SAMPLE

Temperature and Heat

From Absolute Zero to Stellar Cores

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Chapter 1: The Discovery of Temperature and Heat

The customary figure quoted for healthy adults is a band between 36.5 and 37.5 °C, that is, 97.7 to 99.5 °F. Reviews of the literature, though, have found adult normals spread from 33.2 up to 38.2 °C, or 91.8 to 100.8 °F, varying with sex and with where on the body the reading is taken. Where the reading is taken matters too: an under-tongue figure differs from a rectal or vaginal one.

A rectal or vaginal measurement taken directly inside the body cavity is typically slightly higher than oral measurement, and oral measurement is somewhat higher than skin measurement. Other places, such as under the arm or in the ear, produce different typical temperatures. While some people think of these averages as representing normal or ideal measurements, a wide range of temperatures has been found in healthy people.

The body temperature of a healthy person varies during the day by about 0.5 °C (0.9 °F) with lower temperatures in the morning and higher temperatures in the late afternoon and evening, as the body's needs and activities change. Other circumstances also affect the body's temperature.

The core body temperature of an individual tends to have the lowest value in the second half of the sleep cycle; the lowest point, called the nadir, is one of the primary markers for circadian rhythms.

The body temperature also changes when a person is hungry, sleepy, sick, or cold. Body temperature normally fluctuates over the day following circadian rhythms, with the lowest levels around 4 a.m. Therefore, an oral temperature of 37.3 °C (99.1 °F) would, strictly speaking, be a normal, healthy temperature in the afternoon but not in the early morning.

An individual's temperature typically swings by roughly half a degree Celsius between its daily high and its daily low. Body temperature is sensitive to many hormones, so women have a temperature rhythm that varies with the menstrual cycle, called a circamensal rhythm. A woman's basal body temperature rises sharply after ovulation, as estrogen production decreases and progesterone increases. Fertility awareness programs use this change to identify when a woman has ovulated to achieve or avoid pregnancy.

During the luteal phase of the menstrual cycle, both the lowest and the average temperatures are slightly higher than during other parts of the cycle. However, the amount that the temperature rises during each day is slightly lower than typical, so the highest temperature of the day is not very much higher than usual. Hormonal contraceptives both suppress the circamensal rhythm and raise the typical body temperature by about 0.6 °C (1.1 °F).

Temperature also may vary with the change of seasons during each year.

This pattern is called a circannual rhythm. Studies of seasonal variations have produced inconsistent results. People living in different climates may have different seasonal patterns. It has been found that physically active individuals have larger changes in body temperature throughout the day. Physically active people have been reported to have lower body temperatures than their less active peers in the early morning and similar or higher body temperatures later in the day.

With increased age, both average body temperature and the amount of daily variability in the body temperature tend to decrease. Elderly people may have a decreased ability to generate body heat during a fever, so even a somewhat elevated temperature can indicate a serious underlying cause in geriatrics. One study suggested that the average body temperature has also decreased since the 1850s.

The study's authors believe the most likely explanation for the change is a reduction in inflammation at the population level due to decreased chronic infections and improved hygiene. Different methods used for measuring temperature produce different results. The temperature reading depends on which part of the body is being measured.

The typical daytime temperatures among healthy adults are as follows: Temperature in the rectum (rectal), vagina, or in the ear (tympanic) is about 37.5 °C (99.5 °F) Temperature in the mouth (oral) is about 36.8 °C (98.2 °F) Temperature under the arm (axillary) is about 36.5 °C (97.7 °F) Generally, oral, rectal, gut, and core body temperatures, although slightly different, are well-correlated. Oral temperatures are influenced by drinking, chewing, smoking, and breathing with the mouth open.

Mouth breathing, cold drinks or food reduce oral temperatures; hot drinks, hot food, chewing, and smoking raise oral temperatures. Each measurement method also has different normal ranges depending on sex. As of 2016, reviews of infrared thermometers have found them to be of variable accuracy. This includes tympanic infrared thermometers in children. Sleep disturbances also affect temperatures. Normally, body temperature drops significantly at a person's normal bedtime and throughout the night.

Short-term sleep deprivation produces a higher temperature at night than normal, but long-term sleep deprivation appears to reduce temperatures. Insomnia and poor sleep quality are associated with smaller and later drops in body temperature. Similarly, waking up unusually early, sleeping in, jet lag and changes to shift work schedules may affect body temperature. A temperature setpoint is the level at which the body attempts to maintain its temperature. When the setpoint is raised, the result is a fever.

For reference, the usual measurement spots are the underarm (axillary), the oral cavity, the rectum, the ear (tympanic), and heat-flux sensors, each carrying its own expected range.

37.6 °C (99.7 °F) — Classed as a slight fever. 35 °C (95 °F) – Threshold for hypothermia.

Shivering is absent. Reflex may be absent or very slight. 31 °C (87.8 °F) – Comatose, very rarely conscious. No or slight reflexes. The person may appear to be dead.

Chapter 2: Understanding Temperature and Heat

Most fevers are caused by infectious disease and can be lowered, if desired, with antipyretic medications. An early morning temperature higher than 37.3 °C (99.1 °F) or a late afternoon temperature higher than 37.7 °C (99.9 °F) is normally considered a fever, assuming that the temperature is elevated due to a change in the hypothalamus's setpoint. Lower thresholds are sometimes appropriate for elderly people.

The normal daily temperature variation is typically 0.5 °C (0.90 °F), but can be greater among people recovering from a fever.

An organism at optimum temperature is considered afebrile, meaning "without fever". If temperature is raised, but the setpoint is not raised, then the result is hyperthermia. Hyperthermia occurs when the body produces or absorbs more heat than it can dissipate. It is usually caused by prolonged exposure to high temperatures. The heat-regulating mechanisms of the body eventually become overwhelmed and unable to deal effectively with the heat, causing the body temperature to climb uncontrollably.

Hyperthermia at or above about 40 °C (104 °F) is a life-threatening medical emergency that requires immediate treatment. Common symptoms include headache, confusion, and fatigue. If sweating has resulted in dehydration, then the affected person may have dry, red skin. In a medical setting, mild hyperthermia is commonly called heat exhaustion or heat prostration; severe hyperthermia is called heat stroke. Heatstroke may come on suddenly, but it usually follows the untreated milder stages.

Treatment involves cooling and rehydrating the body; fever-reducing drugs are useless for this condition. This may be done by moving out of direct sunlight to a cooler and shaded environment, drinking water, removing clothing that might keep heat close to the body, or sitting in front of a fan. Bathing in tepid or cool water, or even just washing the face and other exposed areas of the skin, can be helpful.

With fever, the body's core temperature rises to a higher temperature through the action of the part of the brain that controls the body temperature; with hyperthermia, the body temperature is raised without the influence of the heat control centers. In hypothermia, body temperature drops below that required for normal metabolism and bodily functions. In humans, this is usually due to excessive exposure to cold air or water, but it can be deliberately induced as a medical treatment.

Symptoms usually appear when the body's core temperature drops by 1–2 °C (1.8–3.6 °F) below normal temperature. Basal body temperature is the lowest temperature attained by the body during rest (usually during sleep). It is generally measured immediately after awakening and before any physical activity has been undertaken, although the temperature measured at that time is somewhat higher than the true

basal body temperature.

In women, temperature differs at various points in the menstrual cycle, and this can be used in the long term to track ovulation both to aid conception or avoid pregnancy. This process is called fertility awareness. Core temperature, also called core body temperature, is the operating temperature of an organism, specifically in deep structures of the body such as the liver, in comparison to temperatures of peripheral tissues.

Core temperature is normally maintained within a narrow range so that essential enzymatic reactions can occur.

Significant core temperature elevation (hyperthermia) or depression (hypothermia) over more than a brief period of time is fatal. Temperature examination in the heart, using a catheter, is the traditional gold standard measurement used to estimate core temperature (oral temperature is affected by hot or cold drinks, ambient temperature fluctuations as well as mouth-breathing). Since catheters are highly invasive, the generally accepted alternative for measuring core body temperature is through rectal measurements.

Rectal temperature is expected to be approximately 1 °F (0.56 °C) higher than an oral temperature taken on the same person at the same time. Ear thermometers measure temperature from the tympanic membrane using infrared sensors and also aim to measure core body temperature, since the blood supply of this membrane is directly shared with the brain.

However, this method of measuring body temperature is not as accurate as rectal measurement and has a low sensitivity for fever, failing to determine three or four out of every ten fever measurements in children. Ear temperature measurement may be acceptable for observing trends in body temperature but is less useful in consistently identifying and diagnosing fever. Until recently, direct measurement of core body temperature required either an ingestible device or surgical insertion of a probe.

Therefore, a variety of indirect methods have commonly been used as the preferred alternative to these more accurate albeit more invasive methods. The rectal or vaginal temperature is generally considered to give the most accurate assessment of core body temperature, particularly in hypothermia.

In the early 2000s, ingestible thermistors in capsule form were produced, allowing the temperature inside the digestive tract to be transmitted to an external receiver; one study found that these were comparable in accuracy to rectal temperature measurement.

More recently, a new method using heat flux sensors have been developed. Several research papers show that its accuracy is similar to the invasive methods. Measurement within the body finds internal variation temperatures as different as 21.5 °C (70.7 °F) for the radial artery and 31.1 °C (88.0 °F) for the brachial artery. It has been observed that "chaos" has been "introduced into physiology by the fictitious assumption of a constant blood temperature".

Normal body temperature may also differ as much as 0.5 °C (0.90 °F) from one day to the next. Normal human body temperature varies slightly from person to person and by the time of day. Consequently, each type of measurement has a range of normal temperatures. The range for normal human body temperatures, taken orally, is 36.8 ± 0.5 °C (98.2 ± 0.9 °F).

This means that any oral temperature between 36.3 and 37.3 °C (97.3 and 99.1 °F) is likely to be normal.

Normal human body temperature, as it is usually quoted, sits between 97.7 and 99.5 °F, or 36.5–37.5 °C.

Chapter 3: Key Characteristics of Temperature and Heat

44 °C (111.2 °F) or more – Almost certainly death will occur; however, people have been known to survive up to 46.5 °C (115.7 °F). 43 °C (109.4 °F) – Normally death, or there may be serious brain damage, convulsions, and shock. Cardio-respiratory collapse will likely occur. 42 °C (107.6 °F) – Subject may turn red.

They may become comatose, be in severe delirium, and convulsions can occur. 41 °C (105.8 °F) – (Medical emergency) – Fainting, severe headache, dizziness, confusion, hallucinations, delirium, and drowsiness can occur. There may also be palpitations and breathlessness. 40 °C (104 °F) – Fainting, dehydration, weakness, headache, breathlessness, and dizziness may occur as well as profuse sweating. 39 °C (102.2 °F) – Severe sweating, and red. Fast heart rate and breathlessness. There may be exhaustion accompanying this.

Children and people with epilepsy may suffer convulsions at this temperature. 38 °C (100.4 °F) – (Classed as hyperthermia if not caused by a fever) – Feeling hot, sweating, feeling thirsty, feeling very uncomfortable. 37.6 °C (99.7 °F) — a mild fever by most definitions; appetite may fade, with feelings of heat, discomfort, and thirst. The range running from 36.5 to 37.5 °C, or 97.7–99.5 °F, is what gets reported as normal. 35.5 °C (95.9 °F) – Feeling cold, mild to moderate shivering.

This can be a normal body temperature for sleeping. 35 °C (95 °F) – Threshold for hypothermia. Intense shivering, numbness and bluish/grayness of the skin. There is the possibility of heart irritability. 34 °C (93.2 °F) – Severe shivering, loss of movement of fingers, blueness, and confusion. Some behavioral changes may take place. 33 °C (91.4 °F) – Moderate to severe confusion, sleepiness, depressed reflexes, progressive loss of shivering, slow heartbeat, shallow breathing. Shivering may stop.

The subject may be unresponsive to certain stimuli.

32 °C (89.6 °F) – (Medical emergency) – Hallucinations, delirium, complete confusion, extreme sleepiness that is progressively becoming comatose. Shivering has stopped. Reflexes may be absent or barely detectable. 31 °C (87.8 °F) – The person is comatose and seldom conscious, reflexes faint or absent, breathing gone very shallow

and the heart rate slowed. Possibility of serious heart rhythm problems. 28 °C (82.4 °F) – Severe heart rhythm disturbances are likely and breathing may stop at any time.

The person may appear to be dead.

24–26 °C (75.2–78.8 °F) or less – Death usually occurs due to irregular heart beat or respiratory arrest; however, some patients have been known to survive with body temperatures lower than 12.7 °C (54.9 °F). The lowest recorded core temperature from a patient with accidental hypothermia who survived without neurological sequelae is 11.8 °C (53.2 °F).

There are non-verbal corporal cues that can hint at an individual experiencing a low body temperature, which can be used for those with dysphasia or infants.

Examples of non-verbal cues of coldness include stillness and being lethargic, unusual paleness of skin among light-skinned people, and, among males, shrinkage, and contraction of the scrotum. Environmental conditions, primarily temperature and humidity, affect the ability of the mammalian body to thermoregulate. The psychrometric temperature, of which the wet-bulb temperature is the main component, largely limits thermoregulation. It was thought that a wet-bulb temperature of about 35 °C (95 °F) was the highest sustained value consistent with human life.

A 2022 study on the effect of heat on young people found that the critical wet-bulb temperature at which heat stress can no longer be compensated, Twb,crit, in young, healthy adults performing tasks at modest metabolic rates mimicking basic activities of daily life was much lower than the 35 °C (95 °F) usually assumed, at about 30.55 °C (86.99 °F) in 36–40 °C (97–104 °F) humid environments, but progressively decreased in hotter, dry ambient environments.

At low temperatures the body thermoregulates by generating heat, but this becomes unsustainable at extremely low temperatures. In the 19th century, most books quoted "blood heat" as 98 °F, until a study published the mean (but not the variance) of a large sample as 36.88 °C (98.38 °F). Subsequently, that mean was widely quoted as "37 °C or 98.4 °F" until editors realized 37 °C is equal to 98.6 °F, not 98.4 °F.

The 37 °C value was set by German physician Carl Reinhold August Wunderlich in his 1868 book, which put temperature charts into widespread clinical use. Dictionaries and other sources that quoted these averages did add the word "about" to show that there is some variance, but generally did not state how wide the variance is.

In thermodynamics, heat is defined as energy in transfer between a body and its surroundings, other than through thermodynamic work or through transfer of matter.

Rather than by mechanical or other effects in the surroundings, thermodynamic work is defined through changes in the system's macroscopic state variables, in conjugate pairs such as pressure and volume, or magnetisation and magnetic field strength. The thermodynamic definition of heat is by exclusion of other defined modes of transfer in order to ensure a strict logical distinction. In the process of transfer, heat is not necessarily conserved, but can be generated (though not destroyed) by friction.

In thermodynamics, temperature is defined in macroscopic terms, through the concepts of heat and work. Heat is not a state variable or state function; it is a process quantity. A thermodynamic system does not contain heat. Heat can enter or leave a body of matter by thermal conduction, by electromagnetic radiation, or through friction due to macroscopic mechanical movement. When heat is generated by friction, it may end up partly in each of the two engaged bodies.

Thermoregulation is the ability of an organism to keep its body temperature within certain boundaries, even when the surrounding temperature is very different.

Lying on cool ground. Staying wet in a river, lake or sea. Covering in cool mud. Entering a warm water or air current. Building an insulated nest or burrow. Conduction:

Lying on a hot surface. Folding skin to reduce exposure. Concealing wing surfaces.

Chapter 4: The Science Behind Temperature and Heat

When energy enters or leaves a body through transfer of matter, it cannot be resolved uniquely into work and heat. By assuming conservation of heat in a transfer, calorimetry measures it by its effect on the states of interacting bodies, for example, by the amount of ice melted or by change in temperature of a body. In SI units, heat is measured in joules (J).

As a form of energy, heat has the unit joule (J) in the International System of Units (SI). In addition, many applied branches of engineering use other, traditional units, such as the British thermal unit (BTU) and the calorie. The standard unit for the rate of heating is the watt (W), defined as one joule per second. The symbol Q for heat was introduced by Rudolf Clausius and Macquorn Rankine in c. 1859.

Heat released by a system into its surroundings is by convention, as a contributor to internal energy, a negative quantity ($Q < 0$); when a system absorbs heat from its surroundings, it is positive ($Q > 0$).

Heat transfer rate, or heat flow per unit time, is denoted by $\dot{Q}$, but it is not a time derivative of a function of state (which can also be written with the dot notation) since heat is not a function of state.

Heat flux is defined as rate of heat transfer per unit cross-sectional area (watts per square metre). In ordinary language, English 'heat' or 'warmth', just as French chaleur, German Hitze or Wärme, Latin calor, Greek θάλπος, etc. Later, chaleur (as used by Sadi Carnot), 'heat', and Wärme became equivalents also as specific scientific terms at an early stage of thermodynamics.

Speculation on 'heat' as a separate form of matter has a long history, involving the phlogiston theory, the caloric theory, and fire. Many careful and accurate historical experiments practically exclude friction, mechanical and thermodynamic work and matter transfer, investigating transfer of energy only by thermal conduction and radiation. Such experiments give impressive rational support to the caloric theory of

heat.

To account also for changes of internal energy due to friction, and mechanical and thermodynamic work, the caloric theory was, around the end of the eighteenth century, replaced by the "mechanical" theory of heat, which is accepted today.

As scientists of the early modern age began to adopt the view that matter consists of particles, a close relationship between heat and the motion of those particles was widely surmised, or even the equivalency of the concepts, boldly expressed by the English philosopher Francis Bacon in 1620.

I suspect that people in general have a concept of this which is very remote from the truth. For they believe that heat is a real phenomenon, or property...

Galileo wrote that heat and pressure are apparent properties only, caused by the movement of particles, which is a real phenomenon. In 1665, and again in 1681, English polymath Robert Hooke reiterated that heat is nothing but the motion of the constituent particles of objects, and in 1675, his colleague, Anglo-Irish scientist Robert Boyle repeated that this motion is what heat consists of. Heat has been discussed in ordinary language by philosophers.

An example is this 1720 quote from the English philosopher John Locke: Heat, is a very brisk agitation of the insensible parts of the object, which produces in us that sensation from whence we denominate the object hot; so what in our sensation is heat, in the object is nothing but motion.

This appears by the way, whereby heat is produc'd: for we see that the rubbing of a brass nail upon a board, will make it very hot; and the axle-trees of carts and coaches are often hot, and sometimes to a degree, that it sets them on fire, by the rubbing of the nave of the wheel upon it.

When Bacon, Galileo, Hooke, Boyle and Locke wrote "heat", they might more have referred to what we would now call "temperature".

No clear distinction was made between heat and temperature until the mid-18th century, nor between the internal energy of a body and the transfer of energy as heat until the mid-19th century. Locke's description of heat was repeatedly quoted by English physicist James Prescott Joule. Also the transfer of heat was explained by the motion of particles. Scottish physicist and chemist Joseph Black wrote: "Many have supposed that heat is a tremulous...

Evaporation of water, either across respiratory surfaces or across the skin in those animals possessing sweat glands, helps in cooling body temperature to within the organism's tolerance range. Animals with a body covered by fur have a limited ability to sweat, relying heavily on panting to increase evaporation of water across the moist surfaces of the lungs and the tongue and mouth.

Mammals like cats, dogs, and pigs rely on panting or other means for thermal regulation and have sweat glands only in their foot pads and snouts. The sweat produced on pads of paws and on palms and soles mostly serves to increase friction

and enhance grip. Birds also counteract overheating by gular fluttering, or rapid vibrations of the gular (throat) skin.

Down feathers trap warm air, acting as an excellent insulator just as hair in mammals acts as a good insulator.

Chapter 5: Observation and Measurement of Temperature and Heat

The theory was developed in academic publications in French, English and German. Unstated distinctions between heat and "hotness" may be very old, heat seen as something dependent on the quantity of a hot substance, "heat", vaguely perhaps distinct from the quality of "hotness".

In 1723, the English mathematician Brook Taylor measured the temperature—the expansion of the liquid in a thermometer—of mixtures of various amounts of hot water in cold water. As expected, the increase in temperature was in proportion to the proportion of hot water in the mixture. The distinction between heat and temperature is implicitly expressed in the last sentence of his report. I successively fill'd the Vessels with one, two, three, &c.

Parts of hot boiling Water, and the rest cold...

And having first observed where the Thermometer stood in cold Water, I found that its rising from that Mark... In 1748, an account was published in The Edinburgh Physical and Literary Essays of an experiment by the Scottish physician and chemist William Cullen. Cullen had used an air pump to lower the pressure in a container with diethyl ether.

The ether boiled, while no heat was withdrawn from it, and its temperature decreased. And in 1758 on a warm day in Cambridge, England, Benjamin Franklin and fellow scientist John Hadley experimented by continually wetting the ball of a mercury thermometer with ether and using bellows to evaporate the ether. With each subsequent evaporation, the thermometer read a lower temperature, eventually reaching 7 °F (−14 °C).

In 1756 or soon thereafter, Joseph Black, Cullen's friend and former assistant, began an extensive study of heat.

In 1760 Black realized that when two different substances of equal mass but different temperatures are mixed, the changes in number of degrees in the two substances differ, though the heat gained by the cooler substance and lost by the hotter is the same. Black related an experiment conducted by Daniel Gabriel Fahrenheit on behalf of Dutch physician Herman Boerhaave.

For clarity, he then described a hypothetical but realistic variant of the experiment: If equal masses of 100 °F water and 150 °F mercury are mixed, the water temperature increases by 20 ° and the mercury temperature decreases by 30 ° (both arriving at

120 °F), even though the heat gained by the water and lost by the mercury is the same. This clarified the distinction between heat and temperature.

It also introduced the concept of specific heat capacity, being different for different substances.

Black wrote: "Quicksilver [mercury]... This unit was context-dependent and could only be used when circumstances were identical. It was based on change in temperature multiplied by the mass of the substance involved. If the stone and water...

1000 degrees hotter before it was plunged into the water than it is now, for otherwise it could not have communicated 10 degrees of heat to... [the] water. It was known that when the air temperature rises above freezing—air then becoming the obvious heat source—snow melts very slowly and the temperature of the melted snow is close to its freezing point.

In 1757, Black started to investigate if heat, therefore, was required for the melting of a solid, independent of any rise in temperature. As far Black knew, the general view at that time was that melting was inevitably accompanied by a small increase in temperature, and that no additional heat was needed beyond what this increase in temperature would require in itself.

Soon, however, Black was able to show that much more heat was required during melting than could be explained by any increase in temperature alone. He was also able to show that heat is released by a liquid during its freezing; again, much more than could be explained by the decrease of its temperature alone. In 1762, Black announced the following research and results to a society of professors at the University of Glasgow.

Black had placed equal masses of ice at 32 °F (0 °C) and water at 33 °F (0.6 °C) respectively in two identical, well separated containers. The water and the ice were both evenly heated to 40 °F by the air in the room, which was at a constant 47 °F (8 °C). The water had therefore received 40 – 33 = 7 "degrees of heat".

The ice had been heated for 21 times longer and had therefore received 7 × 21 = 147 "degrees of heat". The temperature of the ice had increased by 8 °F.

Mammalian skin is much thicker than that of birds and often has a continuous layer of insulating fat beneath the dermis. In marine mammals, such as whales, or animals that live in very cold regions, such as polar bears, this is called blubber. Dense coats found in desert endotherms also aid in preventing heat gain, such as in the case of camels.

A cold weather strategy is to temporarily decrease metabolic rate, decreasing the temperature difference between the animal and the air and thereby minimizing heat loss. Furthermore, having a lower metabolic rate is less energetically expensive. Many animals survive cold frosty nights through torpor, a short-term temporary drop in body temperature.

Organisms, when presented with the problem of regulating body temperature, have

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Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.