, public information campaigns have been created to remind people to change smoke detector batteries regularly. In Australia, for example, it is advertised that all smoke alarm batteries should be replaced on the first day of April every year. In regions using daylight saving time, these campaigns may suggest that people change their batteries when they change their clocks or on a birthday.

Some detectors are also being sold with a lithium battery that can run for about 7 to 10 years, though this might actually make it less likely for people to change batteries, since their replacement is needed so infrequently. By that time, the whole detector may need to be replaced. Though relatively expensive, user-replaceable 9-volt lithium batteries are also available.

Common NiMH and NiCd rechargeable batteries have a high self-discharge rate, making them unsuitable for use in smoke detectors. This is true even though they may provide much more power than alkaline batteries if used soon after charging, such as in a portable stereo. Also, a problem with rechargeable batteries is a rapid voltage drop at the end of their useful charge. This is of concern in devices such as smoke detectors, since the battery may transition from "charged" to "dead" so quickly that the low-battery warning period from the detector is either so brief as to go unnoticed, or may not occur at all.

The NFPA, recommends that home-owners replace smoke detector batteries with a new battery at least once per year, when it starts chirping (a signal that its charge is low), or when it fails a test, which the NFPA recommends to be carried out at least once per month by pressing the "test" button on the alarm.

Reliability

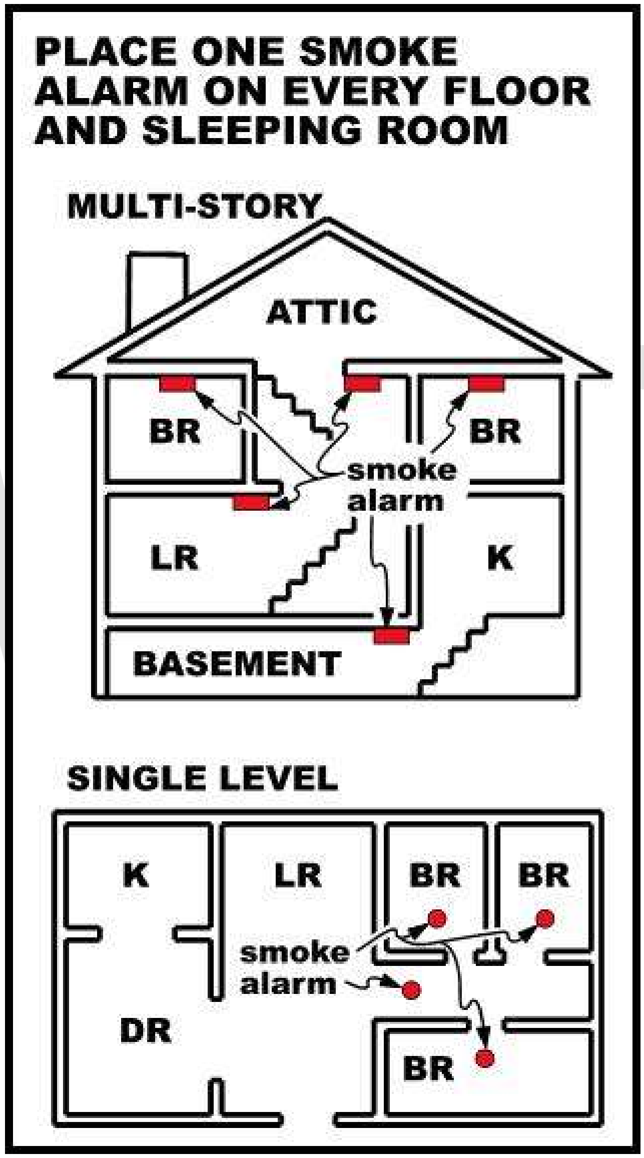
In 2004, NIST issued a comprehensive report that concludes, among other things, that "smoke alarms of either the ionization type or the photoelectric type consistently provided time for occupants to escape from most residential fires", and "consistent with prior findings, ionization type alarms provided somewhat better response to flaming fires than photoelectric alarms, and photoelectric alarms provided (often) considerably faster response to smoldering fires than ionization type alarms".

The NFPA strongly recommends the replacement of home smoke alarms every 10 years. Smoke alarms become less reliable with time, primarily due to aging of their electronic components, making them susceptible to nuisance false alarms. In ionization type alarms, decay of the ^{241}Am radioactive source is a negligible factor, as its half-life is far greater than the expected useful life of the alarm unit.

Regular cleaning can prevent false alarms caused by the build up of dust or other objects such as flies, particularly on optical type alarms as they are more susceptible to these factors. A vacuum cleaner can be used to clean ionization and optical detectors externally and internally. However, on commercial ionisation detectors it is not recommended for a lay person to clean internally. To reduce false alarms caused by cooking fumes, use an optical or 'toast proof' alarm near the kitchen.

A jury in the United States District Court for the Northern District of New York decided in 2006 that First Alert and its parent company, BRK Brands, was liable for millions of dollars in damages because the ionization technology in the smoke alarm in the Hackert's house was defective, failing to detect the slow-burning fire and choking smoke that filled the home as the family slept.

Installation and placement



A 2007 U.S. guide to placing smoke detectors, suggesting that one be placed on every floor of a building, and in each bedroom.

In the United States, most state and local laws regarding the required number and placement of smoke detectors are based upon standards established in Article 72 of the NFPA fire code.

Laws governing the installation of smoke detectors vary depending on the locality. Homeowners with questions or concerns regarding smoke detector placement may contact their local fire marshal or building inspector for assistance. However, some rules and guidelines for existing homes are relatively consistent throughout the developed world. For example, Canada and Australia require a building to have a working smoke detector on every level. The United States requires smoke detectors on every habitable level and within the vicinity of all bedrooms. Habitable levels include attics that are tall enough to allow access.

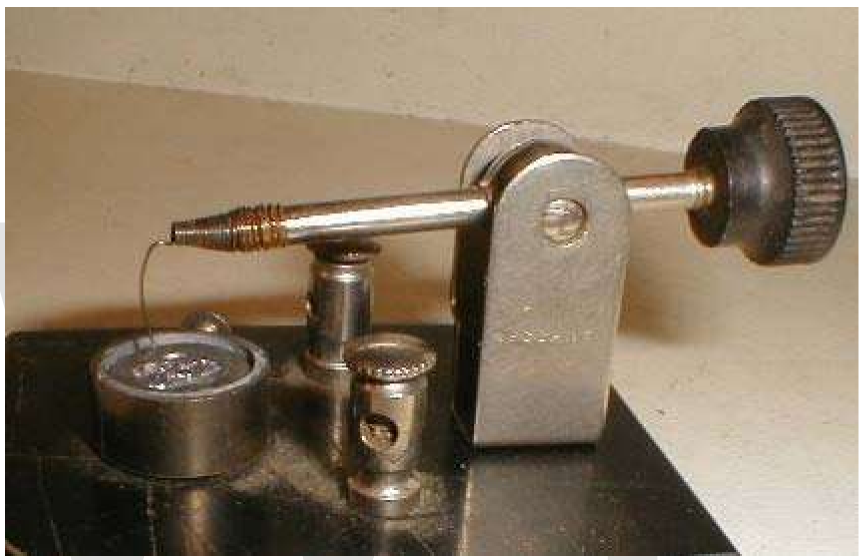
In new construction, minimum requirements are typically more stringent. All smoke detectors must be hooked directly to the electrical wiring, be interconnected and have a battery backup. In addition, smoke detectors are required either inside or outside every bedroom, depending on local codes. Smoke detectors on the outside will detect fires more quickly, assuming the fire does not begin in the bedroom, but the sound of the alarm will be reduced and may not wake some people. Some areas also require smoke detectors in stairways, main hallways and garages.

Wired units with a third "interconnect" wire allow a dozen or more detectors to be connected, so that if one detects smoke, the alarms will sound on all the detectors in the network, improving the chances that occupants will be alerted, even if they are behind closed doors or if the alarm is triggered one or two floors from their location. Wired interconnection may only be practical for use in new construction, especially if the wire needs to be routed in areas that are inaccessible without cutting open walls and ceilings. As of the mid-2000s, development has begun on wirelessly networking smoke alarms, using technologies such as ZigBee, which will allow interconnected alarms to be easily retrofitted in a building without costly wire installations. Some wireless systems using Wi-Safe technology will also detect smoke or carbon monoxide through the detectors, which simultaneously alarm themselves with vibrating pads, strobes and remote warning handsets. As these systems are wireless they can easily be transferred from one property to another.

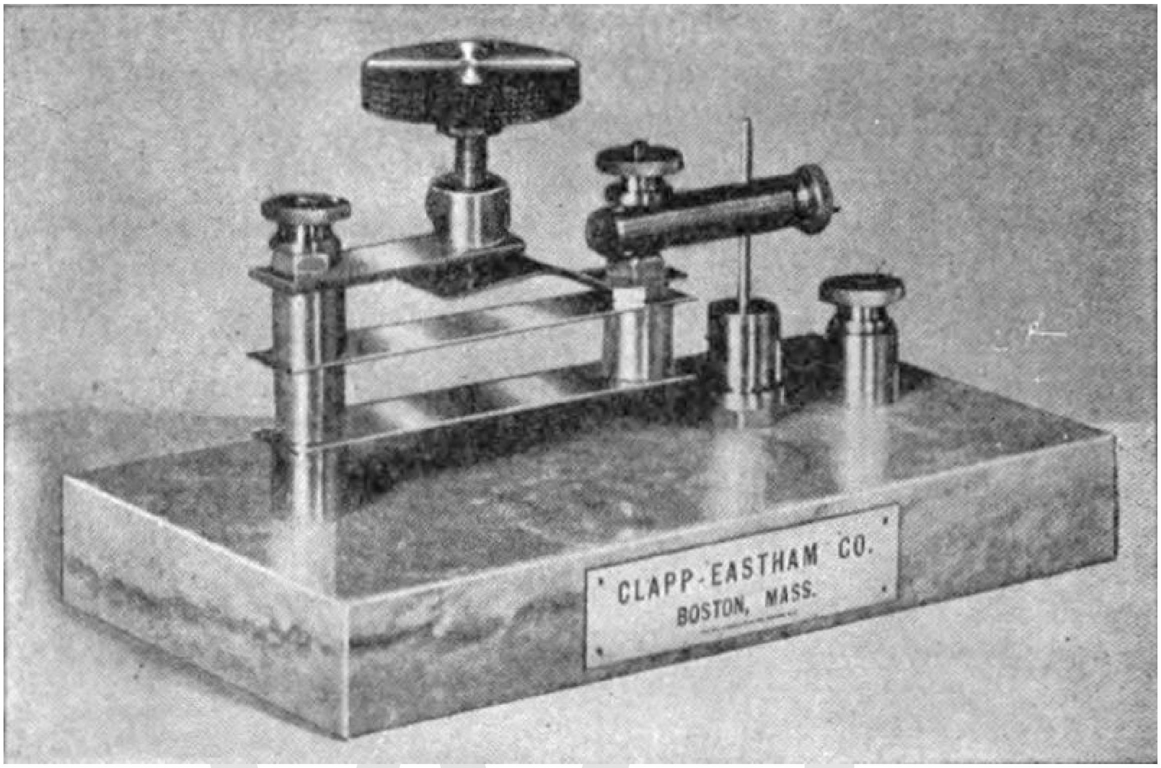
In the UK the placement of detectors are similar however the installation of smoke alarms in new builds need to comply to the British Standards BS5839 pt6. BS 5839: Pt.6: 2004 recommends that a new-build property consisting of no more than 3 floors (less than 200sqm per floor)) should be fitted with a Grade D, LD2 system. Building Regulations in England, Wales and Scotland recommend that BS 5839: Pt.6 should be followed, but as a minimum a Grade D, LD3 system should be installed. Building Regulations in Northern Ireland require a Grade D, LD2 system to be installed, with smoke alarms fitted in the escape routes and the main living room and a heat alarm in the kitchen, this standard also requires all detectors to have a main supply and a battery back up.

Chapter- 4

Cat’s-whisker Detector



Galena cat's whisker detector



Precision cat's whisker detector using iron pyrite crystal, early 1900s. The crystal is inside the metal capsule under the vertical needle "whisker" *(right)*.

A **cat's whisker detector** (also called a **crystal detector**, a term that now also refers to modern semiconductor diodes) is an antique electronic component consisting of a thin wire that lightly touches a crystal of semiconducting mineral to make a crude contact-junction rectifier. Developed by early radio researchers Jagadish Chandra Bose, G. W. Pickard and others, this device was used as the detector in early crystal radios, from about 1906 through World War 2. It gave this type of radio receiver its name. It was the first type of semiconductor diode, and in fact the first semiconductor electronic device. The term cat's whisker was also sometimes used to describe the crystal receiver itself. Cat's whisker detectors are obsolete and are now only used in antique or antique-reproduction radios.

Description

A small portable crystal radio, with a cat's whisker detector visible at top

The wire touching the surface of the crystal formed a crude and unstable metal–semiconductor point-contact P-N junction, forming a Schottky barrier diode. This junction conducts electric current in only one direction and resists current flowing in the other direction. In a crystal radio its function was to rectify the radio signal, converting it from alternating current to a pulsing direct current, to extract the audio signal (modulation) from the radio frequency carrier wave.

Only certain sites on the crystal surface functioned as rectifying junctions. Thus, the device was very sensitive to the exact geometry and pressure of contact between wire and crystal. Therefore it was made adjustable, and a usable point of contact was found by trial and error before each use. The wire was suspended from a moveable arm, and was dragged across the crystal face by the operator until the device began functioning. In a crystal radio, the operator would tune the radio to a strong local station, and then adjust the cat's whisker until the station was heard in the radio's earphones. This required some skill and a great deal of patience; even then a good contact could easily be lost by the slightest vibration. An alternate method of adjustment was to use a battery-operated buzzer to generate a test signal. The spark at the buzzer's contacts functioned as a weak radio transmitter, so when the crystal began functioning the buzz could be heard in the earphones, and the buzzer was turned off. The temperamental, unreliable action of the crystal detector was a barrier to its acceptance as a standard component in commercial radio equipment, and was one reason for its rapid replacement by vacuum tubes after 1920. Frederick Seitz, a later semiconductor researcher, wrote:

Such variability, bordering on what seemed the mystical, plagued the early history of crystal detectors and caused many of the vacuum tube experts of a later generation to regard the art of crystal rectification as being close to disreputable.

Crystal

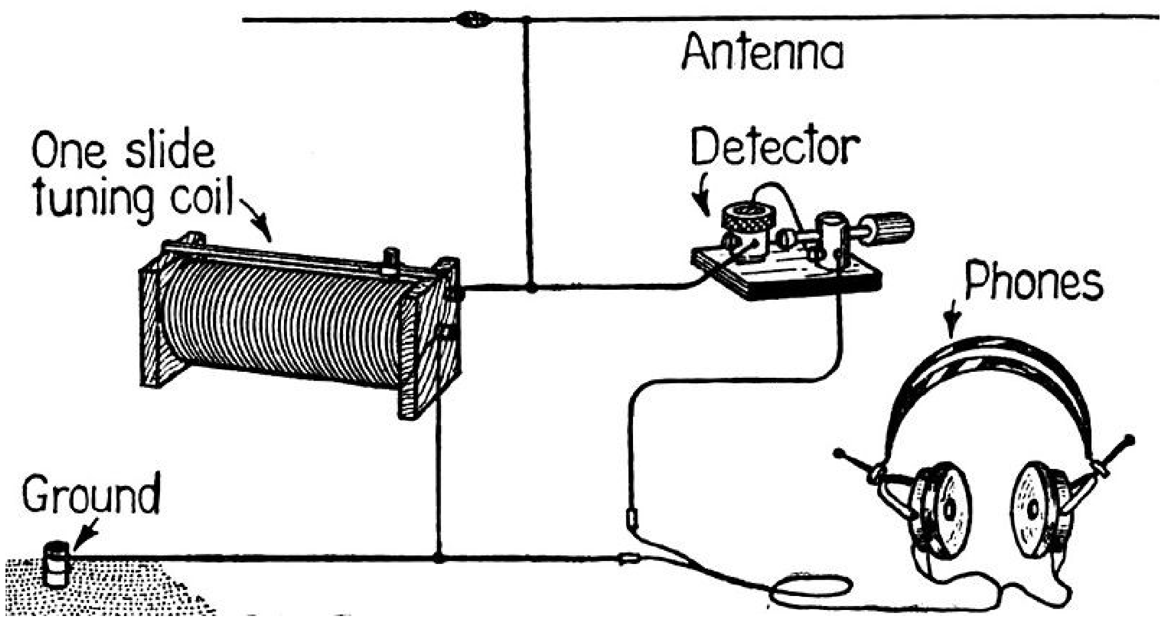
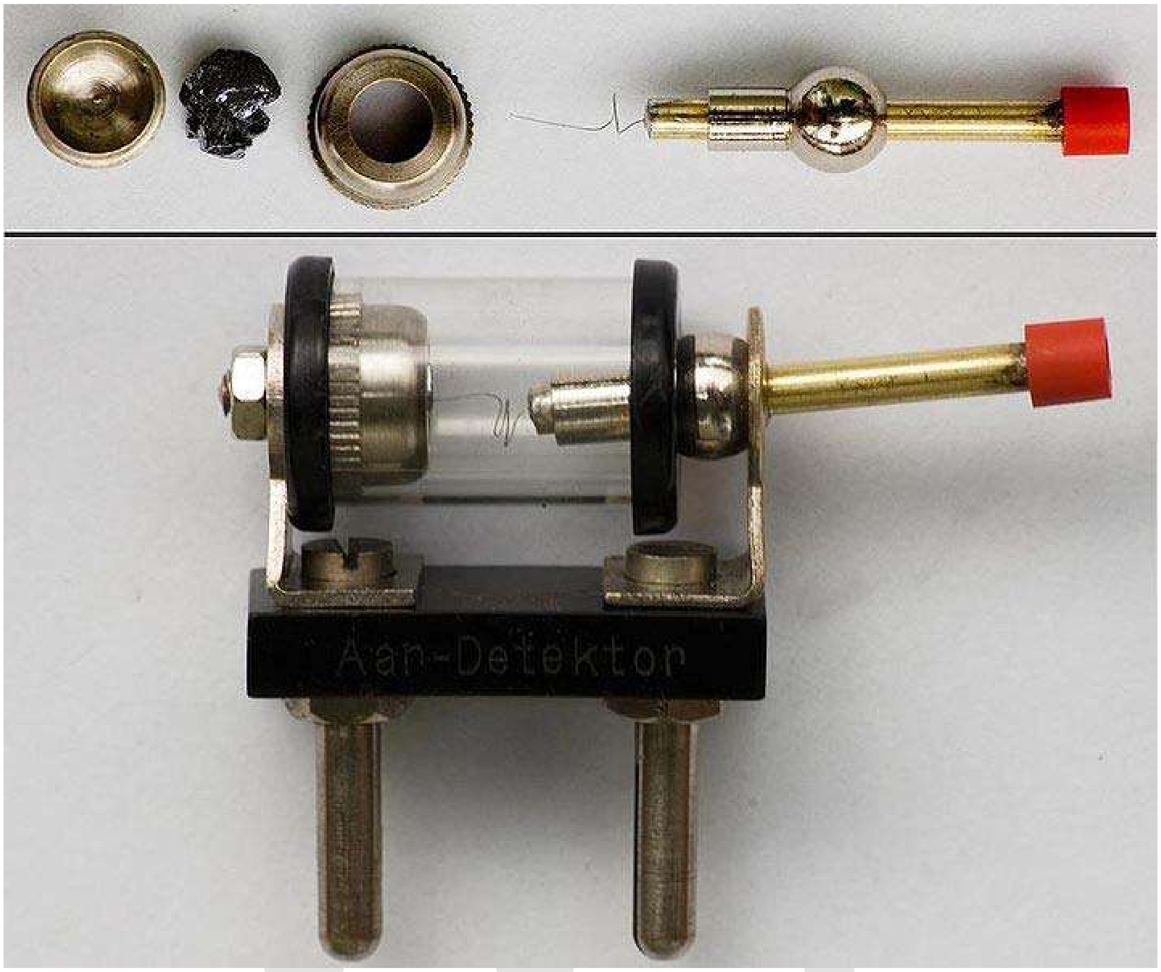


Diagram of a crystal set using a cat's-whisker detector

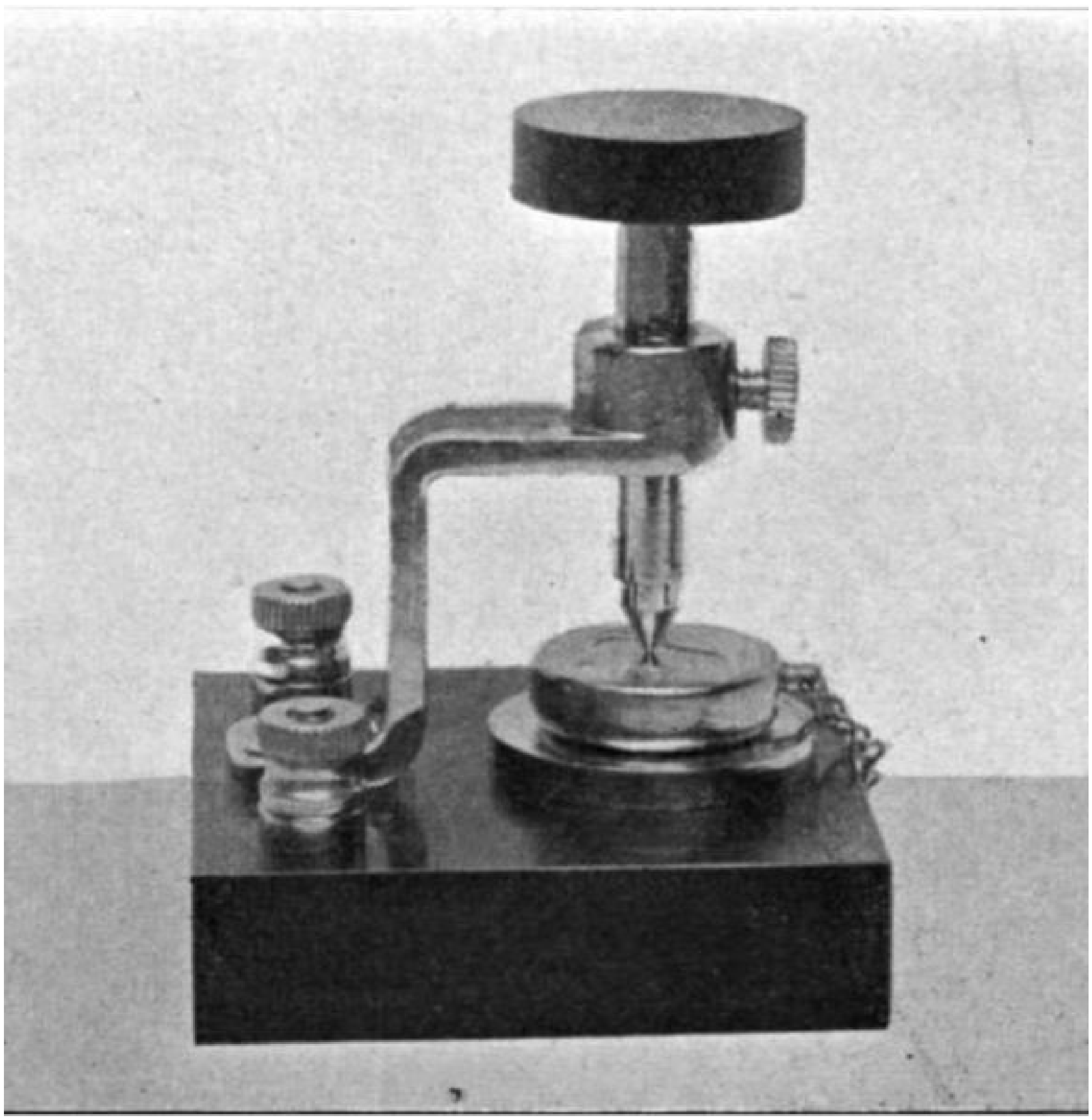


Modern galena cat's whisker detector, showing parts. The galena crystal *(upper left)* is held in the metal capsule with a screw cap, leaving its face exposed.

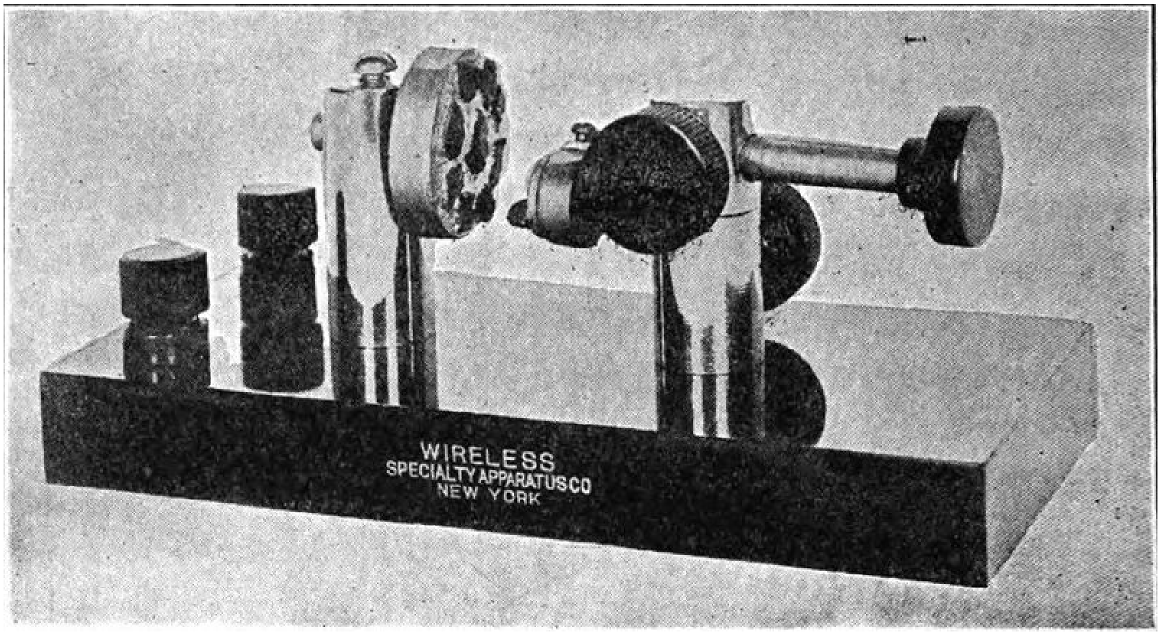
A natural mineral crystal forms the semiconductor side of the junction. The most common crystal used was galena (PbS, lead sulfide), a naturally occurring ore of lead. Galena is a semiconductor with a small bandgap of about 0.4 eV, and is used without treatment directly as it is mined. Galena with good detecting properties is rare and has no reliable visual characteristics distinguishing it from galena samples with poor detecting properties. A rough pebble of detecting mineral about the size of a pea was mounted in a metal cup, which formed one side of the circuit. The electrical contact between the cup and the crystal had to be good, because this contact must *not* act as a second rectifying junction. To make good contact with the crystal, it was either clamped with setscrews or mounted in solder. Because the relatively high temperature of tin-lead solder can damage many crystals, a low melting point (well under 200°F) alloy such as Wood's metal was used. One surface was left exposed to allow contact with the cat's whisker wire.

Whisker

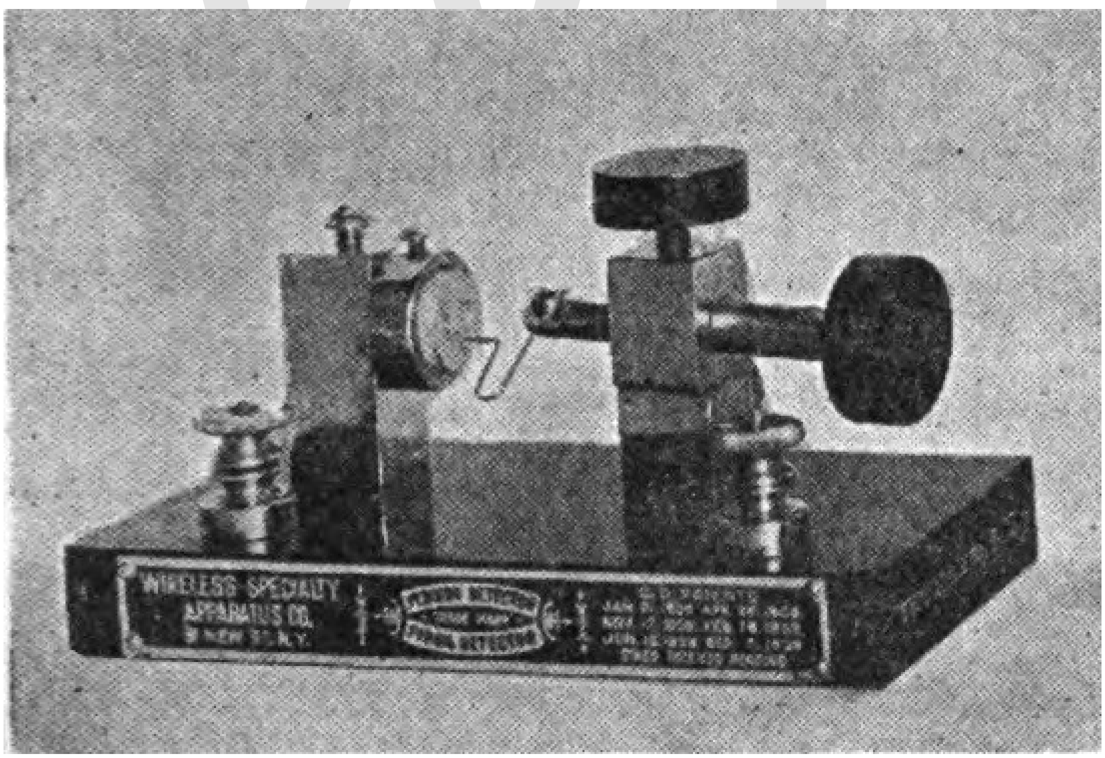
The "cat's whisker", a springy piece of thin metal wire, formed the metal side of the junction. Phosphor bronze wire of about 30 gauge was commonly used because it had the right amount of springiness. It was mounted on an adjustable arm with an insulated handle so that the entire exposed surface of the crystal could be probed from many directions to try to find the most sensitive spot. Cat's whiskers in simple detectors were straight or curved, but most cat's whiskers had a coiled section that acted as a spring near the arm, with a straight section just in back of the tip that probes the crystal. The crystal required just the right gentle pressure by the wire; too much pressure caused the device to conduct in both directions. Precision detectors often used a metal needle instead of a cat's whisker, mounted on a thumbscrew-operated leaf spring to adjust the pressure applied.



The first crystal detector commercially produced, Pickard's silicon detector, from 1906. Silicon didn't require the delicate "cat's whisker" contact.

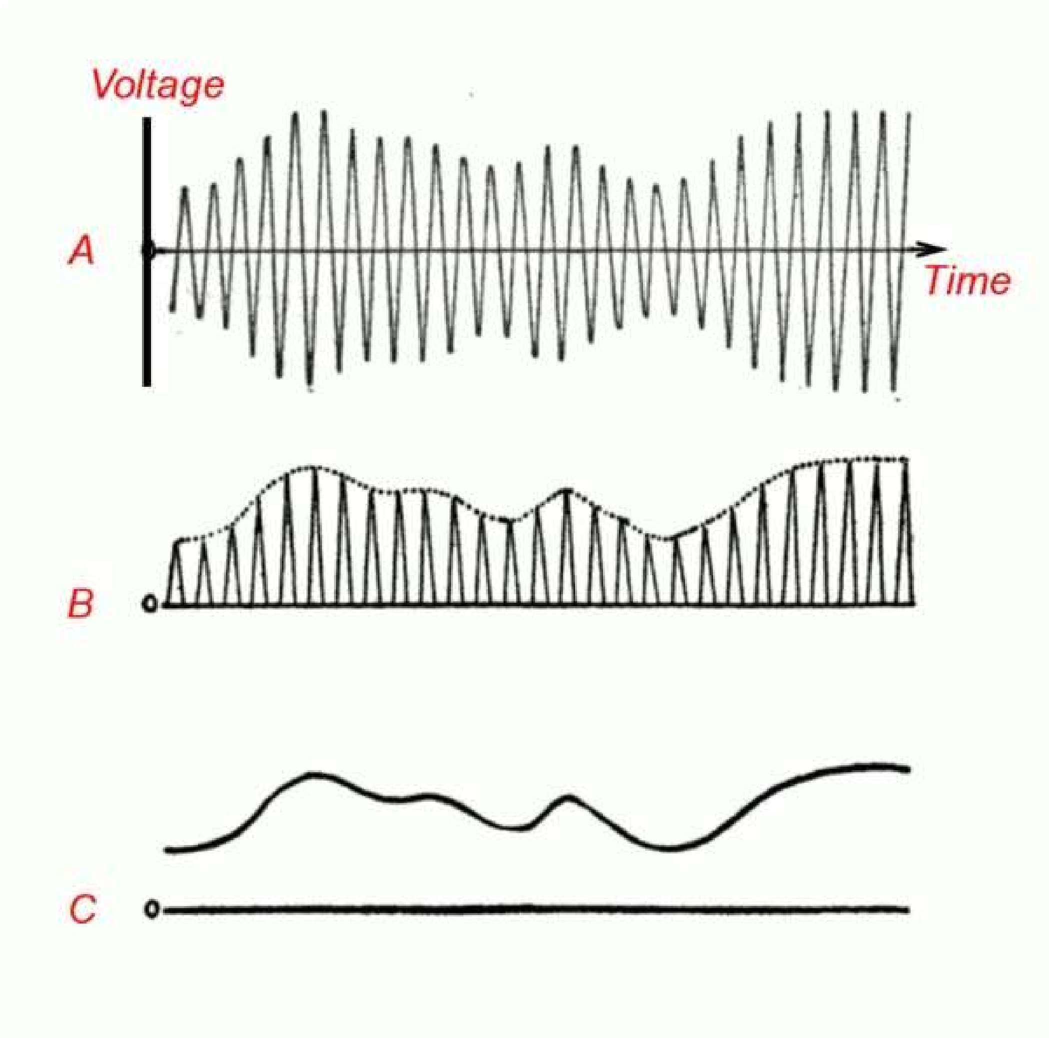


A "Perikon" detector, 1914. Instead of a wire-to-crystal contact, this had a crystal-to-crystal contact. The bornite crystal *(right)* on the adjustable arm was moved forward until it touched one of the zincite crystals on the carousel *(left)*. Multiple zincite crystals were provided because the zincite was vulnerable to damage from atmospheric electricity.



Pyrite detector

Types



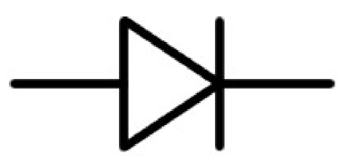
How a crystal detector works in a radio receiver. *(A)* The amplitude modulated radio signal from the receiver's tuning section. The rapid oscillations are the radio frequency carrier wave. The audio signal (the sound) is contained in the slow variations (modulation) of the size of the waves. This signal cannot be converted to sound by the earphone, because the audio excursions are the same on both sides of the axis, averaging out to zero, resulting in no net motion of the earphone's diaphragm. *(B)* The crystal conducts current in only one direction, stripping off the oscillations on one side of the signal, leaving a pulsing direct current whose amplitude does not average zero but varies with the audio signal. *(C)* A bypass capacitor across the earphone smoothes the waveform, removing the radio frequency carrier pulses, leaving the audio signal.

Historically, many other minerals and compounds besides galena were used for the crystal, the most important being iron pyrite ("fool's gold", iron disulfide), silicon, molybdenite (MoS_2), and silicon carbide (carborundum, SiC). Some were used with gold or graphite "cat's whiskers". Another type had a crystal-to-crystal junction instead of a "cat's whisker", with two crystals mounted facing each other. One crystal was moved forward on an adjustable mount until the crystal faces touched. The most common of these was a zincite-bornite (ZnO-Cu_5FeS_4) junction trade-named *Perikon*, but zincite-chalcopyrite, silicon-arsenic and silicon-antimony junctions were also used. The goal of researchers was to find junctions that were not as sensitive to vibration and unreliable as galena and pyrite. Some of these other junctions, particularly carborundum, were stable enough that they used a more permanent spring-loaded contact rather than a "cat's whisker". For this reason carborundum detectors were preferred in large commercial wireless stations, and military and shipboard stations which were subject to vibration from waves and gunnery exercises. Another quality desired was the ability to withstand high currents without damage, because in wireless stations the fragile detector junction could be "burned out" by atmospheric electric charge from the antenna, or high radio frequency current leaking into the receiver from the powerful spark-gap transmitter during transmissions. Carborundum detectors, which used large area contacts, were also particularly robust in this regard.

To increase sensitivity, some of these junctions such as silicon carbide were "biased" by connecting a battery and potentiometer across them to provide a small constant forward voltage across the junction.

The oxide layers that form on many ordinary metal surfaces have semiconducting properties, and detectors for crystal radios have been improvised from a variety of everyday objects such as rusty needles and corroded pennies. The *foxhole radio* was a crystal radio receiver improvised by soldiers during World War 2 without access to conventional sets. It used a razor blade and a safety pin or lead pencil to form a demodulating junction. Much patience was required to find an active detecting site on the blade. Stray rectifying junctions between metal parts of radio transmitter installations are still a source for interference, because they can radiate harmonics of the transmitter frequency.

History



The modern circuit symbol for a diode originated as a schematic drawing of a cat's whisker detector.

Unlike modern radio stations that transmit audio (sound), the first radio transmitters during the first three decades of radio (1887-1917) transmitted information by telegraphy, turning the transmitter on and off with a switch called a telegraph key to spell out messages in Morse code, consisting of "dots" and "dashes". So early radio receiving apparatus merely had to detect the presence or absence of the radio signal, not convert it into audio. The device that did this was called a detector. The crystal detector was the most successful of many detector devices that were used in the early days of radio. It replaced electrolytic, magnetic, and particularly coherer detectors in radio receivers around 1906. Later, when AM radio transmission was developed to transmit sound, around World War 1, crystal detectors proved able to receive this as well.

The "unilateral conduction" of crystals, as it was then called, was discovered by Ferdinand Braun, a German physicist in 1874 at the University of Würzburg, before radio had been invented. Based on this work G.W. Pickard developed the cat's whisker diode using a silicon crystal, which was patented in 1906. However, Bengali scientist Jagadish Chandra Bose was the first to use a crystal to detect radio waves, in his experiments with microwaves in 1894, applying for a patent on a galena detector in 1901.

When these devices were in common use, more advanced proprietary versions of "permanent" detectors were developed, many of them by G. W. Pickard, who tested more than 30,000 combinations of crystal and wire contacts. One consisted of various combinations of pairs of different crystals such as Zincite touching Bornite or Chalcopyrite, in fairly heavily spring-loaded contact. Pickard named this the **Perikon detector**, from "**PER**fect p**I**c**K**ard c**ON**tact". Other detectors patented by Pickard included the common crystal iron pyrite. Pickard has the distinction of having brought silicon into use as a detector, patenting it in 1906. At nearly the same time, General Henry Harrison Chase Dunwoody patented the use of the silicon carbide (carborundum) detector, an artificial substance created accidentally during attempts by Edward Acheson to create diamonds.

Unamplified radio receivers, most of which were crystal radios, were the only way to receive radio signals during most of the wireless telegraphy era, which ended around 1920. Mineral detectors were largely superseded by vacuum tubes, invented in 1906, although the expense of tube receivers meant that full replacement took several decades. By the 1920s crystal radios were relegated to use by hobbyists and youth groups.

A crystal detector in commercial form from the 1960's

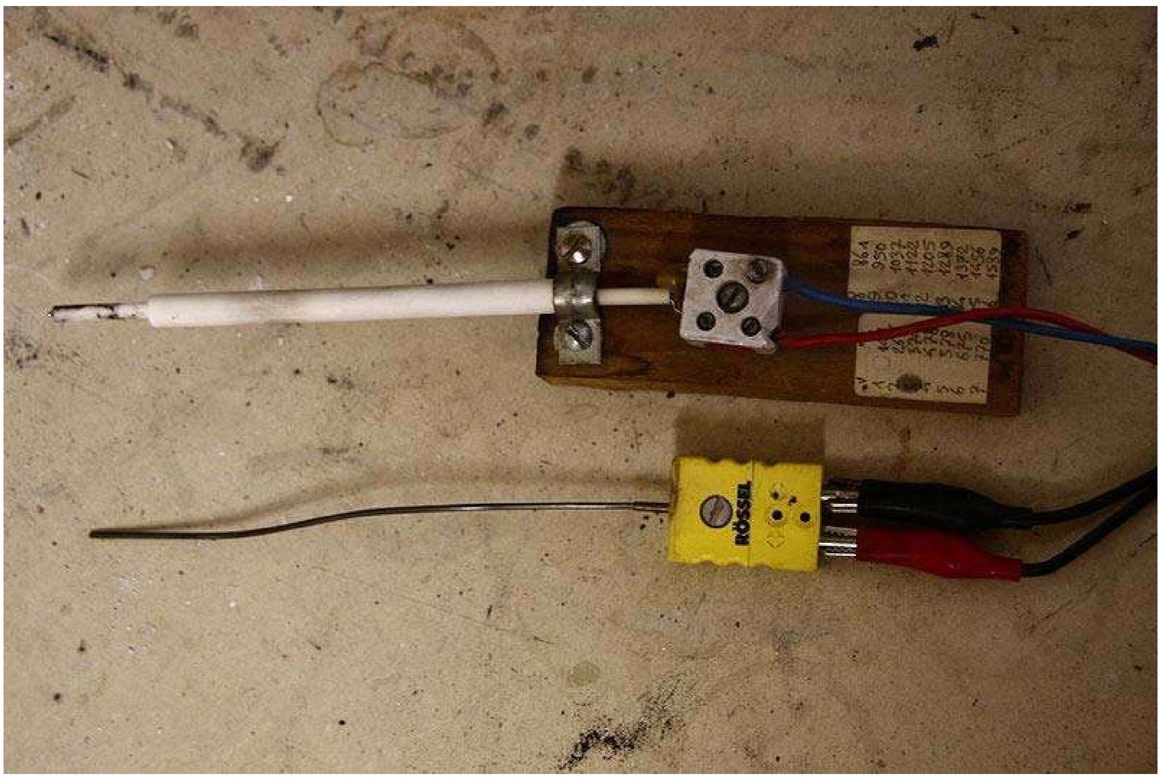
The point-contact semiconductor detector was subsequently resurrected around World War 2 because of the military requirement for microwave radar detectors. Vacuum tube detectors do not work at microwave frequencies. The small area of the point contact minimized minority carrier storage and capacitance, making these diodes fast enough to function at radar frequencies. Silicon and germanium point contact diodes were developed. Wartime research on PN junctions in crystals paved the way for the invention of the transistor in 1956. The first transistors also used cat's whisker contacts.

The germanium diodes that became widely available after the war proved to be as sensitive as galena and didn't require any adjustment, so they replaced cat's whisker detectors in crystal radios, largely putting an end to the manufacture of this antique radio component. Although cat's whisker detectors are obsolete, modern point-contact silicon detectors are still commercially produced. Thus the point contact method used to make these first semiconductor diodes 100 years ago is still being used today.

Copies of original cat's-whisker detectors are still manufactured and sold, for antique radio hobbyists.

Chapter- 5

Sensors



Thermocouple sensor for high temperature measurement

A *sensor*; is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument. For example, a mercury-in-glass thermometer converts the measured temperature into expansion and contraction of a liquid which can be read on a calibrated glass tube. A thermocouple converts temperature to an output voltage which can be read by a voltmeter. For accuracy, most sensors are calibrated against known standards.

Use

Sensors are used in everyday objects such as touch-sensitive elevator buttons (tactile sensor) and lamps which dim or brighten by touching the base. There are also innumerable applications for sensors of which most people are never aware. Applications include cars, machines, aerospace, medicine, manufacturing and robotics.

A sensor is a device which receives and responds to a signal. A sensor's sensitivity indicates how much the sensor's output changes when the measured quantity changes. For instance, if the mercury in a thermometer moves 1 cm when the temperature changes by 1 °C, the sensitivity is 1 cm/°C (it is basically the slope Dy/Dx assuming a linear characteristic). Sensors that measure very small changes must have very high sensitivities. Sensors also have an impact on what they measure; for instance, a room temperature thermometer inserted into a hot cup of liquid cools the liquid while the liquid heats the thermometer. Sensors need to be designed to have a small effect on what is measured, making the sensor smaller often improves this and may introduce other advantages. Technological progress allows more and more sensors to be manufactured on a microscopic scale as microsensors using MEMS technology. In most cases, a microsensor reaches a significantly higher speed and sensitivity compared with macroscopic approaches.

Classification of measurement errors

A good sensor obeys the following rules:

- Is sensitive to the measured property
- Is insensitive to any other property likely to be encountered in its application
- Does not influence the measured property

Ideal sensors are designed to be linear or linear to some simple mathematical fuction of the measurement, typically logarithmic. The output signal of such a sensor is linearly proportional to the value or simple function of the measured property. The sensitivity is then defined as the ratio between output signal and measured property. For example, if a sensor measures temperature and has a voltage output, the sensitivity is a constant with the unit [V/K]; this sensor is linear because the ratio is constant at all points of measurement.

Sensor deviations

If the sensor is not ideal, several types of deviations can be observed:

- The sensitivity may in practice differ from the value specified. This is called a sensitivity error, but the sensor is still linear.
- Since the range of the output signal is always limited, the output signal will eventually reach a minimum or maximum when the measured property exceeds the limits. The full scale range defines the maximum and minimum values of the measured property.
- If the output signal is not zero when the measured property is zero, the sensor has an offset or bias. This is defined as the output of the sensor at zero input.

- If the sensitivity is not constant over the range of the sensor, this is called nonlinearity. Usually this is defined by the amount the output differs from ideal behavior over the full range of the sensor, often noted as a percentage of the full range.
- If the deviation is caused by a rapid change of the measured property over time, there is a dynamic error. Often, this behaviour is described with a bode plot showing sensitivity error and phase shift as function of the frequency of a periodic input signal.
- If the output signal slowly changes independent of the measured property, this is defined as drift (telecommunication).
- Long term drift usually indicates a slow degradation of sensor properties over a long period of time.
- Noise is a random deviation of the signal that varies in time.
- Hysteresis is an error caused by when the measured property reverses direction, but there is some finite lag in time for the sensor to respond, creating a different offset error in one direction than in the other.
- If the sensor has a digital output, the output is essentially an approximation of the measured property. The approximation error is also called digitization error.
- If the signal is monitored digitally, limitation of the sampling frequency also can cause a dynamic error, or if the variable or added noise noise changes periodically at a frequency near a multiple of the sampling rate may induce aliasing errors.
- The sensor may to some extent be sensitive to properties other than the property being measured. For example, most sensors are influenced by the temperature of their environment.

All these deviations can be classified as systematic errors or random errors. Systematic errors can sometimes be compensated for by means of some kind of calibration strategy. Noise is a random error that can be reduced by signal processing, such as filtering, usually at the expense of the dynamic behaviour of the sensor.

Resolution

The resolution of a sensor is the smallest change it can detect in the quantity that it is measuring. Often in a digital display, the least significant digit will fluctuate, indicating that changes of that magnitude are only just resolved. The resolution is related to the precision with which the measurement is made. For example, a scanning tunneling probe (a fine tip near a surface collects an electron tunnelling current) can resolve atoms and molecules.

Types

This is a list of sensors sorted by sensor type.

Acoustic, sound, vibration

- Geophone
- Hydrophone
- Lace Sensor a guitar pickup
- Microphone
- Seismometer
- Accelerometer

Automotive, transportation

- Air-fuel ratio meter
- Crank sensor
- Curb feeler, used to warn driver of curbs
- Defect detector, used on railroads to detect axle and signal problems in passing trains
- MAP sensor, Manifold Absolute Pressure, used in regulating fuel metering.
- Parking sensors, used to alert the driver of unseen obstacles during parking manoeuvres
- Radar gun, used to detect the speed of other objects
- Speedometer, used measure the instantaneous speed of a land vehicle
- Speed sensor, used to detect the speed of an object
- Throttle position sensor, used to monitor the position of the throttle in an internal combustion engine
- Variable reluctance sensor, used to measure position and speed of moving metal components
- Water sensor or water-in-fuel sensor, used to indicate the presence of water in fuel
- Wheel speed sensor, used for reading the speed of a vehicle's wheel rotation

Chemical

- Breathalyzer
- Carbon dioxide sensor
- Carbon monoxide detector
- Catalytic bead sensor
- Chemical field-effect transistor
- Electrochemical gas sensor
- Electronic nose
- Electrolyte–insulator–semiconductor sensor
- Hydrogen sensor
- Hydrogen sulfide sensor
- Infrared point sensor
- Ion-selective electrode
- Nondispersive infrared sensor
- Microwave chemistry sensor

- Nitrogen oxide sensor
- Olfactometer
- Optode
- Oxygen sensor
- Pellistor
- pH glass electrode
- Potentiometric sensor
- Redox electrode
- Smoke detector
- Zinc oxide nanorod sensor

Electric current, electric potential, magnetic, radio

- Ammeter
- Current sensor
- Galvanometer
- Hall effect sensor
- Hall probe
- Leaf electroscope
- Magnetic anomaly detector
- Magnetometer
- Metal detector
- Multimeter
- Ohmmeter
- Radio direction finder
- Telescope
- Voltmeter
- Voltage detector
- Watt-hour meter

Environment, weather, moisture, humidity

- Bedwetting alarm
- Dew warning
- Fish counter
- Gas detector
- Hook gauge evaporimeter
- Hygrometer
- Leaf sensor
- Pyranometer
- Pyrgeometer
- Psychrometer
- Rain gauge
- Rain sensor
- Seismometers

- Snow gauge
- Soil moisture sensor
- Stream gauge
- Tide gauge

Flow, fluid velocity

- Air flow meter
- Anemometer
- Flow sensor
- Gas meter
- Mass flow sensor
- Water meter

Ionising radiation, subatomic particles

- Bubble chamber
- Cloud chamber
- Geiger counter
- Neutron detection
- Particle detector
- Scintillation counter
- Scintillator
- Wire chamber

Navigation instruments

- Air speed indicator
- Altimeter
- Attitude indicator
- Depth gauge
- Fluxgate compass
- Gyroscope
- Inertial reference unit
- Magnetic compass
- MHD sensor
- Ring laser gyroscope
- Turn coordinator
- Variometer
- Vibrating structure gyroscope
- Yaw rate sensor

Position, angle, displacement, distance, speed, acceleration

- Accelerometer
- Capacitive displacement sensor
- Free fall sensor
- Gravimeter
- Inclinometer
- Laser rangefinder
- Linear encoder
- Linear variable differential transformer (LVDT)
- Liquid capacitive inclinometers
- Odometer
- Piezoelectric accelerometer
- Position sensor
- Rotary encoder
- Rotary variable differential transformer
- Selsyn
- Sudden Motion Sensor
- Tilt sensor
- Tachometer
- Ultrasonic thickness gauge

Optical, light, imaging

- Charge-coupled device
- Colorimeter
- Contact image sensor
- Electro-optical sensor
- Flame detector
- Infra-red sensor
- LED as light sensor
- Nichols radiometer
- Fiber optic sensors
- Photodetector
- Photodiode
- Photomultiplier tubes
- Phototransistor
- Photoelectric sensor
- Photoionization detector
- Photomultiplier
- Photoresistor
- Photoswitch
- Phototube
- Proximity sensor
- Scintillometer
- Shack-Hartmann
- Wavefront sensor

Pressure

- Barograph
- Barometer
- Boost gauge
- Bourdon gauge
- Hot filament ionization gauge
- Ionization gauge
- McLeod gauge
- Oscillating U-tube
- Permanent Downhole Gauge
- Pirani gauge
- Pressure sensor
- Pressure gauge
- Tactile sensor
- Time pressure gauge

Force, density, level

- Bhangmeter
- Hydrometer
- Force gauge
- Level sensor
- Load cell
- Magnetic level gauge
- Nuclear density gauge
- Piezoelectric sensor
- Strain gauge
- Torque sensor
- Viscometer

Thermal, heat, temperature

- Bolometer
- Calorimeter
- Exhaust gas temperature gauge
- Gardon gauge
- Heat flux sensor
- Infrared thermometer
- Microbolometer
- Microwave radiometer
- Net radiometer
- Resistance temperature detector
- Resistance thermometer
- Silicon bandgap temperature sensor

- Temperature gauge
- Thermistor
- Thermocouple
- Thermometer

Proximity, presence

- Alarm sensor
- Motion detector
- Occupancy sensor
- Passive infrared sensor
- Reed switch
- Stud finder
- Triangulation sensor
- Touch switch
- Wired glove

Sensor technology

- Active pixel sensor
- Machine vision
- Biochip
- Biosensor
- Capacitance probe
- Catadioptric sensor
- Carbon paste electrode
- Displacement receiver
- Electromechanical film
- Electro-optical sensor
- Fabry–Pérot interferometer
- Image sensor
- Inductive sensor
- Intelligent sensor
- Lab-on-a-chip
- Leaf sensor
- Micro-sensor arrays
- RADAR
- Sensor array
- Sensor grid
- Sensor node
- Soft sensor
- SONAR
- Staring array
- Transducer
- Ultrasonic sensor

- Video sensor
- Visual sensor network
- Wheatstone bridge
- Photoelasticity

Sensors in Nature

All living organisms contain biological sensors with functions similar to those of the mechanical devices described. Most of these are specialized cells that are sensitive to:

- Light, motion, temperature, magnetic fields, gravity, humidity, vibration, pressure, electrical fields, sound, and other physical aspects of the external environment
- Physical aspects of the internal environment, such as stretch, motion of the organism, and position of appendages (proprioception)
- Environmental molecules, including toxins, nutrients, and pheromones
- Estimation of biomolecules interaction and some kinetics parameters
- Internal metabolic milieu, such as glucose level, oxygen level, or osmolality
- Internal signal molecules, such as hormones, neurotransmitters, and cytokines
- Differences between proteins of the organism itself and of the environment or alien creatures

Biosensor

A **biosensor** is an analytical device for the detection of an analyte that combines a biological component with a physicochemical detector component.

It consists of 3 parts:

- the *sensitive biological element* (biological material (eg. tissue, microorganisms, organelles, cell receptors, enzymes, antibodies, nucleic acids, etc), a biologically derived material or biomimic) The sensitive elements can be created by biological engineering.
- the *transducer* or the *detector element* (works in a physicochemical way; optical, piezoelectric, electrochemical, etc.) that transforms the signal resulting from the interaction of the analyte with the biological element into another signal (i.e., transducers) that can be more easily measured and quantified;
- associated electronics or signal processors that are primarily responsible for the display of the results in a user-friendly way.. This sometimes accounts for the most expensive part of the sensor device, however it is possible to generate a user friendly display that includes transducer and sensitive element.

A common example of a commercial biosensor is the blood glucose biosensor, which uses the enzyme glucose oxidase to break blood glucose down. In doing so it first oxidizes glucose and uses two electrons to reduce the FAD (a component of the enzyme) to FADH2. This in turn is oxidized by the electrode (accepting two electrons from the electrode) in a number of steps. The resulting current is a measure of the concentration of glucose. In this case, the electrode is the transducer and the enzyme is the biologically active component.

Recently, arrays of many different detector molecules have been applied in so called electronic nose devices, where the pattern of response from the detectors is used to fingerprint a substance.. Current commercial electronic noses, however, do not use biological elements.

A canary in a cage, as used by miners to warn of gas, could be considered a biosensor. Many of today's biosensor applications are similar, in that they use organisms which respond to toxic substances at a much lower concentrations than humans can detect to warn of the presence of the toxin. Such devices can be used in environmental monitoring, trace gas detection and in water treatment facilities.

Principles of Detection

Photometric

Many optical biosensors based on the phenomenon of surface plasmon resonance are evanescent wave techniques. This utilises a property of gold and other materials; specifically that a thin layer of gold on a high refractive index glass surface can absorb laser light, producing electron waves (surface plasmons) on the gold surface. This occurs only at a specific angle and wavelength of incident light and is highly dependent on the surface of the gold, such that binding of a target analyte to a receptor on the gold surface produces a measurable signal.

Surface plasmon resonance sensors operate using a sensor chip consisting of a plastic cassette supporting a glass plate, one side of which is coated with a microscopic layer of gold. This side contacts the optical detection apparatus of the instrument. The opposite side is then contacted with a microfluidic flow system. The contact with the flow system creates channels across which reagents can be passed in solution. This side of the glass sensor chip can be modified in a number of ways, to allow easy attachment of molecules of interest. Normally it is coated in carboxymethyl dextran or similar compound.

Light of a fixed wavelength is reflected off the gold side of the chip at the angle of total internal reflection, and detected inside the instrument. This induces the evanescent wave to penetrate through the glass plate and some distance into the liquid flowing over the surface.

The refractive index at the flow side of the chip surface has a direct influence on the behaviour of the light reflected off the gold side. Binding to the flow side of the chip has an effect on the refractive index and in this way biological interactions can be measured to a high degree of sensitivity with some sort of energy.

Other evanescent wave biosensors have been commercialised using waveguides where the propagation constant through the waveguide is changed by the absorption of molecules to the waveguide surface. One such example, Dual Polarisation Interferometry uses a buried waveguide as a reference against which the change in propagation constant is measured. Other configurations such as the Mach-Zehnder have reference arms lithographically defined on a substrate. Higher levels of integration can be achieved using resonator geometries where the resonant frequency of a ring resonator changes when molecules are absorbed.

Other optical biosensors are mainly based on changes in absorbance or fluorescence of an appropriate indicator compound and do not need a total internal reflection geometry. For example, a fully operational prototype device detecting casein in milk has been fabricated. The device is based on detecting changes in absorption of a gold layer. A widely used research tool, the micro-array, can also be considered a biosensor.

Biological biosensors often incorporate a genetically modified form of a native protein or enzyme. The protein is configured to detect a specific analyte and the ensuing signal is read by a detection instrument such as a fluorometer or luminometer. An example of a recently developed biosensor is one for detecting cytosolic concentration of the analyte cAMP (cyclic adenosine monophosphate), a second messenger involved in cellular signaling triggered by ligands interacting with receptors on the cell membrane. Similar systems have been created to study cellular responses to native ligands or xenobiotics (toxins or small molecule inhibitors). Such "assays" are commonly used in drug discovery development by pharmaceutical and biotechnology companies. Most cAMP assays in current use require lysis of the cells prior to measurement of cAMP. A live-cell biosensor for cAMP can be used in non-lysed cells with the additional advantage of multiple reads to study the kinetics of receptor response.

Electrochemical

Electrochemical biosensors are normally based on enzymatic catalysis of a reaction that produces or consumes electrons (such enzymes are rightly called redox enzymes). The sensor substrate usually contains three electrodes; a reference electrode, a working electrode and a sink electrode. An auxiliary electrode (also known as a counter electrode) may also be present as an ion source. The target analyte is involved in the reaction that takes place on the active electrode surface, and the ions produced create a potential which is subtracted from that of the reference electrode to give a signal. We can either measure the current (rate of flow of electrons is now proportional to the analyte concentration) at a fixed potential or the potential can be measured at zero current (this gives a logarithmic response). Note that potential of the working or active electrode is space charge sensitive and this is often used. Further, the label-free and direct electrical detection of small peptides and proteins is possible by their intrinsic charges using biofunctionalized ion-sensitive field-effect transistors.

Another example, the potentiometric biosensor, works contrary to the current understanding of its ability. Such biosensors are screenprinted, conducting polymer coated, open circuit potential biosensors based on conjugated polymers immunoassays. They have only two electrodes and are extremely sensitive and robust. They enable the detection of analytes at levels previously only achievable by HPLC and LC/MS and without rigorous sample preparation. The signal is produced by electrochemical and physical changes in the conducting polymer layer due to changes occurring at the surface of the sensor. Such changes can be attributed to ionic strength, pH, hydration and redox reactions, the latter due to the enzyme label turning over a substrate().

Others

Piezoelectric sensors utilise crystals which undergo an elastic deformation when an electrical potential is applied to them. An alternating potential (A.C.) produces a standing wave in the crystal at a characteristic frequency. This frequency is highly dependent on the elastic properties of the crystal, such that if a crystal is coated with a biological recognition element the binding of a (large) target analyte to a receptor will produce a change in the resonance frequency, which gives a binding signal. In a mode that uses surface acoustic waves (SAW), the sensitivity is greatly increased. This is a specialised application of the Quartz crystal microbalance as a biosensor.

Thermometric and magnetic based biosensors are rare.

Applications

There are many potential applications of biosensors of various types. The main requirements for a biosensor approach to be valuable in terms of research and commercial applications are the identification of a target molecule, availability of a suitable biological recognition element, and the potential for disposable portable detection systems to be preferred to sensitive laboratory-based techniques in some situations. Some examples are given below:

- Glucose monitoring in diabetes patients ←**historical market driver**
- Other medical health related targets
- Environmental applications e.g. the detection of pesticides and river water contaminants
- Remote sensing of airborne bacteria e.g. in counter-bioterrorist activities
- Detection of pathogens
- Determining levels of toxic substances before and after bioremediation
- Detection and determining of organophosphate
- Routine analytical measurement of folic acid, biotin, vitamin B12 and pantothenic acid as an alternative to microbiological assay
- Determination of drug residues in food, such as antibiotics and growth promoters, particularly meat and honey.
- Drug discovery and evaluation of biological activity of new compounds.
- Protein engineering in biosensors
- Detection of toxic metabolites such as mycotoxins

Glucose monitoring

Commercially available gluocose monitors rely on amperometric sensing of glucose by means of glucose oxidase, which oxidises glucose producing hydrogen peroxide which is detected by the electrode. To overcome the limitation of ameperometric sensors, a flurry of research is present into novel sensing methods, such as fluorescent glucose biosensors.

Biosensors in food analysis

There are several applications of biosensors in food analysis. In food industry optic coated with antibodies are commonly used to detect pathogens and food toxins. The light system in these biosensors has been fluorescence, since this type of optical measurement can greatly amplify the signal.

A range of immuno- and ligand-binding assays for the detection and measurement of small molecules such as water-soluble vitamins and chemical contaminants (drug residues) such as sulfonamides and Beta-agonists have been developed for use on SPR based sensor systems, often adapted from existing ELISA or other immunological assay. These are in widespread use across the food industry.

Surface Attachment of the biological elements

An important part in a biosensor is to attach the biological elements (small molecules/protein/cells) to the surface of the sensor (be it metal, polymer or glass). The simplest way is to functionalize the surface in order to coat it with the biological elements. This can be done by polylysine, aminosilane, epoxysilane or nitrocellulose in the case of silicon chips/silica glass. Subsequently the bound biological agent may be for example fixed by Layer by layer depositation of alternatively charged polymer coatings Alternatively three dimensional lattices (hydrogel/xerogel) can be used to chemically or physically entrap these (where by chemically entraped it is meant that the biological element is kept in place by a strong bond, while physically they are kept in place being unable to pass through the pores of the gel matrix). The most commonly used hydrogel is sol-gel, a glassy silica generated by polymerization of silicate monomers (added as tetra alkyl orthosilicates, such as TMOS or TEOS) in the presence of the biological elements (along with other stabilizing polymers, such as PEG) in the case of physical entrapment. Another group of hydrogels, which set under conditions suitable for cells or protein, are acrylate hydrogel, which polymerize upon radical initiation. One type of radical initiator is a peroxide radical, typically generated by combining a persulfate with TEMED (Polyacrylamide gel are also commonly commonly used for protein electrophoresis), alternatively light can be used in combination with a photoinitiator, such as DMPA (2,2-dimethoxy-2-phenylacetophenone). Smart materials that mimic the biological components of a sensor can also be classified as biosensors using only the active or catalytic site or analogous configurations of a biomolecule.

Chapter- 6

Microphone

A Neumann U87 condenser microphone with shock mount

A **microphone** (colloquially called a **mic** or **mike**; both pronounced /ˈma ɪk/) is an acoustic-to-electric transducer or sensor that converts sound into an electrical signal. In 1876, Emile Berliner invented the first microphone used as a telephone voice transmitter. Microphones are used in many applications such as telephones, tape recorders, karaoke systems, hearing aids, motion picture production, live and recorded audio engineering, FRS radios, megaphones, in radio and television broadcasting and in computers for recording voice, speech recognition, VoIP, and for non-acoustic purposes such as ultrasonic checking or knock sensors.

Most microphones today use electromagnetic induction (dynamic microphone), capacitance change (condenser microphone), piezoelectric generation, or light modulation to produce an electrical voltage signal from mechanical vibration.

Varieties

The sensitive transducer element of a microphone is called its *element* or *capsule.* A complete microphone also includes a housing, some means of bringing the signal from the element to other equipment, and often an electronic circuit to adapt the output of the capsule to the equipment being driven. Microphones are referred to by their transducer principle, such as condenser, dynamic, etc., and by their directional characteristics. Sometimes other characteristics such as diaphragm size, intended use or orientation of the principal sound input to the principal axis (end- or side-address) of the microphone are used to describe the microphone.

Condenser microphone

Inside the Oktava 319 condenser microphone

The **condenser microphone**, invented at Bell Labs in 1916 by E. C. Wente is also called a **capacitor microphone** or **electrostatic microphone**. Here, the diaphragm acts as one plate of a capacitor, and the vibrations produce changes in the distance between the plates. There are two types, depending on the method of extracting the audio signal from the transducer: DC-biased and radio frequency (RF) or high frequency (HF) condenser microphones. With a DC-biased microphone, the plates are biased with a fixed charge (*Q*). The voltage maintained across the capacitor plates changes with the vibrations in the air, according to the capacitance equation (C = Q / V), where Q = charge in coulombs, C = capacitance in farads and V = potential difference in volts. The capacitance of the plates is inversely proportional to the distance between them for a parallel-plate capacitor. The assembly of fixed and movable plates is called an "element" or "capsule."

A nearly constant charge is maintained on the capacitor. As the capacitance changes, the charge across the capacitor does change very slightly, but at audible frequencies it is sensibly constant. The capacitance of the capsule (around 5 to 100 pF) and the value of the bias resistor (100 megohms to tens of gigohms) form a filter that is high-pass for the audio signal, and low-pass for the bias voltage. Note that the time constant of an RC circuit equals the product of the resistance and capacitance.

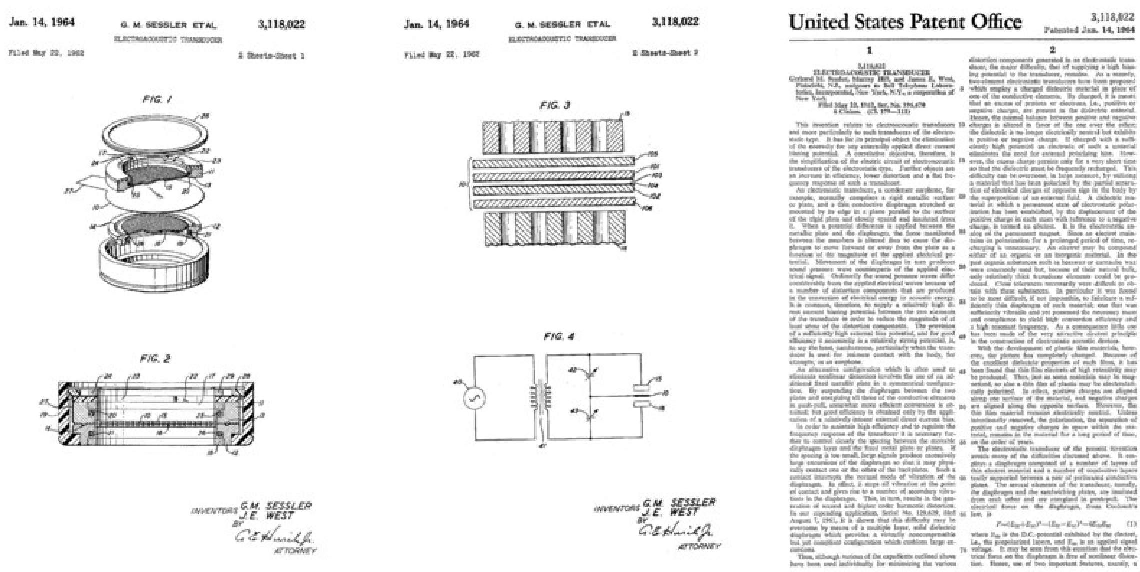
Within the time-frame of the capacitance change (as much as 50 ms at 20 Hz audio signal), the charge is practically constant and the voltage across the capacitor changes instantaneously to reflect the change in capacitance. The voltage across the capacitor varies above and below the bias voltage. The voltage difference between the bias and the capacitor is seen across the series resistor. The voltage across the resistor is amplified for performance or recording.

AKG C451B small-diaphragm condenser microphone

RF condenser microphones use a comparatively low RF voltage, generated by a low-noise oscillator. The oscillator may either be amplitude modulated by the capacitance changes produced by the sound waves moving the capsule diaphragm, or the capsule may be part of a resonant circuit that modulates the frequency of the oscillator signal. Demodulation yields a low-noise audio frequency signal with a very low source impedance. The absence of a high bias voltage permits the use of a diaphragm with looser tension, which may be used to achieve wider frequency response due to higher compliance. The RF biasing process results in a lower electrical impedance capsule, a useful by-product of which is that RF condenser microphones can be operated in damp weather conditions that could create problems in DC-biased microphones with contaminated insulating surfaces. The Sennheiser "MKH" series of microphones use the RF biasing technique.

Condenser microphones span the range from telephone transmitters through inexpensive karaoke microphones to high-fidelity recording microphones. They generally produce a high-quality audio signal and are now the popular choice in laboratory and studio recording applications. The inherent suitability of this technology is due to the very small mass that must be moved by the incident sound wave, unlike other microphone types that require the sound wave to do more work. They require a power source, provided either via microphone outputs as phantom power or from a small battery. Power is necessary for establishing the capacitor plate voltage, and is also needed to power the microphone electronics (impedance conversion in the case of electret and DC-polarized microphones, demodulation or detection in the case of RF/HF microphones). Condenser microphones are also available with two diaphragms that can be electrically connected to provide a range of polar patterns (see below), such as cardioid, omnidirectional, and figure-eight. It is also possible to vary the pattern continuously with some microphones, for example the Røde NT2000 or CAD M179.

Electret condenser microphone



First patent on foil electret microphone

An electret microphone is a relatively new type of capacitor microphone invented at Bell laboratories in 1962 by Gerhard Sessler and Jim West. The externally applied charge described above under condenser microphones is replaced by a permanent charge in an electret material. An electret is a ferroelectric material that has been permanently electrically charged or *polarized*. The name comes from *electr*ostatic and magn*et*; a static charge is embedded in an electret by alignment of the static charges in the material, much the way a magnet is made by aligning the magnetic domains in a piece of iron.

Due to their good performance and ease of manufacture, hence low cost, the vast majority of microphones made today are electret microphones; a semiconductor manufacturer estimates annual production at over one billion units. Nearly all cell-phone, computer, PDA and headset microphones are electret types. They are used in many applications, from high-quality recording and lavalier use to built-in microphones in small sound recording devices and telephones. Though electret microphones were once considered low quality, the best ones can now rival traditional condenser microphones in every respect and can even offer the long-term stability and ultra-flat response needed for a measurement microphone. Unlike other capacitor microphones, they require no polarizing voltage, but often contain an integrated preamplifier that does require power (often incorrectly called polarizing power or bias). This preamplifier is frequently phantom powered in sound reinforcement and studio applications. Microphones designed for personal computer (PC) use, sometimes called multimedia microphones, use a stereo 3.5 mm plug (though a mono source) with the ring receiving power via a resistor from (normally) a 5 V supply in the computer; unfortunately, a number of incompatible dynamic microphones are fitted with 3.5 mm plugs too. While few electret microphones rival the best DC-polarized units in terms of noise level, this is not due to any inherent limitation of the electret. Rather, mass production techniques needed to produce microphones cheaply don't lend themselves to the precision needed to produce the highest quality microphones, due to the tight tolerances required in internal dimensions. These tolerances are the same for all condenser microphones, whether the DC, RF or electret technology is used.

Dynamic microphone

Patti Smith singing into a Shure SM58 (dynamic cardioid type) microphone

Dynamic microphones work via electromagnetic induction. They are robust, relatively inexpensive and resistant to moisture. This, coupled with their potentially high gain before feedback makes them ideal for on-stage use.

Moving-coil microphones use the same dynamic principle as in a loudspeaker, only reversed. A small movable induction coil, positioned in the magnetic field of a permanent magnet, is attached to the diaphragm. When sound enters through the windscreen of the microphone, the sound wave moves the diaphragm. When the diaphragm vibrates, the coil moves in the magnetic field, producing a varying current in the coil through electromagnetic induction. A single dynamic membrane does not respond linearly to all audio frequencies. Some microphones for this reason utilize multiple membranes for the different parts of the audio spectrum and then combine the resulting signals. Combining the multiple signals correctly is difficult and designs that do this are rare and tend to be expensive. There are on the other hand several designs that are more specifically aimed towards isolated parts of the audio spectrum. The AKG D 112, for example, is designed for bass response rather than treble. In audio engineering several kinds of microphones are often used at the same time to get the best result.

Ribbon Microphone

Edmund Lowe using a ribbon microphone

Ribbon microphones use a thin, usually corrugated metal ribbon suspended in a magnetic field. The ribbon is electrically connected to the microphone's output, and its vibration within the magnetic field generates the electrical signal. Ribbon microphones are similar to moving coil microphones in the sense that both produce sound by means of magnetic induction. Basic ribbon microphones detect sound in a bi-directional (also called figure-eight) pattern because the ribbon, which is open to sound both front and back, responds to the pressure gradient rather than the sound pressure. Though the symmetrical front and rear pickup can be a nuisance in normal stereo recording, the high side rejection can be used to advantage by positioning a ribbon microphone horizontally, for example above cymbals, so that the rear lobe picks up only sound from the cymbals. Crossed figure 8, or Blumlein pair, stereo recording is gaining in popularity, and the figure 8 response of a ribbon microphone is ideal for that application.

Other directional patterns are produced by enclosing one side of the ribbon in an acoustic trap or baffle, allowing sound to reach only one side. The classic RCA Type 77-DX microphone has several externally adjustable positions of the internal baffle, allowing the selection of several response patterns ranging from "Figure-8" to "Unidirectional". Such older ribbon microphones, some of which still provide high quality sound reproduction, were once valued for this reason, but a good low-frequency response could only be obtained when the ribbon was suspended very loosely, which made them relatively fragile. Modern ribbon materials, including new nanomaterials have now been introduced that eliminate those concerns, and even improve the effective dynamic range of ribbon microphones at low frequencies. Protective wind screens can reduce the danger of damaging a vintage ribbon, and also reduce plosive artifacts in the recording. Properly designed wind screens produce negligible treble attenuation. In common with other classes of dynamic microphone, ribbon microphones don't require phantom power; in fact, this voltage can damage some older ribbon microphones. Some new modern ribbon microphone designs incorporate a preamplifier and, therefore, do require phantom power, and circuits of modern passive ribbon microphones, *i.e.*, those without the aforementioned preamplifier, are specifically designed to resist damage to the ribbon and transformer by phantom power. Also there are new ribbon materials available that are immune to wind blasts and phantom power.

Carbon microphone

A carbon microphone, also known as a carbon button microphone (or sometimes just a button microphone), use a capsule or button containing carbon granules pressed between two metal plates like the Berliner and Edison microphones. A voltage is applied across the metal plates, causing a small current to flow through the carbon. One of the plates, the diaphragm, vibrates in sympathy with incident sound waves, applying a varying pressure to the carbon. The changing pressure deforms the granules, causing the contact area between each pair of adjacent granules to change, and this causes the electrical resistance of the mass of granules to change. The changes in resistance cause a corresponding change in the current flowing through the microphone, producing the electrical signal. Carbon microphones were once commonly used in telephones; they have extremely low-quality sound reproduction and a very limited frequency response range, but are very robust devices. The Boudet microphone, which used relatively large carbon balls, was similar to the granule carbon button microphones.

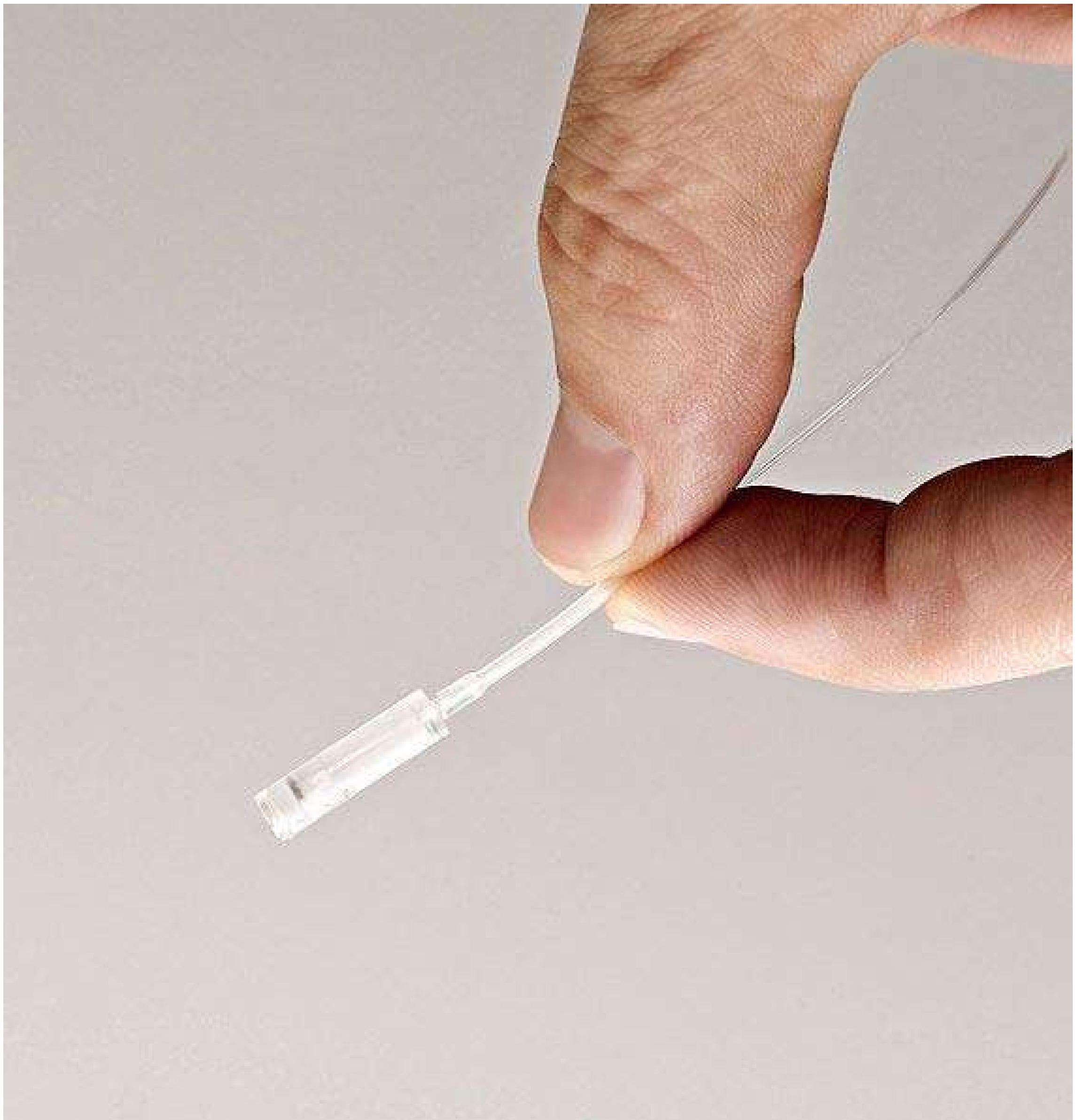
Unlike other microphone types, the carbon microphone can also be used as a type of amplifier, using a small amount of sound energy to control a larger amount of electrical energy. Carbon microphones found use as early telephone repeaters, making long distance phone calls possible in the era before vacuum tubes. These repeaters worked by mechanically coupling a magnetic telephone receiver to a carbon microphone: the faint signal from the receiver was transferred to the microphone, with a resulting stronger electrical signal to send down the line. One illustration of this amplifier effect was the oscillation caused by feedback, resulting in an audible squeal from the old "candlestick" telephone if its earphone was placed near the carbon microphone.

Piezoelectric microphone

A **crystal microphone** or **piezo microphone** uses the phenomenon of piezoelectricity — the ability of some materials to produce a voltage when subjected to pressure — to convert vibrations into an electrical signal. An example of this is potassium sodium tartrate, which is a piezoelectric crystal that works as a transducer, both as a microphone and as a slimline loudspeaker component. Crystal microphones were once commonly supplied with vacuum tube (valve) equipment, such as domestic tape recorders. Their high output impedance matched the high input impedance (typically about 10 megohms) of the vacuum tube input stage well. They were difficult to match to early transistor equipment, and were quickly supplanted by dynamic microphones for a time, and later small electret condenser devices. The high impedance of the crystal microphone made it very susceptible to handling noise, both from the microphone itself and from the connecting cable.

Piezoelectric transducers are often used as contact microphones to amplify sound from acoustic musical instruments, to sense drum hits, for triggering electronic samples, and to record sound in challenging environments, such as underwater under high pressure. Saddle-mounted pickups on acoustic guitars are generally piezoelectric devices that contact the strings passing over the saddle. This type of microphone is different from magnetic coil pickups commonly visible on typical electric guitars, which use magnetic induction, rather than mechanical coupling, to pick up vibration.

Fiber optic microphone



The Optoacoustics 1140 fiber optic microphone

A fiber optic microphone converts acoustic waves into electrical signals by sensing changes in light intensity, instead of sensing changes in capacitance or magnetic fields as with conventional microphones.

During operation, light from a laser source travels through an optical fiber to illuminate the surface of a tiny, sound-sensitive reflective diaphragm. Sound causes the diaphragm to vibrate, thereby minutely changing the intensity of the light it reflects. The modulated light is then transmitted over a second optical fiber to a photo detector, which transforms the intensity-modulated light into analog or digital audio for transmission or recording.

Fiber optic microphones possess high dynamic and frequency range, similar to the best high fidelity conventional microphones.

Fiber optic microphones do not react to or influence any electrical, magnetic, electrostatic or radioactive fields (this is called EMI/RFI immunity). The fiber optic microphone design is therefore ideal for use in areas where conventional microphones are ineffective or dangerous, such as inside industrial turbines or in magnetic resonance imaging (MRI) equipment environments.

Fiber optic microphones are robust, resistant to environmental changes in heat and moisture, and can be produced for any directionality or impedance matching. The distance between the microphone's light source and its photo detector may be up to several kilometers without need for any preamplifier and/or other electrical device, making fiber optic microphones suitable for industrial and surveillance acoustic monitoring.

Fiber optic microphones are used in very specific application areas such as for infrasound monitoring and noise-canceling. They have proven especially useful in medical applications, such as allowing radiologists, staff and patients within the powerful and noisy magnetic field to converse normally, inside the MRI suites as well as in remote control rooms.) Other uses include industrial equipment monitoring and sensing, audio calibration and measurement, high-fidelity recording and law enforcement.

Laser microphone

Laser microphones are often portrayed in movies as spy gadgets. A laser beam is aimed at the surface of a window or other plane surface that is affected by sound. The slight vibrations of this surface displace the returned beam, causing it to trace the sound wave. The vibrating laser spot is then converted back to sound. In a more robust and expensive implementation, the returned light is split and fed to an interferometer, which detects movement of the surface. The former implementation is a tabletop experiment; the latter requires an extremely stable laser and precise optics.

A new type of laser microphone is a device that uses a laser beam and smoke or vapor to detect sound vibrations in free air. On 25 August 2009, U.S. patent 7,580,533 issued for a Particulate Flow Detection Microphone based on a laser-photocell pair with a moving stream of smoke or vapor in the laser beam's path. Sound pressure waves cause disturbances in the smoke that in turn cause variations in the amount of laser light reaching the photo detector. A prototype of the device was demonstrated at the 127th Audio Engineering Society convention in New York City from 9 through 12 October 2009.

Liquid microphone

Early microphones did not produce intelligible speech, until Alexander Graham Bell made improvements including a variable resistance microphone/transmitter. Bell's liquid transmitter consisted of a metal cup filled with water with a small amount of sulfuric acid added. A sound wave caused the diaphragm to move, forcing a needle to move up and down in the water. The electrical resistance between the wire and the cup was then inversely proportional to the size of the water meniscus around the submerged needle. Elisha Gray filed a caveat for a version using a brass rod instead of the needle. Other minor variations and improvements were made to the liquid microphone by Majoranna, Chambers, Vanni, Sykes, and Elisha Gray, and one version was patented by Reginald Fessenden in 1903. These were the first working microphones, but they were not practical for commercial application. The famous first phone conversation between Bell and Watson took place using a liquid microphone.

MEMS microphone

The MEMS (MicroElectrical-Mechanical System) microphone is also called a microphone chip or silicon microphone. The pressure-sensitive diaphragm is etched directly into a silicon chip by MEMS techniques, and is usually accompanied with integrated preamplifier. Most MEMS microphones are variants of the condenser microphone design. Often MEMS microphones have built in analog-to-digital converter (ADC) circuits on the same CMOS chip making the chip a digital microphone and so more readily integrated with modern digital products. Major manufacturers producing MEMS silicon microphones are Wolfson Microelectronics (WM7xxx), Analog Devices, Akustica (AKU200x), Infineon (SMM310 product), Knowles Electronics, Memstech (MSMx), NXP Semiconductors, Sonion MEMS, AAC Acoustic Technologies, and Omron.

Speakers as microphones

A loudspeaker, a transducer that turns an electrical signal into sound waves, is the functional opposite of a microphone. Since a conventional speaker is constructed much like a dynamic microphone (with a diaphragm, coil and magnet), speakers can actually work "in reverse" as microphones. The result, though, is a microphone with poor quality, limited frequency response (particularly at the high end), and poor sensitivity. In practical use, speakers are sometimes used as microphones in applications where high quality and sensitivity are not needed such as intercoms, walkie-talkies or Video game voice chat peripherals, or when conventional microphones are in short supply.

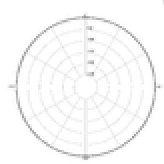
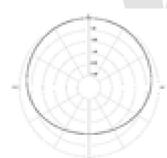
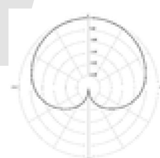
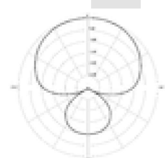
However, there is at least one other practical application of this principle: Using a medium-size woofer placed closely in front of a "kick" (bass drum) in a drum set to act as a microphone. The use of relatively large speakers to transduce low frequency sound sources, especially in music production, is becoming fairly common. A product example of this type of device is the Yamaha Subkick, a 6.5-inch (170 mm) woofer shock-mounted it into a 10" drum shell used in front of kick drums. Since a relatively massive membrane is unable to transduce high frequencies, placing a speaker in front of a kick drum is often ideal for reducing cymbal and snare bleed into the kick drum sound. Less commonly, microphones themselves can be used as speakers, almost always as tweeters. Microphones, however, are not designed to handle the power that speaker components are routinely required to cope with. One instance of such an application was the STC microphone-derived 4001 super-tweeter, which was successfully used in a number of high quality loudspeaker systems from the late 1960s to the mid-70s.

Capsule design and directivity

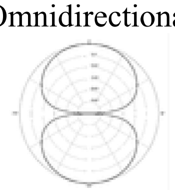
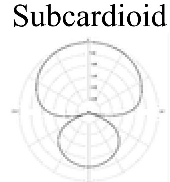
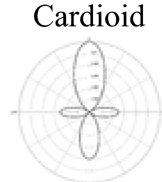
The inner elements of a microphone are the primary source of differences in directivity. A pressure microphone uses a diaphragm between a fixed internal volume of air and the environment, and responds uniformly to pressure from all directions, so it is said to be omnidirectional. A pressure-gradient microphone uses a diaphragm that is at least partially open on both sides. The pressure difference between the two sides produces its directional characteristics. Other elements such as the external shape of the microphone and external devices such as interference tubes can also alter a microphone's directional response. A pure pressure-gradient microphone is equally sensitive to sounds arriving from front or back, but insensitive to sounds arriving from the side because sound arriving at the front and back at the same time creates no gradient between the two. The characteristic directional pattern of a pure pressure-gradient microphone is like a figure-8. Other polar patterns are derived by creating a capsule that combines these two effects in different ways. The cardioid, for instance, features a partially closed backside, so its response is a combination of pressure and pressure-gradient characteristics.

Microphone polar patterns

(Microphone facing top of page in diagram, parallel to page):

Omnidirectional Subcardioid Cardioid Supercardioid

Bi-directional or Figure of 8Hypercardioid Shotgun

A microphone's directionality or polar pattern indicates how sensitive it is to sounds arriving at different angles about its central axis. The polar patterns illustrated above represent the locus of points that produce the same signal level output in the microphone if a given sound pressure level is generated from that point. How the physical body of the microphone is oriented relative to the diagrams depends on the microphone design. For large-membrane microphones such as in the Oktava (pictured above), the upward direction in the polar diagram is usually perpendicular to the microphone body, commonly known as "side fire" or "side address". For small diaphragm microphones such as the Shure (also pictured above), it usually extends from the axis of the microphone commonly known as "end fire" or "top/end address".

Some microphone designs combine several principles in creating the desired polar pattern. This ranges from shielding (meaning diffraction/dissipation/absorption) by the housing itself to electronically combining dual membranes.

Omnidirectional

An omnidirectional (or nondirectional) microphone's response is generally considered to be a perfect sphere in three dimensions. In the real world, this is not the case. As with directional microphones, the polar pattern for an "omnidirectional" microphone is a function of frequency. The body of the microphone is not infinitely small and, as a consequence, it tends to get in its own way with respect to sounds arriving from the rear, causing a slight flattening of the polar response. This flattening increases as the diameter of the microphone (assuming it's cylindrical) reaches the wavelength of the frequency in question. Therefore, the smallest diameter microphone gives the best omnidirectional characteristics at high frequencies.

The wavelength of sound at 10 kHz is little over an inch (3.4 cm) so the smallest measuring microphones are often 1/4" (6 mm) in diameter, which practically eliminates directionality even up to the highest frequencies. Omnidirectional microphones, unlike cardioids, do not employ resonant cavities as delays, and so can be considered the "purest" microphones in terms of low coloration; they add very little to the original sound. Being pressure-sensitive they can also have a very flat low-frequency response down to 20 Hz or below. Pressure-sensitive microphones also respond much less to wind noise and plosives than directional (velocity sensitive) microphones.

An example of a nondirectional microphone is the round black *eight ball*.

Unidirectional

A unidirectional microphone is sensitive to sounds from only one direction. The diagram above illustrates a number of these patterns. The microphone faces upwards in each diagram. The sound intensity for a particular frequency is plotted for angles radially from 0 to 360°. (Professional diagrams show these scales and include multiple plots at different frequencies. The diagrams given here provide only an overview of typical pattern shapes, and their names.)

Cardioids

US664A University Sound Dynamic Supercardioid Microphone

The most common unidirectional microphone is a cardioid microphone, so named because the sensitivity pattern is heart-shaped. A hyper-cardioid microphone is similar but with a tighter area of front sensitivity and a smaller lobe of rear sensitivity. A super-cardioid microphone is similar to a hyper-cardioid, except there is more front pickup and less rear pickup. These three patterns are commonly used as vocal or speech microphones, since they are good at rejecting sounds from other directions.

A cardioid microphone is effectively a superposition of an omnidirectional and a figure-8 microphone; for sound waves coming from the back, the negative signal from the figure-8 cancels the positive signal from the omnidirectional element, whereas for sound waves coming from the front, the two add to each other. A hypercardioid microphone is similar, but with a slightly larger figure-8 contribution. Since pressure gradient transducer microphones are directional, putting them very close to the sound source (at distances of a few centimeters) results in a bass boost. This is known as the proximity effect.

Bi-directional

"Figure 8" or bi-directional microphones receive sound from both the front and back of the element. Most ribbon microphones are of this pattern.

Shotgun

An Audio-Technica shotgun microphone

Shotgun microphones are the most highly directional. They have small lobes of sensitivity to the left, right, and rear but are significantly less sensitive to the side and rear than other directional microphones. This results from placing the element at the end of a tube with slots cut along the side; wave cancellation eliminates much of the off-axis sound. Due to the narrowness of their sensitivity area, shotgun microphones are commonly used on television and film sets, in stadiums, and for field recording of wildlife.

Boundary or "PZM"

Several approaches have been developed for effectively using a microphone in less-than-ideal acoustic spaces, which often suffer from excessive reflections from one or more of the surfaces (boundaries) that make up the space. If the microphone is placed in, or very close to, one of these boundaries, the reflections from that surface are not sensed by the microphone. Initially this was done by placing an ordinary microphone adjacent to the surface, sometimes in a block of acoustically transparent foam. Sound engineers Ed Long and Ron Wickersham developed the concept of placing the diaphgram parallel to and facing the boundary. While the patent has expired, "Pressure Zone Microphone" and "PZM" are still active trademarks of Crown International, and the generic term "boundary microphone" is preferred. While a boundary microphone was initially implemented using an omnidirectional element, it is also possible to mount a directional microphone close enough to the surface to gain some of the benefits of this technique while retaining the directional properties of the element. Crown's trademark on this approach is "Phase Coherent Cardioid" or "PCC," but there are other makers who employ this technique as well.

Application-specific designs

A lavalier microphone is made for hands-free operation. These small microphones are worn on the body. Originally, they were held in place with a lanyard worn around the neck, but more often they are fastened to clothing with a clip, pin, tape or magnet. The lavalier cord may be hidden by clothes and either run to an RF transmitter in a pocket or clipped to a belt (for mobile use), or run directly to the mixer (for stationary applications).

A wireless microphone transmits the audio as a radio or optical signal rather than via a cable. It usually sends its signal using a small FM radio transmitter to a nearby receiver connected to the sound system, but it can also use infrared waves if the transmitter and receiver are within sight of each other.

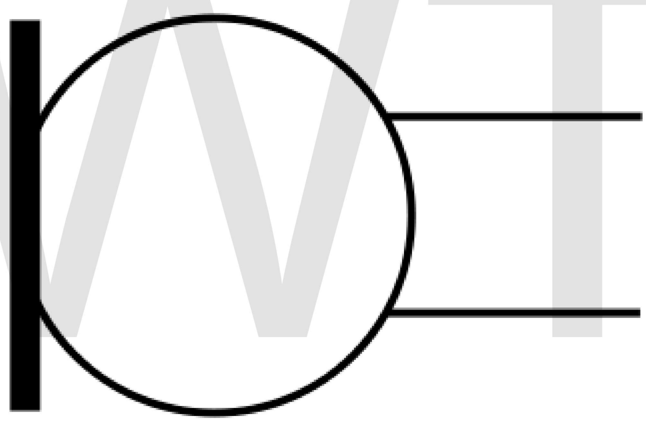
A contact microphone picks up vibrations directly from a solid surface or object, as opposed to sound vibrations carried through air. One use for this is to detect sounds of a very low level, such as those from small objects or insects. The microphone commonly consists of a magnetic (moving coil) transducer, contact plate and contact pin. The contact plate is placed directly on the vibrating part of a musical instrument or other surface, and the contact pin transfers vibrations to the coil. Contact microphones have been used to pick up the sound of a snail's heartbeat and the footsteps of ants. A portable version of this microphone has recently been developed. A throat microphone is a variant of the contact microphone that picks up speech directly from a person's throat, which it is strapped to. This lets the device be used in areas with ambient sounds that would otherwise make the speaker inaudible.

A parabolic microphone uses a parabolic reflector to collect and focus sound waves onto a microphone receiver, in much the same way that a parabolic antenna (e.g. satellite dish) does with radio waves. Typical uses of this microphone, which has unusually focused front sensitivity and can pick up sounds from many meters away, include nature recording, outdoor sporting events, eavesdropping, law enforcement, and even espionage. Parabolic microphones are not typically used for standard recording applications, because they tend to have poor low-frequency response as a side effect of their design.

A stereo microphone integrates two microphones in one unit to produce a stereophonic signal. A stereo microphone is often used for broadcast applications or field recording where it would be impractical to configure two separate condenser microphones in a classic X-Y configuration for stereophonic recording. Some such microphones have an adjustable angle of coverage between the two channels.

A noise-canceling microphone is a highly directional design intended for noisy environments. One such use is in aircraft cockpits where they are normally installed as boom microphones on headsets. Another use is on loud concert stages for vocalists. Many noise-canceling microphones combine signals received from two diaphragms that are in opposite electrical polarity or are processed electronically. In dual diaphragm designs, the main diaphragm is mounted closest to the intended source and the second is positioned farther away from the source so that it can pick up environmental sounds to be subtracted from the main diaphragm's signal. After the two signals have been combined, sounds other than the intended source are greatly reduced, substantially increasing intelligibility. Other noise-canceling designs use one diaphragm that is affected by ports open to the sides and rear of the microphone, with the sum being a 16 dB rejection of sounds that are farther away. One noise-canceling headset design using a single diaphragm has been used prominently by vocal artists such as Garth Brooks and Janet Jackson. A few noise-canceling microphones are throat microphones.

Connectors



Electronic symbol for a microphone

The most common connectors used by microphones are:

- Male XLR connector on professional microphones
- ¼ inch (sometimes referred to as 6.5 mm) jack plug also known as 1/4 inch TRS connector on less expensive consumer microphones. Many consumer microphones use an unbalanced 1/4 inch phone jack. Harmonica microphones commonly use a high impedance 1/4 inch TS connection to be run through guitar amplifiers.
- 3.5 mm (sometimes referred to as 1/8 inch mini) stereo (wired as mono) mini phone plug on very inexpensive and computer microphones

Some microphones use other connectors, such as a 5-pin XLR, or mini XLR for connection to portable equipment. Some lavalier (or 'lapel', from the days of attaching the microphone to the news reporters suit lapel) microphones use a proprietary connector for connection to a wireless transmitter. Since 2005, professional-quality microphones with USB connections have begun to appear, designed for direct recording into computer-based software.

Impedance-matching

Microphones have an electrical characteristic called impedance, measured in ohms (Ω), that depends on the design. Typically, the *rated impedance* is stated. Low impedance is considered under 600 Ω. Medium impedance is considered between 600 Ω and 10 kΩ. High impedance is above 10 kΩ. Condenser microphones (after the built-in preamp) typically have an output impedance between 50 and 200 ohms.

The output of a given microphone delivers the same power whether it is low or high impedance. If a microphone is made in high and low impedance versions, the high impedance version has a higher output voltage for a given sound pressure input, and is suitable for use with vacuum-tube guitar amplifiers, for instance, which have a high input impedance and require a relatively high signal input voltage to overcome the tubes' inherent noise. Most professional microphones are low impedance, about 200 Ω or lower. Professional vacuum-tube sound equipment incorporates a transformer that steps up the impedance of the microphone circuit to the high impedance and voltage needed to drive the input tube; the impedance conversion inherently creates voltage gain as well. External matching transformers are also available that can be used in-line between a low impedance microphone and a high impedance input.

Low-impedance microphones are preferred over high impedance for two reasons: one is that using a high-impedance microphone with a long cable results in high frequency signal loss due to cable capacitance, which forms a low-pass filter with the microphone output impedance. The other is that long high-impedance cables tend to pick up more hum (and possibly radio-frequency interference (RFI) as well). Nothing is damaged if the impedance between microphone and other equipment is mismatched; the worst that happens is a reduction in signal or change in frequency response.

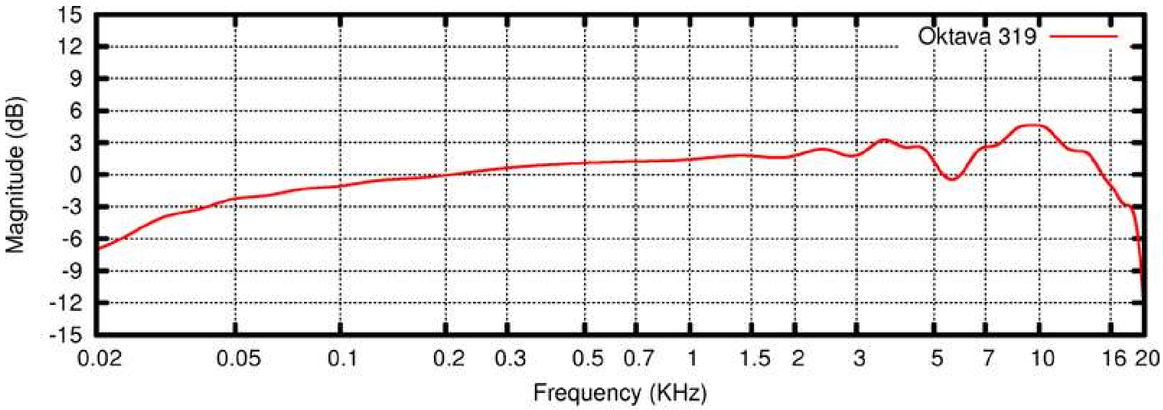
Most microphones are designed *not* to have their impedance matched by the load they are connected to. Doing so can alter their frequency response and cause distortion, especially at high sound pressure levels. Certain ribbon and dynamic microphones are exceptions, due to the designers' assumption of a certain load impedance being part of the internal electro-acoustical damping circuit of the microphone.

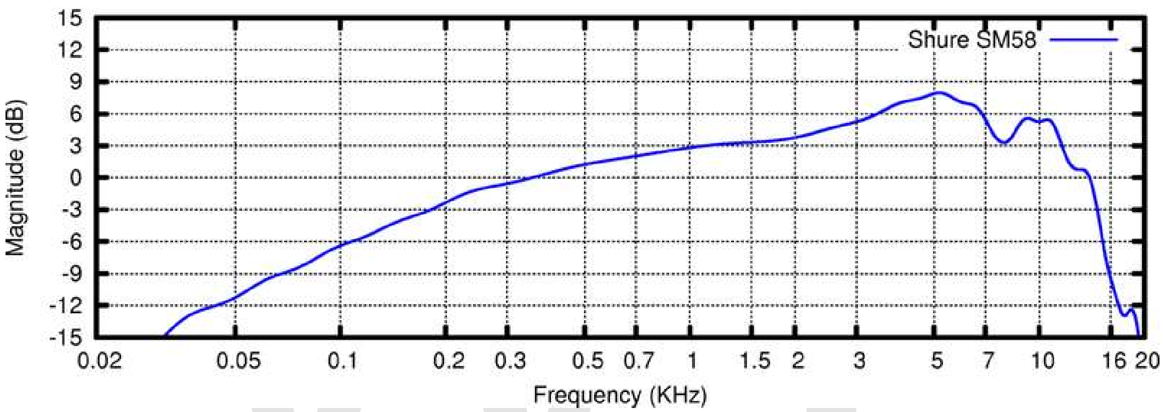
Digital microphone interface

Neumann D-01 digital microphone and Neumann DMI-8 8-channel USB Digital Microphone Interface

The AES 42 standard, published by the Audio Engineering Society, defines a digital interface for microphones. Microphones conforming to this standard directly output a digital audio stream through an XLR male connector, rather than producing an analog output. Digital microphones may be used either with new equipment with appropriate input connections that conform to the AES 42 standard, or else via a suitable interface box. Studio-quality microphones that operate in accordance with the AES 42 standard are now available from a number of microphone manufacturers.

Measurements and specifications





A comparison of the far field on-axis frequency response of the Oktava 319 and the Shure SM58

Because of differences in their construction, microphones have their own characteristic responses to sound. This difference in response produces non-uniform phase and frequency responses. In addition, microphones are not uniformly sensitive to sound pressure, and can accept differing levels without distorting. Although for scientific applications microphones with a more uniform response are desirable, this is often not the case for music recording, as the non-uniform response of a microphone can produce a desirable coloration of the sound. There is an international standard for microphone specifications, but few manufacturers adhere to it. As a result, comparison of published data from different manufacturers is difficult because different measurement techniques are used. The Microphone Data Website has collated the technical specifications complete with pictures, response curves and technical data from the microphone manufacturers for every currently listed microphone, and even a few obsolete models, and shows the data for them all in one common format for ease of comparison.. Caution should be used in drawing any solid conclusions from this or any other published data, however, unless it is known that the manufacturer has supplied specifications in accordance with IEC 60268-4.

A frequency response diagram plots the microphone sensitivity in decibels over a range of frequencies (typically at least 0–20 kHz), generally for perfectly on-axis sound (sound arriving at 0° to the capsule). Frequency response may be less informatively stated textually like so: "30 Hz–16 kHz ±3 dB". This is interpreted as meaning a nearly flat, linear, plot between the stated frequencies, with variations in amplitude of no more than plus or minus 3 dB. However, one cannot determine from this information how *smooth* the variations are, nor in what parts of the spectrum they occur. Note that commonly made statements such as "20 Hz–20 kHz" are meaningless without a decibel measure of tolerance. Directional microphones' frequency response varies greatly with distance from the sound source, and with the geometry of the sound source. IEC 60268-4 specifies that frequency response should be measured in *plane progressive wave* conditions (very far away from the source) but this is seldom practical. *Close talking* microphones may be measured with different sound sources and distances, but there is no standard and therefore no way to compare data from different models unless the measurement technique is described.

The self-noise or equivalent noise level is the sound level that creates the same output voltage as the microphone does in the absence of sound. This represents the lowest point of the microphone's dynamic range, and is particularly important should you wish to record sounds that are quiet. The measure is often stated in dB(A), which is the equivalent loudness of the noise on a decibel scale frequency-weighted for how the ear hears, for example: "15 dBA SPL" (SPL means sound pressure level relative to 20 micropascals). The lower the number the better. Some microphone manufacturers state the noise level using ITU-R 468 noise weighting, which more accurately represents the way we hear noise, but gives a figure some 11–14 dB higher. A quiet microphone typically measures 20 dBA SPL or 32 dB SPL 468-weighted. Very quiet microphones have existed for years for special applications, such the Brüel & Kjaer 4179, with a noise level around 0 dB SPL. Recently some microphones with low noise specifications have been introduced in the studio/entertainment market, such as models from Neumann and Røde that advertise noise levels between 5–7 dBA. Typically this is achieved by altering the frequency response of the capsule and electronics to result in lower noise within the A-weighting curve while broadband noise may be increased.

The maximum SPL (sound pressure level) the microphone can accept is measured for particular values of total harmonic distortion (THD), typically 0.5%. This amount of distortion is generally inaudible, so one can safely use the microphone at this SPL without harming the recording. Example: "142 dB SPL peak (at 0.5% THD)". The higher the value, the better, although microphones with a very high maximum SPL also have a higher self-noise.

The clipping level is perhaps a better indicator of maximum usable level, as the 1% THD figure usually quoted under max SPL is really a very mild level of distortion, quite inaudible especially on brief high peaks. Harmonic distortion from microphones is usually of low-order (mostly third harmonic) type, and hence not very audible even at 3–5%. Clipping, on the other hand, usually caused by the diaphragm reaching its absolute displacement limit (or by the preamplifier), produces a harsh sound on peaks, and should be avoided if at all possible. For some microphones the clipping level may be much higher than the max SPL.

The dynamic range of a microphone is the difference in SPL between the noise floor and the maximum SPL. If stated on its own, for example "120 dB", it conveys significantly less information than having the self-noise and maximum SPL figures individually.

Sensitivity indicates how well the microphone converts acoustic pressure to output voltage. A high sensitivity microphone creates more voltage and so needs less amplification at the mixer or recording device. This is a practical concern but is not directly an indication of the mic's quality, and in fact the term sensitivity is something of a misnomer, 'transduction gain' being perhaps more meaningful, (or just "output level") because true sensitivity is generally set by the noise floor, and too much "sensitivity" in terms of output level compromises the clipping level. There are two common measures. The (preferred) international standard is made in millivolts per pascal at 1 kHz. A higher value indicates greater sensitivity. The older American method is referred to a 1 V/Pa standard and measured in plain decibels, resulting in a negative value. Again, a higher value indicates greater sensitivity, so −60 dB is more sensitive than −70 dB.

Measurement microphones

Some microphones are intended for testing speakers, measuring noise levels and otherwise quantifying an acoustic experience. These are calibrated transducers and are usually supplied with a calibration certificate that states absolute sensitivity against frequency. The quality of measurement microphones is often referred to using the designations "Class 1," "Type 2" etc., which are references not to microphone specifications but to sound level meters. A more comprehensive standard for the description of measurement microphone performance was recently adopted.

Measurement microphones are generally scalar sensors of pressure; they exhibit an omnidirectional response, limited only by the scattering profile of their physical dimensions. Sound intensity or sound power measurements require pressure-gradient measurements, which are typically made using arrays of at least two microphones, or with hot-wire anemometers.

Microphone calibration

To take a scientific measurement with a microphone, its precise sensitivity must be known (in volts per pascal). Since this may change over the lifetime of the device, it is necessary to regularly calibrate measurement microphones. This service is offered by some microphone manufacturers and by independent certified testing labs. All microphone calibration is ultimately traceable to primary standards at a national measurement institute such as NPL in the UK, PTB in Germany and NIST in the USA, which most commonly calibrate using the reciprocity primary standard. Measurement microphones calibrated using this method can then be used to calibrate other microphones using comparison calibration techniques.

Depending on the application, measurement microphones must be tested periodically (every year or several months, typically) and after any potentially damaging event, such as being dropped (most such mikes come in foam-padded cases to reduce this risk) or exposed to sounds beyond the acceptable level.

Microphone array and array microphones

A microphone array is any number of microphones operating in tandem. There are many applications:

- Systems for extracting voice input from ambient noise (notably telephones, speech recognition systems, hearing aids)
- Surround sound and related technologies
- Locating objects by sound: acoustic source localization, e.g. military use to locate the source(s) of artillery fire. Aircraft location and tracking.
- High fidelity original recordings
- 3D spatial beamforming for localized acoustic detection of subcutaneous sounds

Typically, an array is made up of omnidirectional microphones distributed about the perimeter of a space, linked to a computer that records and interprets the results into a coherent form.

Microphone windscreens

Windscreens are used to protect microphones that would otherwise be buffeted by wind or vocal plosives from consonants such as "P", "B", etc. Most microphones have an integral windscreen built around the microphone diaphragm. A screen of plastic, wire mesh or a metal cage is held at a distance from the microphone diaphragm, to shield it. This cage provides a first line of defense against the mechanical impact of objects or wind. Some microphones, such as the Shure SM58, may have an additional layer of foam inside the cage to further enhance the protective properties of the shield. One disadvantage of all windscreen types is that the microphone's high frequency response is attenuated by a small amount, depending on the density of the protective layer.

Beyond integral microphone windscreens, there are three broad classes of additional wind protection.

Microphone covers

Various microphone covers

Microphone covers are often made of soft open-cell polyester or polyurethane foam because of the inexpensive, disposable nature of the foam. Optional windscreens are often available from the manufacturer and third parties. A visible example of an optional accessory windscreen is the A2WS from Shure, one of which is fitted over each of the two Shure SM57 microphones used on the United States president's lectern. One disadvantage of polyurethane foam microphone covers is that they can deteriorate over time. Windscreens also tend to collect dirt and moisture in their open cells and must be cleaned to prevent high frequency loss, bad odor and unhealthy conditions for the person using the microphone. On the other hand, a major advantage of concert vocalist windscreens is that one can quickly change to a clean windscreen between users, reducing the chance of transferring germs. Windscreens of various colors can be used to distinguish one microphone from another on a busy, active stage.

Pop filters

Pop filters or pop screens are used in controlled studio environments to minimize plosives when recording. A typical pop filter is composed of one or more layers of acoustically transparent gauze-like material, such as woven nylon (e.g. pantyhose) stretched over a circular frame and a clamp and a flexible mounting bracket to attach to the microphone stand. The pop shield is placed between the vocalist and the microphone. The need for a pop filter increases the closer a vocalist brings his or her lips to the microphone. Singers can be trained either to soften their plosives or direct the air blast away from the microphone, in which cases they don't need a pop filter.

Pop filters also keep spittle off the microphone. Most condenser microphones can be damaged by spittle.

Blimps

Two recordings being made—A *blimp* is being used on the left. An open-cell foam windscreen is being used on the right.

Blimps (also known as Zeppelins) are large, hollow windscreens used to surround microphones for outdoor location audio, such as nature recording, electronic news gathering, and for film and video shoots. They can cut wind noise by as much as 25 dB, especially low-frequency noise. The blimp is essentially a hollow cage or basket with acoustically transparent material stretched over the outer frame. The blimp works by creating a volume of still air around the microphone. The microphone is often further isolated from the blimp by an elastic suspension inside the basket. This reduces wind vibrations and handling noise transmitted from the cage. To extend the range of wind speed conditions in which the blimp remains effective, many have the option of a secondary cover over the outer shell. This is usually an acoustically transparent, synthetic fur material with long, soft hairs. Common and slang names for this include "dead cat" or "windmuff". The hairs deaden the noise caused by the shock of wind hitting the blimp. A synthetic fur cover can reduce wind noise by an additional 10 dB.

Chapter- 7

Speed Sensors

Speed sensors are machines used to detect the speed of an object, usually a transport vehicle.

Wheel speed sensor

A **wheel speed sensor** or vehicle speed sensor (VSS) is a type of tachometer. It is a sender device used for reading the speed of a vehicle's wheel rotation. It usually consists of a toothed ring and pickup.

Special purpose speed sensors

Road vehicles

Wheel speed sensors are used in anti-lock braking systems.

Rotary speed sensors for rail vehicles

Many of the subsystems in a rail vehicle, such as a locomotive or multiple unit, depend on a reliable and precise rotary speed signal, in some cases as a measure of the speed or changes in the speed. This applies in particular to traction control, but also to wheel slide protection, registration, train control, door control and so on. These tasks are performed by a number of rotary speed sensors that may be found in various parts of the vehicle.

In the past, sensors for this purpose often failed to function satisfactorily or were not reliable enough and gave rise to vehicle faults. This was particularly the case for the early mainly analogue sensors, but digital models were also affected.

This was mainly due to the extremely harsh operating conditions encountered in rail vehicles. The relevant standards specify detailed test criteria, but in practical operation the conditions encountered are often even more extreme (such as shock/vibration and especially electromagnetic compatibility (EMC)).

Rotary speed sensors for motors

Bearingless motor speed sensors

Although rail vehicles occasionally do use drives without sensors, most need a rotary speed sensor for their regulator system. The most common type is a two-channel sensor that scans a toothed wheel on the motor shaft or gearbox and therefore does not require a bearing of its own.

The target wheel can be provided especially for this purpose or may be already present in the drive system. Modern sensors of this type make use of the principle of magnetic field modulation and are suitable for ferromagnetic target wheels with a module between m =1 and m = 3.5 (D.P.=25 to D.P.=7). The form of the teeth is of secondary importance; target wheels with involute or rectangular toothing can be scanned. Depending on the diameter and teeth of the wheel it is possible to get between 60 and 300 pulses per revolution, which is sufficient for drives of lower and medium traction performance.

This type of sensor normally consists of two hall effect sensors, a rare earth magnet and appropriate evaluation electronics. The field of the magnet is modulated by the passing target teeth. This modulation is registered by the Hall sensors, converted by a comparator stage to a square wave signal and amplified in a driver stage.

Unfortunately, the Hall effect varies greatly with temperature. The sensors' sensitivity and also the signal offset therefore depend not only on the air gap but also on the temperature. This also very much reduces the maximum permissible air gap between the sensor and the target wheel. At room temperature an air gap of 2 to 3 mm can be tolerated without difficulty for a typical target wheel of module m = 2, but in the required temperature range of from 40°C to 120°C the maximum gap for effective signal registration drops to 1.3 mm. Smaller pitch target wheels with module m = 1 are often used to get a higher time resolution or to make the construction more compact. In this case the maximum possible air gap is only 0.5 to 0.8 mm.

For the design engineer, the visible air gap that the sensor ends up with is primarily the result of the specific machine design, but is subject to whatever constraints are needed to register the rotary speed. If this means that the possible air gap has to lie within a very small range, then this will also restrict the mechanical tolerances of the motor housing and target wheels to prevent signal dropouts during operation. This means that in practice there may be problems, particularly with smaller pitched target wheels of module m = 1 and disadvantageous combinations of tolerances and extreme temperatures. From the point of view of the motor manufacturer, and even more so the operator, it is therefore better to look for speed sensors with a wider range of air gap.

The primary signal from a Hall sensor loses amplitude sharply as the air gap increases. For sensor manufacturers this means that they need to provide maximum possible compensation for the Hall signal's physically induced offset drift. The conventional way of doing this is to measure the temperature at the sensor and use this information to compensate the offset, but this fails for two reasons: firstly because the drift does not vary linearly with the temperature, and secondly because not even the sign of the drift is the same for all sensors.

For a new sensor generation it was therefore necessary to find another way: an integrated signal processor now corrects the offset and amplitude of the Hall sensor signals. This correction is so effective that one can almost double the maximum permissible air gap at the speed sensor. On a module m = 1 target wheel these new sensors can tolerate an air gap of 1.4 mm, which is wider than that for conventional speed sensors on module m = 2 target wheels. On a module m = 2 target wheel the new speed sensors can tolerate gap of as much as 2.2 mm. It has also been possible to markedly increase the signal quality. Both the duty cycle and the phase displacement between the two channels is at least three times as stable in the face of fluctuating air gap and temperature drift.

In addition, in spite of the complex electronics it has also been possible to increase the MTBF for the new speed sensors by a factor of three to four. So they not only provide more precise signals, their signal availability is also significantly better.

These new sensors, still with the familiar appearance, thus open up whole new possibilities for the designers of drives for rolling stock. The sensors are attractively priced and operate without wear and tear.

Motor encoders with integrated bearings

There is a limit on the number of pulses achievable by sensors without integrated bearings: with a 300 mm diameter target wheel it is normally not possible to get beyond 300 pulses per revolution. But many locomotives and electric multiple units (EMUs) need higher numbers of pulses for proper operation of the traction converter, for instance when there are tight constraints on the traction regulator at low speeds. Such applications really need encoders with built-in bearings, which can tolerate an air gap many orders of magnitude smaller because of the greatly reduced play on the actual sensor as opposed to that of the motor bearing. This makes it possible to choose a much smaller pitch for the measuring scale, right down to module m = 0.22. There are a number of types of encoder with this property. One of them is used in large numbers in EMUs. It can be used to achieve values from less than 100 to more than 130 000 pulses per revolution. In railway applications however, the maximum possible pulses per revolution are not required.

For even greater robustness and signal accuracy a precision encoder can be used.

The functional principles of the two encoders are similar: a multichannel magneto-resistive sensor scans a target wheel with 256 teeth, generating sine and cosine signals. Arctangent interpolation is used to generate up to 512 rectangular pulses from each of the 256 signal periods per revolution. The precision encoder also possesses amplitude and offset correction functions that are housed in the external interpolation unit. This makes it possible to further improve the signal quality, which has a very positive effect on the traction regulator.

Speed sensors on the wheelset

Bearingless wheelset speed sensors

Bearingless speed sensors may be found in almost every wheelset of a rail vehicle. They are principally used for wheel slide protection and usually supplied by the manufacturer of the wheel slide protection system. These sensors require a sufficiently small air gap and need to be particularly reliable. One special feature of rotary speed sensors that are used for wheel slide protection is their integrated monitoring functions. Two-wire sensors with a current output of 7 mA/14 mA are used to detect broken cables. Other designs provide for an output voltage of around 7 V as soon as the signal frequency drops below 1 Hz. Another method used is to detect a 50 MHz output signal from the sensor when the power supply is periodically modulated at 50 MHz. It is also common for two-channel sensors to have electrically isolated channels.

Occasionally it is necessary to take off the wheel slide protection signal at the traction motor, and the output frequency is then often too high for the wheel slide protection electronics. For this application there is a speed sensor with an integrated frequency divider. There are now products available that are compliant with all the usual standards, with considerably improved technical properties and markedly longer useful lives.

Wheelset pulse generator with integrated bearing

A rail vehicle, particularly a locomotive, generally possesses numerous subsystems that require a separate electrically separated speed signal. There usually is neither enough mounting places nor is there sufficient space where separate pulse generators could be installed.

For many years there have therefore been multichannel pulse generators that are flange-mounted onto the bearing shells or covers of wheelsets. These have the advantage over bearingless models that they can generate markedly higher pulse numbers. Using a number of bearingless speed sensors would also involve additional cables, which should preferably be avoided for outdoor equipment because they are so susceptible to damage, for instance from flying track ballast.

Optical sensor

All the manufacturers previously active in this market used mainly optical sensors.

From one to four channels can be implemented, each channel having a photosensor that scans one of at most two signal tracks on a slotted disk. Experience shows that the possible number of channels achievable by this technique is still not enough. A number of subsystems therefore have to make do with looped-through signals from the wheel slide protection electronics and are therefore forced to accept, for instance, the available number of pulses, although a separate speed signal might well have some advantages.

The use of optical sensors has been familiar for many years and is widespread in industry. Unfortunately they do have two fundamental weaknesses that have always made it very difficult to get them to function reliably over a number of years, namely - the optical components are extremely susceptible to dirt, and - the light source ages too quickly.

Even traces of dirt greatly reduce the amount of light that passes through the lens and can cause signal dropout. These encoders are therefore required to be very well sealed. Even sealing the encoder bearing to prevent it emitting grease is a problem that even the ingenuity of designers has been unable to fully resolve. Further problems are encountered when the pulse generators are used in environments in which the dew point is passed: the lenses fog and the signal is frequently interrupted.

The light sources used are light-emitting diodes (LEDs). But LEDs are always subject to ageing, which over a few years leads to a noticeably reduced beam. Attempts are made to compensate for this by using special regulators that gradually increase the current through the LED, but unfortunately this further accelerates the ageing process.

Magnetic sensor

The principle used in scanning a ferromagnetic measuring scale magnetically does not exhibit these deficiencies. During many years' experience of using magnetic encoders there have been occasions when a seal has failed and a pulse generator has been found to be completely covered in a thick layer of brake dust and other dirt, but such pulse generators still functioned perfectly.

Magnetic scanning systems were previously simply too expensive to use, but recently a multichannel pulse generator became available that is not only fundamentally superior to previous pulse generators in its robustness and resistant to dirt, but also sets a new standard for flexibility. Here, for comparison, are a few of its key features:

- from one to eight channels, instead of the previous one to four
- up to three different pulse values per revolution from a single encoder, instead of the previous two
- from 1 to 400 pulses per revolution, instead of the previously achieved 200
- voltage output, current output, signals with a 7 V idle voltage, instead of only a voltage output as previously

There is now a new variant with a maximised hysteresis of ± 90° relative to a signal period. When installed under unfavourable conditions and exposed to severe vibration this variant suppresses any extraneous pulses while the vehicle is at a standstill.

Altogether, these innovative pulse generators offer new features that also open up entirely new possibilities for system integrators.

It is possibly to supply significantly more subsystems with independent, electrically isolated output signals. And naturally installation compatible pulse generators can be configured for all the usual previously marketed products.

The magnetic measuring principle and optimised bearing technology increases the pulse generators' reliability, not only increasing maintenance intervals but also significantly reducing maintenance costs.

Pulse generators constructed in accordance with this principle have been successfully field tested by several rail operators since the beginning of 2005. The type test specified in EN 50155 has also been successfully completed, so that these pulse generators can now be delivered.

Wheelset pulse generators with integrated bearings for inside-journal bogies

Inside-journal bogies make particular demands on the pulse generator designer because they have no bearing cover on the end to serve as the basis from which the rotation of the wheelset shaft could be registered. In this case the pulse generator has to be mounted on a shaft stub attached to the wheelset and fitted with a torque converter connected to the bogie frame to prevent it from rotating.

The extreme vibration in this location leads to a considerable load on the pulse generator bearing, which, with this method of installation has to carry not only the relatively small mass of the pulse generator shaft but that of the entire pulse generator. When we consider that bearing life reduces with at least the third power of the load we can see that a reliable and durable pulse generator for such a situation cannot merely be adapted from the more common standard pulse generator for outside-journal bogies merely by fitting and intermediate flange or similar construction. It really is necessary to have a pulse generator with a modified design adapted to the requirements of such a location.

Previously these pulse generator were available only with considerably restricted technical properties, for instance limited to at most 140 pulses per revolution or a limited number of channels. A new product has now been developed that offers the complete specification for a wheelset pulse generator in a housing that was specially designed for installation in inside-journal bogies.

Speed sensors for non-magnetic target wheels or applications that produce swarf

Some transport companies are faced with a special problem: the circulating air that keeps the motors cool carries swarf abraded from the wheels and rails. This collects on the heads of magnetic sensors and can cause malfunctions. Such a "magnetic short circuit" can cause dropouts or complete loss of signal. And there have been cases where encoders have been physically damaged by the abrasive effect of the particles.

There are also increasingly motors in which sensors have to scan aluminium target wheels, for instance because the impellers are made of an aluminium alloy and the manufacturer does not wish to have to shrink on a separate ferromagnetic gear rim.

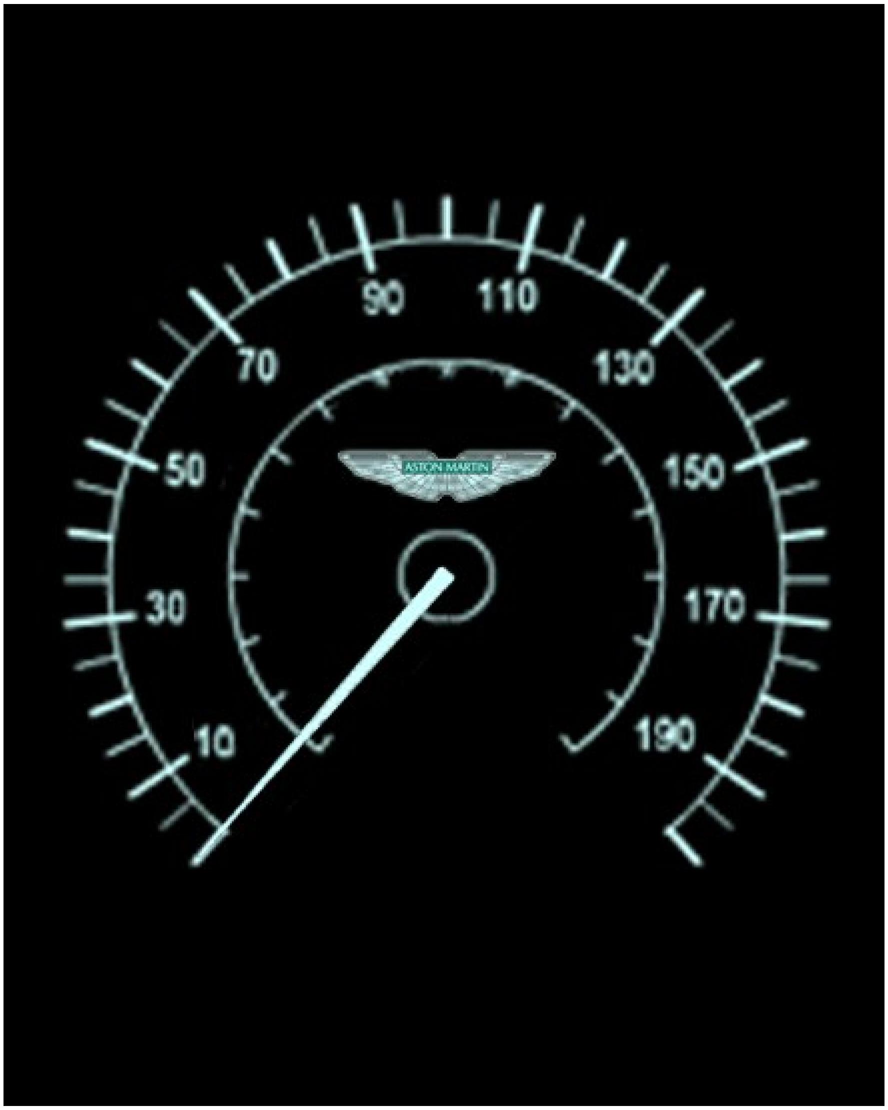
For these applications there is a speed sensor available that gets by without a magnet. A number of transmitting and receiving coils are used to generate an alternating electric field with a frequency of the order of 1 MHz and the modulation of the coupling between senders and receivers is then evaluated. This sensor is installation and signal compatible to the magnetic sensors; for most common target wheel modules the units can simply be replaced without any other measures being necessary.

Over the last few years these sensor have been able to drastically reduce the failure rates of many transport companies when installed in the critical environments described above.

Speed sensors with pulse doubling

Customers often want a higher number of pulses per revolution than can be achieved in the space available and with the smallest module m = 1. An industry standard flange-compatible speed sensor has been developed for such applications that generates two pulses for each tooth of the wheel. This makes it possible to achieve 600 pulses per revolution with a target wheel module m = 1 and a diameter of 300 mm. These speed sensors are currently being tested at a major system integrators.

Speedometer



An image of an Aston Martin speedometer, showing how an eddy-current speedometer indicates the vehicle's speed.

A **speedometer** is a device that measures the instantaneous speed of a land vehicle.

Now universally fitted to motor vehicles, they started to be available as options in the 1900s, and as standard equipment from about 1910 onwards.

Speedometers for other vehicles have specific names and use other means of sensing speed. For a boat, this is a pit log. For an aircraft, this is an airspeed indicator.

The speedometer was invented by the Croatian Josip Belušić in 1888, and was originally called a velocimeter.

Operation

Eddy current

An eddy-current speedometer gauge on a car, showing the speed of the vehicle in kilometres per hour. Also shown is the tachometer, which displays the rate of rotation of the engine's crankshaft.

The eddy current speedometer has been used for over a century and is still in widespread use. Until the 1980s and the appearance of electronic speedometers it was the only type commonly used.

Originally patented by a German, Otto Schulze on 7 October 1902, it uses a rotating flexible cable usually driven by gearing linked to the tail shaft (output) of the vehicle's transmission. The early Volkswagen Beetle and many motorcycles, however, use a cable driven from a front wheel.

A small permanent magnet affixed to the rotating cable interacts with a small aluminum cup (called a *speedcup*) attached to the shaft of the pointer on the analogue instrument. As the magnet rotates near the cup, the changing magnetic field produces eddy currents in the cup, which themselves produce another magnetic field. The effect is that the magnet "drags" the cup, and thus the speedometer pointer, in the direction of its rotation with no mechanical connection between them.

The pointer shaft is held toward zero by a fine spring. The torque on the cup increases with the speed of rotation of the magnet (which is driven by the car's transmission.) Thus an increase in the speed of the car will twist the cup and speedometer pointer against the spring. When the torque due to the eddy currents in the cup equals that provided by the spring on the pointer shaft, the pointer will remain motionless and pointing to the appropriate number on the speedometer's dial.

The return spring is calibrated such that a given revolution speed of the cable corresponds to a specific speed indication on the speedometer. This calibration must take into account several factors, including ratios of the tailshaft gears that drive the flexible cable, the final drive ratio in the differential, and the diameter of the driven tires.

Electronic

Many modern speedometers are electronic. A rotation sensor, usually mounted on the rear of the transmission, delivers a series of electronic pulses whose frequency corresponds to the rotational speed of the driveshaft. The sensor is typically a toothed metal disk positioned between a coil and a magnetic field sensor. As the disk turns, the teeth pass between the two, each time producing a pulse in the sensor as they affect the strength of the magnetic field it is measuring. Alternatively, some manufactures rely on pulses coming from the ABS wheel sensors.

A computer converts the pulses to a speed and displays this speed on an electronically-controlled, analog-style needle or a digital display. Pulse counts may also be used to increment the odometer.

Another early form of electronic speedometer relies upon the interaction between a precision watch mechanism and a mechanical pulsator driven by the car's wheel or transmission. The watch mechanism endeavors to push the speedometer pointer toward zero, while the vehicle-driven pulsator tries to push it toward infinity. The position of the speedometer pointer reflects the relative magnitudes of the outputs of the two mechanisms.

Changing a car's tire size can throw off a speedometer's accuracy.

Bicycle Speedometers

Some speedometers for bicycles measure the time between each wheel revolution. The sensor is mounted on the bike at a fixed location, pulsing when the spoke-mounted magnet passes by. These digital devices can be programmed by tire size or by wheel circumference in order to make accurate distance measurements. Others are cable driven as in the automotive speedometers described above.

Error

Most speedometers have tolerances of some 10% plus or minus due to wear on tires as it occurs. Additional sources of error are tire diameter variations due to temperature, pressure, vehicle load, and nominal tire size.

Excessive speedometer error after manufacture can come from several causes but most commonly is due to nonstandard tire diameter, in which case the

percent error = 100x(1 - "new diameter"/"standard diameter").

Nearly all tires now have their size shown as "T/A_W" on the side of the tire, and the tire's

diameter in inches = TxA/1270 + W.

For example, a standard tire is "185/70R14" with diameter = 185x70/1270 + 14 = 24.20 in. Another is "195/50R15" with 195x50/1270 + 15 = 22.68 in. Replacing the first tire (and wheels) with the second (on 15" wheels), a speedometer reads 1 - 22.68/24.20 = 0.0628 times the correct speed, 6.28%, too high. At an actual speed of 60 mph, the speedometer will indicate 60 * 1.0628 = 63.77 mph, approximately.

International agreements

In many countries the legislated error in speedometer readings is ultimately governed by the United Nations Economic Commission for Europe (UNECE) Regulation 39 which covers those aspects of vehicle type approval which relate to speedometers. The main purpose of the UNECE regulations is to facilitate trade in motor vehicles by agreeing uniform type approval standards rather than requiring a vehicle model to undergo different approval processes in each country in which it is to be sold.

European Union member states must also grant type approval to vehicles meeting similar EU standards. The ones covering speedometers are similar to the UNECE regulation in that they specify that:

- The indicated speed must never be less than the actual speed, i.e. it should not be possible to inadvertently speed because of an incorrect speedometer reading.
- The indicated speed must not be more than 110 percent of the true speed plus 4 km/h at specified test speeds. For example, at 80 km/h, the indicated speed must be no more than 92 km/h.

The standards specify both the limits on accuracy and many of the details of how it should be measured during the approvals process, for example that the test measurements should be made (for most vehicles) at 40, 80 and 120 km/h, and at a particular ambient temperature. There are slight differences between the different standards, for example in the minimum accuracy of the equipment measuring the true speed of the vehicle.

The UNECE regulation relaxes the requirements for vehicles mass produced following type approval. At Conformity of Production Audits the upper limit on indicated speed is increased to 110 percent plus 6 km/h for cars, buses, trucks and similar vehicles, and 110 percent plus 8 km/h for two or three wheeled vehicles which have a maximum speed above 50 km/h (or a cylinder capacity, if powered by a heat engine, of more than 50 cc). European Union Directive 2000/7/EC, which relates to two and three wheeled vehicles, provides similar slightly relaxed limits in production.

Australia

There were no design rules in place for speedometers in Australia prior to July 1988. They had to be introduced when speed cameras were first used. This means there are no legally accurate speedometers for these older vehicles. All vehicles manufactured on or after 1 July 2007, and all models of vehicle introduced on or after 1 July 2006, must conform to UNECE Regulation 39.

The speedometers in vehicles manufactured before these dates but after 1 July 1995 (or 1 January 1995 for forward control passenger vehicles and off-road passenger vehicles) must conform to the previous Australian design rule. This specifies that they need only display the speed to an accuracy of +/- 10% at speeds above 40 km/h, and there is no specified accuracy at all for speeds below 40 km/h. All vehicles manufactured in Australia or imported for supply to the Australian market must comply with the Australian Design Rules.

The state and territory governments may set policies for the tolerance of speed over the posted speed limits that may be lower than the 10% in the earlier versions of the Australian Design Rules permitted, such as in Victoria. This has caused some controversy since it would be possible for a driver to be unaware that he is speeding should his vehicle be fitted with an under-reading speedometer.

United Kingdom

A speedometer showing mph and km/h along with an odometer and a separate 'trip' odometer (both showing distance traveled in miles).

The amended Road Vehicles (Construction and Use) Regulations 1986 permits the use of speedometers that meet either the requirements of EC Council Directive 75/443 (as amended by Directive 97/39) or UNECE Regulation 39.

The Motor Vehicles (Approval) Regulations 2001 permits single vehicles to be approved. As with the UNECE regulation and the EC Directives, the speedometer must never show an indicated speed less than the actual speed. However it differs slightly from them in specifying that for all actual speeds between 25 mph and 70 mph (or the vehicles' maximum speed if it is lower that this), the indicated speed must not exceed 110% of the actual speed, plus 6.25 mph.

For example, if the vehicle is actually travelling at 50 mph, the speedometer must not show more than 61.25 mph or less than 50 mph.

United States

As of 1997, Federal standards in the United States allowed a maximum 5% error on speedometer readings. Aftermarket modifications, such as different tire and wheel sizes or different differential gearing, can cause speedometer inaccuracy.

GPS

GPS devices are capable of showing speed readings based on how far the receiver has moved since the last measurement. As the GPS is an independent* system, its speed calculations are not subject to the same sources of error as the vehicle's speedometer. Instead, the GPS's positional accuracy, and therefore the accuracy of its calculated speed, is dependent on the satellite signal quality at the time. Speed calculations will be more accurate at higher speeds, when the ratio of positional error to positional change is lower. The GPS software may also use a moving average calculation to reduce error.

As mentioned in the satnav article, GPS data has been used to overturn a speeding ticket; the GPS logs showed the defendant traveling below the speed limit when they were ticketed. That the data came from a GPS device was likely less important than the fact that it was logged; logs from the vehicle's speedometer could likely have been used instead, had they existed.

Chapter- 8

Engine Sensors

Oxygen sensor

An **oxygen sensor**, or **lambda sensor**, is an electronic device that measures the proportion of oxygen (O_2) in the gas or liquid being analyzed. It was developed by Robert Bosch GmbH during the late 1960s under supervision by Dr. Günter Bauman. The original sensing element is made with a thimble-shaped zirconia ceramic coated on both the exhaust and reference sides with a thin layer of platinum and comes in both heated and unheated forms. The planar-style sensor entered the market in 1998 (also pioneered by Robert Bosch GmbH) and significantly reduced the mass of the ceramic sensing element as well as incorporating the heater within the ceramic structure. This resulted in a sensor that both started operating sooner and responded faster. The most common application is to measure the exhaust gas concentration of oxygen for internal combustion engines in automobiles and other vehicles. Divers also use a similar device to measure the partial pressure of oxygen in their breathing gas.

Scientists use oxygen sensors to measure respiration or production of oxygen and use a different approach. Oxygen sensors are used in oxygen analyzers which find a lot of use in medical applications such as anesthesia monitors, respirators and oxygen concentrators.

There are many different ways of measuring oxygen and these include technologies such as zirconia, electrochemical (also known as Galvanic), infrared, ultrasonic and very recently laser. Each method has its own advantages and disadvantages.

Automotive applications

A three-wire oxygen sensor suitable for use in a Volvo 240 or similar

Automotive oxygen sensors, colloquially known as O_2 sensors, make modern electronic fuel injection and emission control possible. They help determine, in real time, if the air fuel ratio of a combustion engine is rich or lean. Since oxygen sensors are located in the exhaust stream, they do not directly measure the air or the fuel entering the engine. But when information from oxygen sensors is coupled with information from other sources, it can be used to indirectly determine the air-to-fuel ratio. Closed-loop feedback-controlled fuel injection varies the fuel injector output according to real-time sensor data rather than operating with a predetermined (open-loop) fuel map. In addition to enabling electronic fuel injection to work efficiently, this emissions control technique can reduce the amounts of both unburnt fuel and oxides of nitrogen entering the atmosphere. Unburnt fuel is pollution in the form of air-borne hydrocarbons, while oxides of nitrogen (NO_x gases) are a result of combustion chamber temperatures exceeding 1,300 kelvins due to excess air in the fuel mixture and contribute to smog and acid rain. Volvo was the first automobile manufacturer to employ this technology in the late 1970s, along with the 3-way catalyst used in the catalytic converter.

The sensor does not actually measure oxygen concentration, but rather the amount of oxygen needed to completely oxidize any remaining combustibles in the exhaust gas. Rich mixture causes an oxygen demand. This demand causes a voltage to build up, due to transportation of oxygen ions through the sensor layer. Lean mixture causes low voltage, since there is an oxygen excess.

Modern spark-ignited combustion engines use oxygen sensors and catalytic converters in order to reduce exhaust emissions. Information on oxygen concentration is sent to the engine management computer or ECU, which adjusts the amount of fuel injected into the engine to compensate for excess air or excess fuel. The ECU attempts to maintain, on average, a certain air-fuel ratio by interpreting the information it gains from the oxygen sensor. The primary goal is a compromise between power, fuel economy, and emissions, and in most cases is achieved by an air-fuel-ratio close to stoichiometric. For spark-ignition engines (such as those that burn gasoline, as opposed to diesel), the three types of emissions modern systems are concerned with are: hydrocarbons (which are released when the fuel is not burnt completely, such as when misfiring or running rich), carbon monoxide (which is the result of running slightly rich) and NO_x (which dominate when the mixture is lean). Failure of these sensors, either through normal aging, the use of leaded fuels, or fuel contaminated with silicones or silicates, for example, can lead to damage of an automobile's catalytic converter and expensive repairs.

Tampering with or modifying the signal that the oxygen sensor sends to the engine computer can be detrimental to emissions control and can even damage the vehicle. When the engine is under low-load conditions (such as when accelerating very gently, or maintaining a constant speed), it is operating in "closed-loop mode." This refers to a feedback loop between the ECU and the oxygen sensor(s) in which the ECU adjusts the quantity of fuel and expects to see a resulting change in the response of the oxygen sensor. This loop forces the engine to operate both slightly lean and slightly rich on successive loops, as it attempts to maintain a mostly stoichiometric ratio on average. If modifications cause the engine to run moderately lean, there will be a slight increase in fuel economy, sometimes at the expense of increased NO_x emissions, much higher exhaust gas temperatures, and sometimes a slight increase in power that can quickly turn into misfires and a drastic loss of power, as well as potential engine damage, at ultra-lean air-to-fuel ratios. If modifications cause the engine to run rich, then there will be a slight increase in power to a point (after which the engine starts flooding from too much unburned fuel), but at the cost of decreased fuel economy, and an increase in unburned hydrocarbons in the exhaust which causes overheating of the catalytic converter. Prolonged operation at rich mixtures can cause catastrophic failure of the catalytic converter. The ECU also controls the spark engine timing along with the fuel injector pulse width, so modifications which alter the engine to operate either too lean or too rich may result in inefficient fuel consumption whenever fuel is ignited too soon or too late in the combustion cycle.

When an internal combustion engine is under high load (e.g. wide open throttle), the output of the oxygen sensor is ignored, and the ECU automatically enriches the mixture to protect the engine, as misfires under load are much more likely to cause damage. This is referred to an engine running in 'open-loop mode'. Any changes in the sensor output will be ignored in this state. In many cars (with the exception of some turbocharged models), inputs from the air flow meter are also ignored, as they might otherwise lower engine performance due to the mixture being too rich or too lean, and increase the risk of engine damage due to detonation if the mixture is too lean.

Function of a lambda probe

Lambda probes are used to reduce vehicle emissions by ensuring that engines burn their fuel efficiently and cleanly. Robert Bosch GmbH introduced the first automotive lambda probe in 1976, and it was first used by Volvo and Saab in that year. The sensors were introduced in the US from about 1980, and were required on all models of cars in many countries in Europe in 1993.

By measuring the proportion of oxygen in the remaining exhaust gas, and by knowing the volume and temperature of the air entering the cylinders amongst other things, an ECU can use look-up tables to determine the amount of fuel required to burn at the stoichiometric ratio (14.7:1 air:fuel by mass for gasoline) to ensure complete combustion.

The probe

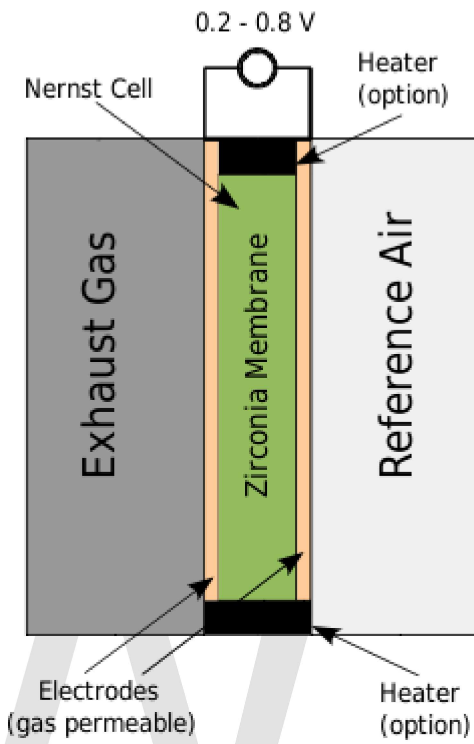
The sensor element is a ceramic cylinder plated inside and out with porous platinum electrodes; the whole assembly is protected by a metal gauze. It operates by measuring the difference in oxygen between the exhaust gas and the external air, and generates a voltage or changes its resistance depending on the difference between the two.

The sensors only work effectively when heated to approximately 316 °C (600 °F), so most newer lambda probes have heating elements encased in the ceramic that bring the ceramic tip up to temperature quickly. Older probes, without heating elements, would eventually be heated by the exhaust, but there is a time lag between when the engine is started and when the components in the exhaust system come to a thermal equilibrium. The length of time required for the exhaust gases to bring the probe to temperature depend on the temperature of the ambient air and the geometry of the exhaust system. Without a heater, the process may take several minutes. There are pollution problems that are attributed to this slow start-up process, including a similar problem with the working temperature of a catalytic converter.

The probe typically has four wires attached to it: two for the lambda output, and two for the heater power, although some automakers use a common ground for the sensor element and heaters, resulting in three wires. Earlier non-electrically-heated sensors had one or two wires.

Operation of the probe

Zirconia sensor



A planar zirconia sensor (schematic picture)

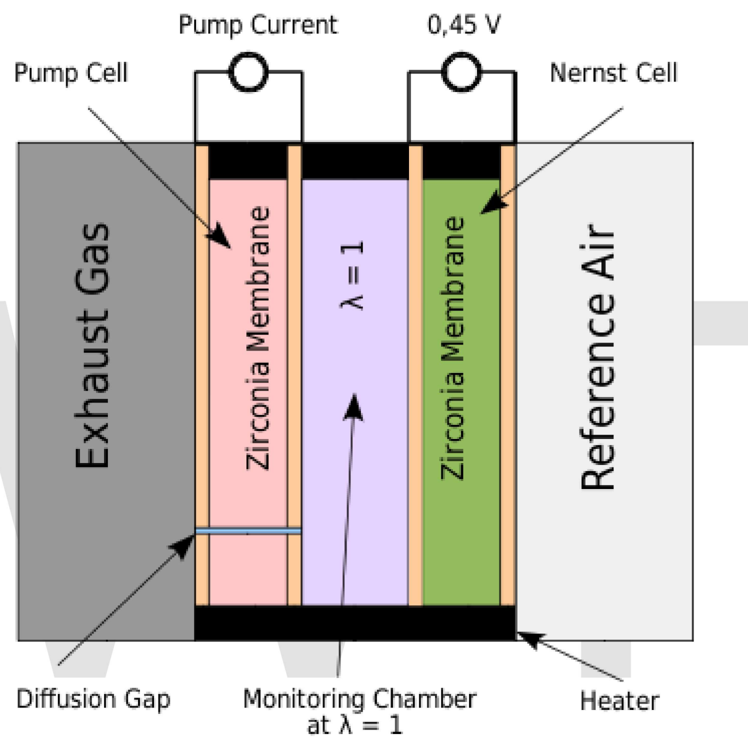
The zirconium dioxide, or zirconia, lambda sensor is based on a solid-state electrochemical fuel cell called the Nernst cell. Its two electrodes provide an output voltage corresponding to the quantity of oxygen in the exhaust relative to that in the atmosphere. An output voltage of 0.2 V (200 mV) DC represents a "lean mixture" of fuel and oxygen, where the amount of oxygen entering the cylinder is sufficient to fully oxidize the carbon monoxide (CO), produced in burning the air and fuel, into carbon dioxide (CO_2). An output voltage of 0.8 V (800 mV) DC represents a "rich mixture", one which is high in unburned fuel and low in remaining oxygen. The ideal setpoint is approximately 0.45 V (450 mV) DC. This is where the quantities of air and fuel are in the optimum ratio, which is ~0.5% lean of the stoichiometric point, such that the exhaust output contains minimal carbon monoxide.

The voltage produced by the sensor is nonlinear with respect to oxygen concentration. The sensor is most sensitive near the stoichiometric point and less sensitive when either very lean or very rich.

The engine control unit (ECU) is a control system that uses feedback from the sensor to adjust the fuel/air mixture. As in all control systems, the time constant of the sensor is important; the ability of the ECU to control the fuel-air-ratio depends upon the response time of the sensor. An aging or fouled sensor tends to have a slower response time, which can degrade system performance. The shorter the time period, the higher the so-called "cross count" and the more responsive the system.

The zirconia sensor is of the "narrow band" type, referring to the narrow range of fuel/air ratios to which it responds.

Wideband zirconia sensor



A planar wideband zirconia sensor (schematic picture)

A variation on the zirconia sensor, called the "wideband" sensor, was introduced by Robert Bosch in 1994 but is (as of 2006) used in only a few vehicles (such as the Subaru Impreza WRX when equipped with a manual transmission). It is based on a planar zirconia element, but also incorporates an electrochemical gas pump. An electronic circuit containing a feedback loop controls the gas pump current to keep the output of the electrochemical cell constant, so that the pump current directly indicates the oxygen content of the exhaust gas. This sensor eliminates the lean-rich cycling inherent in narrow-band sensors, allowing the control unit to adjust the fuel delivery and ignition timing of the engine much more rapidly. In the automotive industry this sensor is also called a *UEGO* (for Universal Exhaust Gas Oxygen) sensor. UEGO sensors are also commonly used in aftermarket dyno tuning and high-performance driver air-fuel display equipment. The wideband zirconia sensor is used in stratified fuel injection systems, and can now also be used in diesel engines to satisfy the forthcoming EURO and ULEV emission limits.

Wideband sensors have three elements:

- Ion Oxygen pump
- Narrowband zirconia sensor
- Heating element

The wiring diagram for the wideband sensor typically has six wires:

- resistive heating element (two wires)
- sensor
- pump
- calibration resistor
- common

Titania sensor

A less common type of narrow-band lambda sensor has a ceramic element made of titanium dioxide (titania). This type does not generate its own voltage, but changes its electrical resistance in response to the oxygen concentration. The resistance of the titania is a function of the oxygen partial pressure and the temperature. Therefore, some sensors are used with a gas temperature sensor to compensate for the resistance change due to temperature. The resistance value at any temperature is about 1/1000th the change in oxygen concentration. Luckily, at lambda = 1, there is a large change of oxygen, so the resistance change is typically 1000 times between rich and lean, depending on the temperature.

As titania is an N-type semiconductor with a structure TiO_{2-x}, the *x* defects in the crystal lattice conduct the charge. So, for fuel-rich exhaust the resistance is low, and for fuel-lean exhaust the resistance is high. The control unit feeds the sensor with a small electrical current and measures the resulting voltage across the sensor, which varies from near 0 volts to about 5 volts. Like the zirconia sensor, this type is nonlinear, such that it is sometimes simplistically described as a binary indicator, reading either "rich" or "lean". Titania sensors are more expensive than zirconia sensors, but they also respond faster.

In automotive applications the titania sensor, unlike the zirconia sensor, does not require a reference sample of atmospheric air to operate properly. This makes the sensor assembly easier to design against water contamination. While most automotive sensors are submersible, zirconia-based sensors require a very small supply of reference air from the atmosphere. In theory, the sensor wire harness and connector are sealed. Air that leaches through the wire harness to the sensor is assumed to come from an open point in the harness - usually the ECU which is housed in an enclosed space like the trunk or vehicle interior.

Location of the probe in a system

The probe is typically screwed into a threaded hole in the exhaust system, located after the branch manifold of the exhaust system combines, and before the catalytic converter. New vehicles are required to have a sensor before and after the exhaust catalyst to meet U.S. regulations requiring that all emissions components be monitored for failure. Pre and post-catalyst signals are monitored to determine catalyst efficiency. Additionally, some catalyst systems require brief cycles of lean (oxygen-containing) gas to load the catalyst and promote additional oxidation reduction of undesirable exhaust components.

Sensor surveillance

The air-fuel ratio and naturally, the status of the sensor, can be monitored by means of using an air-fuel ratio meter that displays the read output voltage of the sensor.

Sensor failures

Normally, the lifetime of an unheated sensor is about 30,000 to 50,000 miles (50,000 to 80,000 km). Heated sensor lifetime is typically 100,000 miles (160,000 km). Failure of an unheated sensor is usually caused by the buildup of soot on the ceramic element, which lengthens its response time and may cause total loss of ability to sense oxygen. For heated sensors, normal deposits are burned off during operation and failure occurs due to catalyst depletion. The probe then tends to report lean mixture, the ECU enriches the mixture, the exhaust gets rich with carbon monoxide and hydrocarbons, and the fuel economy worsens.

Leaded gasoline contaminates the oxygen sensors and catalytic converters. Most oxygen sensors are rated for some service life in the presence of leaded gasoline but sensor life will be shortened to as little as 15,000 miles depending on the lead concentration. Lead-damaged sensors typically have their tips discolored light rusty.

Another common cause of premature failure of lambda probes is contamination of fuel with silicones (used in some sealings and greases) or silicates (used as corrosion inhibitors in some antifreezes). In this case, the deposits on the sensor are colored between shiny white and grainy light gray.

Leaks of oil into the engine may cover the probe tip with an oily black deposit, with associated loss of response.

An overly rich mixture causes buildup of black powdery deposit on the probe. This may be caused by failure of the probe itself, or by a problem elsewhere in the fuel rationing system.

Applying an external voltage to the zirconia sensors, e.g. by checking them with some types of ohmmeter, may damage them.

Some sensors have an air inlet to the sensor in the lead, so contamination from the lead caused by water or oil leaks can be sucked into the sensor and cause failure.

Symptoms of a failing oxygen sensor includes:

- Sensor Light on dash indicates problem
- Increased tailpipe emissions
- Increased fuel consumption
- Hesitation on acceleration
- Stalling
- Rough idling

Diving applications

A diving breathing gas oxygen analyser

The diving type of oxygen sensor, which is sometimes called an **oxygen analyser** or **ppO_2 meter**, is used in scuba diving. They are used to measure the oxygen concentration of breathing gas mixes such as nitrox and trimix. They are also used within the oxygen control mechanisms of closed-circuit rebreathers to keep the partial pressure of oxygen within safe limits. This type of sensor operates by measuring the electricity generated by a small electro-galvanic fuel cell.

Scientific applications

In marine biology or limnology oxygen measurements are usually done in order to measure respiration of a community or an organism, but have also been used to measure primary production of algae. The traditional way of measuring oxygen concentration in a water sample has been to use wet chemistry techniques e.g. the Winkler titration method. There are however commercially available oxygen sensors that measure the oxygen concentration in liquids with great accuracy. There are two types of oxygen sensors available: electrodes (electrochemical sensors) and optodes (optical sensors).

Electrodes

A dissolved oxygen meter for laboratory use

The Clark-type electrode is the most used oxygen sensor for measuring oxygen dissolved in a liquid. The basic principle is that there is a cathode and an anode submersed in an electrolyte. Oxygen enters the sensor through a permeable membrane by diffusion, and is reduced at the cathode, creating a measurable electrical current.

There is a linear relationship between the oxygen concentration and the electrical current. With a two-point calibration (0% and 100% air saturation), it is possible to measure oxygen in the sample.

One drawback to this approach is that oxygen is consumed during the measurement with a rate equal to the diffusion in the sensor. This means that the sensor must be stirred in order to get the correct measurement and avoid stagnant water. With an increasing sensor size, the oxygen consumption increases and so does the stirring sensitivity. In large sensors there tend to also be a drift in the signal over time due to consumption of the electrolyte. However, Clark-type sensors can be made very small with a tip size of 10 µm. The oxygen consumption of such a microsensor is so small that it is practically insensitive to stirring and can be used in stagnant media such as sediments or inside plant tissue.

Optodes

An oxygen optode is a sensor based on optical measurement of the oxygen concentration. A chemical film is glued to the tip of an optical cable and the fluorescence properties of this film depend on the oxygen concentration. Fluorescence is at a maximum when there is no oxygen present. When an O_2 molecule comes along it collides with the film and this quenches the photoluminescence. In a given oxygen concentration there will be a specific number of O_2 molecules colliding with the film at any given time, and the fluorescence properties will be stable.

The signal (fluorescence) to oxygen ratio is not linear, and an optode is most sensitive at low oxygen concentration. That is, the sensitivity decreases as oxygen concentration increases following the Stern-Volmer relationship. The optode sensors can, however, work in the whole region 0% to 100% oxygen saturation in water, and the calibration is done the same way as with the Clark type sensor. No oxygen is consumed and hence the sensor is insensitive to stirring, but the signal will stabilize more quickly if the sensor is stirred after being put in the sample. These type of electrode sensors can be used for insitu and realtime monitoring of Oxygen production in water splitting reactions. The platinized electrodes can accomplish the real time monitoring of Hydrogen production in water splitting device. Calzaferri and his co workers employed this type of electrodes very extensively for photoelectrochemical water splitting research.

Nitrogen oxide sensor

A **nitrogen oxide sensor** or **NOx sensor** is typically a high temperature device built to detect nitrogen oxides in combustion environments such as an automobile or truck tailpipe or a smokestack.

Availability

Continental Automotive Systems/NGK are in production of a NOx sensor for automotive and truck applications. Several automobile and related companies such as Delphi, Ford, Chrysler, and Toyota have also put extensive research into development of NOx sensors. Many academic and government labs are pushing to develop the sensors as well. The term NOx actually represents several forms of nitrogen oxides such as NO (nitric oxide), NO_2 (nitrogen dioxide) and N_2O (nitrous oxide aka laughing gas). In a gasoline engine NO is the most common form of NOx being around 93% while NO_2 is around 5% and the rest is N_2O. There are other forms of NOx such as N_2O_4 (the dimer of NO_2), which only exists at lower temperatures, and N_2O_5, for example. However, owing to lower combustion temperatures, diesel engines produce lower engine-out NOx emissions than do spark-ignition gasoline engines, but the nonexistent NOx after-treatment causes diesel engines to emit significantly more NOx at the tailpipe compared to a typical gasoline engine with a 3-way catalyst. In addition, the diesel oxidation catalyst significantly increases the fraction of NO_2 in "NOx" by oxidizing over 50% of NO using the excess oxygen in the diesel exhaust gases.

Motivating factors

The drive to develop a NOx sensor comes from environmental factors. NOx gases can cause various problems such as smog and acid rain. Many governments around the world have passed laws to limit their emissions (along with other combustion gases such as SOx (oxides of sulfur), CO (carbon monoxide) and CO_2 (carbon dioxide) and hydrocarbons). Companies have realized that one way of minimizing NOx emissions is to first detect them and then employ some sort of feedback loop in the combustion process, minimizing NOx production by, for example, combustion optimization or regeneration of NOx traps.

Difficulties

Harsh environment

Due to the high temperature of the combustion environment only certain types of material can operate *in situ*. The majority of NOx sensors developed have been made out of ceramic type metal oxides with the most common being yttria stabilized zirconia (YSZ), which is currently used in the decades old oxygen sensor. The YSZ is compacted into a dense ceramic and actually conducts oxygen ions (O^{2-}) at the high temperatures of a tailpipe such at 400 °C and above. To get a signal from the sensor a pair of high temperature electrodes such as noble metals (platinum, gold, or palladium) or other metal oxides are placed onto the surface and an electrical signal such as the change in voltage or current is measured as a function of NOx concentration.

High sensitivity and durability required

The levels of NO are around 100-2000 ppm (parts per million) and NO_2 20-200 ppm in a range of 1-10% O_2. The sensor has to be very sensitive to pick up these levels.

The main problems that have limited the development of a successful NOx sensor (which are typical of many sensors) are selectivity, sensitivity, stability, reproducibility, response time, limit of detection and cost. In addition due to the harsh environment of combustion the high gas flow rate can cool the sensor which alters the signal or it can delaminate the electrodes over time and soot particles can degrade the materials.

Conclusion

The NOx sensing element mentioned above is only a part of the whole device, which also includes the packaging and electronics. The development of a very good NOx sensor is highly desirable and has the potential to serve a large market. Thus there is a large push to produce a robust sensor that works reliably and accurately over a wide temperature range. It is currently one of the most sought after combustion gas sensors. Degradation by CO_2 and SO_2 gases, however, remains a major problem of NOx sensors.

Mass flow sensor

A **mass air flow** (MAF) sensor responds to the amount of a fluid (usually a gas) flowing through a chamber containing the sensor. It is intended to be insensitive to the density of the fluid.

Automotive mass airflow sensors

A mass airflow sensor

A mass air flow sensor is used to find out the mass of air entering a fuel-injected internal combustion engine. The air mass information is necessary for the engine control unit (ECU) to balance and deliver the correct fuel mass to the engine. Air changes its density as it expands and contracts with temperature and pressure. In automotive applications, air density varies with the ambient temperature, altitude and use of a turbocharger and this is an ideal application for a mass sensor.

There are two common types of mass airflow sensors in use on automotive engines. These are the vane meter and the hot wire. Neither design employs technology that measures air mass directly. However, with an additional sensor or two, the engine's air mass flow rate can be accurately determined.

Both approaches are used almost exclusively on electronic fuel injection (EFI) engines. Both sensor designs output a 0.0- 5.0 volt or a pulse-width modulation (PWM) signal that is proportional to the air mass flow rate, and both sensors have an intake air temperature (IAT) sensor incorporated into their housings.

When a MAF is used in conjunction with an oxygen sensor, the engine's air/fuel ratio can be controlled very accurately. The MAF sensor provides the open-loop predicted air flow information (the measured air flow) to the ECU, and the oxygen sensor provides closed-loop feedback in order to make minor corrections to the predicted air mass.

Vane meter sensor

A vane, or paddle, projects into the engine's intake air stream on a spring-loaded arm. The vane moves in proportion to the airflow, and a voltage is generated in proportion to the distance the vane moves, or the movement of the vane directly regulates the amount of fuel injected, as in the K-Jetronic system.

The vane moves because of the drag force of the air flow against it, it does not measure volume or mass directly. The drag force depends on air density, velocity and the shape of the vane.

The vane meter approach has some drawbacks:

- it restricts airflow which limits engine output
- its moving electrical or mechanical contacts can wear
- finding a suitable mounting location within a confined engine compartment is problematic
- the vane has to be oriented with respect to gravity.

Hot wire sensor (MAF)

A *hot wire mass airflow sensor* determines the mass of air flowing into the engine's air intake system. The theory of operation of the hot wire mass airflow sensor is similar to that of the hot wire anemometer (which determines air velocity). The General Motors division (GM) was the first car company to use the hot wire sensor. This is achieved by heating a wire with an electric current that is suspended in the engine's air stream, like a toaster wire. The wire's electrical resistance increases as the wire's temperature increases, which limits electrical current flowing through the circuit. When air flows past the wire, the wire cools, decreasing its resistance, which in turn allows more current to flow through the circuit. As more current flows, the wire's temperature increases until the resistance reaches equilibrium again. The amount of current required to maintain the wire's temperature is directly proportional to the mass of air flowing past the wire. The integrated electronic circuit converts the measurement of current into a voltage signal which is sent to the ECU.

If air density increases due to pressure increase or temperature drop, but the air volume remains constant, the denser air will remove more heat from the wire indicating a higher mass airflow. Unlike the vane meter's paddle sensing element, the hot wire responds directly to air density. This sensor's capabilities are well suited to support the gasoline combustion process which fundamentally responds to air mass, not air volume.

Some of the benefits of a hot-wire MAF compared to the older style vane meter are:

- responds very quickly to changes in air flow
- low airflow restriction
- smaller overall package
- less sensitive to mounting location and orientation
- no moving parts improve its durability
- less expensive
- separate temperature and pressure sensors are not required (to determine air mass)

There are some drawbacks:

- dirt and oil can contaminate the hot-wire deteriorating its accuracy
- installation requires a laminar flow across the hot-wire

"Coldwire" sensor

A Holden Commodore's MAF sensor

The GM LS engine series (as well as others) use a "coldwire" MAF system (produced by AC Delco) where the inductance of a tiny sensor changes with the air mass flow over that sensor. The sensor is part of an oscillator circuit whose oscillation frequency changes with sensor inductance; hence the frequency is related to the amount of air (cubic feet per minute) passing over the unit. This oscillating electrical signal is then fed to the car's ECU. These MAF units (such as the one pictured) have 3 pins, denoted +, - and F. F carries the square-wave frequency between - and F. They are powered by +5 V_{DC} from the ECU's regulated power supply.

The mesh on the MAF is used to smooth out airflow to ensure the sensors have the best chance of a steady reading. It is not used for measuring the air flow per se. In situations where owners use oiled-gauze air filters, it is possible for excess oil to coat the MAF sensor and skew its readings. Indeed, General Motors has issued a Technical Service Bulletin, indicating problems from rough idle all the way to possible transmission damage resulting from the contaminated sensors. To clean the delicate MAF sensor components, a specific MAF or Electronics Cleaner should be used, *not* carburetor or brake cleaner. These are alcohol or CFC-based solvents, rather than the harsh petroleum distillates used in the other cleaners... The sensors should be gently sprayed from a careful distance to avoid physically damaging them. Manufacturers claim that a simple but extremely reliable test to ensure correct functionality is to tap the unit with the back of a screwdriver while the car is running, and if this causes any changes in the output frequency then the unit should be discarded and an OEM replacement installed.

Kármán vortex sensor

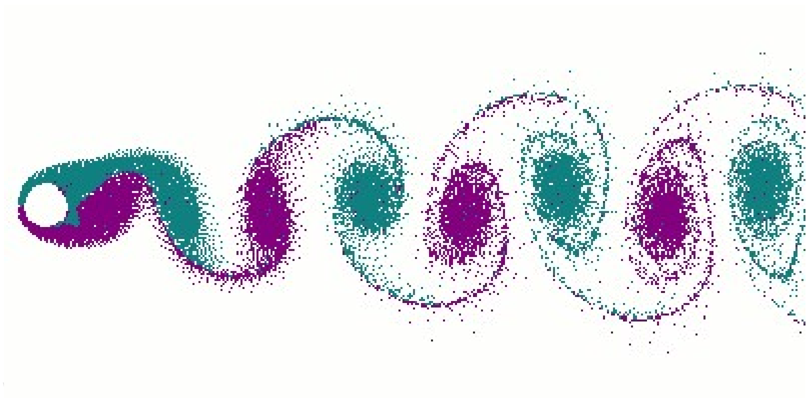


Image of the phenomenon

A Kármán vortex sensor works by setting up a laminar air stream. The air stream is disrupted by a vertical bow in the sensor. This causes a wake in the air stream and subsequently the wake will collapse repeatedly and cause Kármán vortexes. The frequency of the resulting air pressure oscillation is proportional to the air velocity.

These vortexes can either be read directly as a pressure pulse against a sensor, or they can be made to collide with a mirror which will then interrupt or transmit a reflected light beam to generate the pulses in response to the vortexes. The first type can only be used in pull thru air (prior to a turbo- or supercharger), while the second type could theoretically be used push or pull thru air (before or after a forced induction application like the previously mentioned super- or turbocharger). Instead of outputting a constant voltage modified by a resistance factor, this type of MAF outputs a frequency which must then be interpreted by the ECU. This type of MAF can be found on Mitsubishi Lancers/EVOs, all DSMs (Mitsubishi Eclipse, Eagle Talon, Plymouth Laser) and some models from Toyota and Lexus.

Membrane sensor

An emerging technology utilizes a very thin electronic membrane placed in the air stream. The membrane has a thin film temperature sensor printed on the upstream side, and one on the downstream side. A heater is integrated in the center of the membrane which maintains a constant temperature similar to the hot-wire approach. Without any airflow, the temperature profile across the membrane is uniform. When air flows across the membrane, the upstream side cools differently from the downstream side. The difference between the upstream and downstream temperature indicates the mass airflow.

The thermal membrane sensor is also capable of measuring flow in both directions, which sometimes occur in pulsating situations. Technological progress allows this kind of sensor to be manufactured on the microscopic scale as microsensors using Microelectromechanical systems technology. Such a *microsensor* reaches a significantly higher speed and sensitivity compared with macroscopic approaches.

Auto repair technician observation

The MAF sensor senses the incoming air into the engine. This sensor does not regulate the incoming air, this is done by the engine throttle plates. The MAF merely senses incoming air and relates a signal to the ECM. Air flow sensors come in three types. The Vane Air Flow sensor, Hot Wire MAF sensor and Hot Film MAF sensor. They all perform the same function but their operation is quite different.

The VAF sensor measures the air flow into the engine with a spring-loaded air flap/door attached to a variable resistor (potentiometer). The drag force of the incoming air pushes against the spring force of the air flap on the VAF sensor, which also moves the variable resistor's sensing arm (wiper arm). As air flows into the engine the mechanical air flap rotates further, changing the voltage signal output.

The VAF sensor has an air-fuel adjustment screw, which opens or closes a small air passage on the side of the VAF sensor. This screw controls the air-fuel mixture by letting a metered amount of air flow past the air flap, thereby, leaning or richening the mixture. By turning the screw clockwise the mixture is enriched and counterclockwise the mixture is leaned. In addition to the regular air flow measuring function, some VAF sensors also employ an air temperature sensor (IAT sensor) and a fuel pump switch.

The IAT sensor is found inside the VAF casing and has the same electrical characteristics as a regular air temperature sensor. The VAF sensor flap also closes a set of contacts that activate the fuel pump relay coil (circuit opening relay). The contacts are actually closed as soon as the smallest amount of air pushes on the air flow flap. Once this happens the fuel pump starts running and the engine starts.

One of the main drawbacks of the VAF sensor is that it measures volume of air and not weight. As air temperature changes so does its weight. There are more air molecules present when the air is colder than when it is hotter. As air temperature decreases, more air is absorbed by the engine, so there are drastic changes needed in the air fuel ratio (depending on the temperature of the air). The air temperature sensor inside the VAF somewhat compensates by signaling the ECM of any changes in air temperature.

The hot wire MAF sensor is a fully electronic unit. It senses the amount of air flow into the engine by measuring the amount of current needed to maintain a constant temperature through a very thin (70 micrometers) platinum hot wire. Hence the name hot wire MAF sensor. It also measures air by weight, since it takes into consideration the air temperature as well.

This sensor works as follows. As the air enters the intake manifold through the hot wire MAF sensor it cools down the platinum wire, which is heated at a very precise temperature. When the MAF circuitry senses the platinum wire cooling down it increases the amount of current flow through the hot wire trying to maintain a specific temperature. This varying current flow is then converted to a voltage output signal by the MAF electronic circuitry and is used as an air flow indicator by the ECM. Hot wire MAF sensors have a signal that is directly proportional to air flow. So as air flow increases so does its voltage signal output.

This sensor sometimes employs a mixture screw, but this screw is fully electronic and uses a variable resistor (potentiometer) instead of an air bypass screw. The screw needs more turns to achieve the desired results. A hot wire burn-off cleaning circuit is employed on some of these sensors. A burn-off relay applies a high current through the platinum hot wire after the vehicle is turned off for a second or so, thereby burning or vaporizing any contaminants that have stuck to the platinum hot wire element.

The hot film MAF sensor works somewhat similar to the hot wire MAF sensor, but instead it usually outputs a frequency signal. This sensor uses a hot film-grid instead of a hot wire. It is commonly found in late 80's early 90's fuel injected vehicles. The output frequency is directly proportional to the amount of air entering the engine. So as air flow increases so does frequency. These sensors tend to cause intermittent problems due to internal electrical failures. The use of an oscilloscope is strongly recommended to check the output frequency of these sensors. Frequency distortion is also common when the sensor starts to fail. Many technicians in the field use a tap test with very conclusive results. Not all HFM systems output a frequency. In some cases, this sensor works by outputting a regular varying voltage signal.

Conditions that affect operation

VAF sensors are mechanical in nature. Their measuring element (wiper contact, pivot bushings and sensor resistors) get worn out over time. A binding air flap door is also a major problem with these sensors. The air flap mechanism is extremely precise and does not tolerate any misalignments. Always make sure that the air flap can travel freely all the way to its full open position. A broken air duct pipe will also render the VAF useless, since most of the air will be bypassed and enter though the broken duct hole. A thorough air duct check is always a good idea. The resistors also tend to wear out over time, sending the wrong voltage signal to the ECM. This will certainly throw off the air-fuel ratio.

The air temperature sensor and the fuel pump switch are the other reasons for VAF failures. This fuel pump switch activates the fuel pump relay and its contacts also wear down over time, causing a no start-no no-fuel pressure condition. A simple continuity test will quickly reveal a bad fuel pump switch. The air temperature sensor also follows the same electrical characteristics of a normal IAT sensor and the same ohms to temperature tables could be used for diagnostics.

Hot Wire MAF sensors are very prone to sensing wire element contamination. A condition referred to by many technicians as “growing hairs” happens when debris, dirt from cheap air filters and outside air stick to the sensing wire element, shielding it from the incoming air. This shielding effect prevents the MAF sensor from correctly measuring the air flow and mass causing severe air-fuel ratio control problems. An ECM not in control while at pre-load is a strong indication of a dirty MAF.

In any fully electronic device, the electrical connections and circuitry fails after a certain lifespan of operation. An output signal voltage test will surely reveal a bad MAF sensor.

Hot Film MAF sensors tend to get electrical damage more often that the other type of sensors. The tap test ,as mentioned before, is a useful and simple procedure that usually reveals a bad hot film MAF sensor. Contamination or a broken air duct is also a problem for this type of sensor.

Laminar flow elements

Laminar flow elements measure the mass flow of gases directly. They operate on the principle that, given laminar flow, the pressure difference across a pipe is linear to the flow rate. Laminar flow conditions are present in a gas when the Reynolds number of the gas is below the critical figure. The viscosity of the fluid must be compensated for in the result. Laminar flow elements are usual constructed form a large number of parallel pipes to achieve the required flow rating.