

ELEMENTS OF THERMODYNAMICS

The study of mechanics has been performed defining some fundamental concepts such as: mass, energy, force, work, -

In the same manner the description of the thermal phenomena implicates specific concepts such as: the TEMPERATURE, the HEAT, the INTERNAL ENERGY, the WORK, -

The Thermodynamics is the part of the Physics dealing with the energy transformations involving heat, work and other aspects of energy and their correlation with the properties of the matter.

1 Temperature and thermal equilibrium

The concept of temperature is often associated with the ideas of "hot" and "cold" based on our sense of touch. However, this perception is relative (with respect to the reference body) and often qualitative, vague and submitted to significant errors.

A lot of macroscopic properties that can be measured depend on the temperature, the length of a metallic rod, the pressure of steam in a boiler, the electric conductivity of metals, semiconductors, etc...

The temperature is directly correlated to the kinetic energy of molecular constituents of materials (microscopic definition). In this course / in the current section, we develop a macroscopic definition of the temperature.

Understanding the concept of temperature requires defining of two other concepts:

- thermal contact
- thermal equilibrium

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Thermal contact : Two systems (objects) are in thermal contact if between them an energy exchange can occur due to initial different temperature of the systems.

Thermal equilibrium - is the situation in which between two systems in thermal contact there is no energy exchange (heat or electromagnetic radiation). In this situation, the temperature of these two systems is identical.

The zeroth Law of Thermodynamics

If two systems A and B are individually in thermal equilibrium with a third system C, the A and B will be also in equilibrium with each other.

$$\begin{array}{l} A \longleftrightarrow C \\ B \longleftrightarrow C \end{array} \Rightarrow A \longleftrightarrow B$$

ob : C can be a thermometer

One can consider that the temperature is the property that determines if an object is at thermal equilibrium with other objects. Therefore,

Two systems are in thermal equilibrium if they have the same temperature.

Consequently, two systems in thermal contact that do not have the same temperature will not be in equilibrium.

② Thermometers and temperature scales

Thermometers - are the devices used to measure the temperature of a system.

The working principle of a thermometer relates to the dependence with the temperature of some physical property of a system :

- the volume of a liquid
- the dimensions of a solid
- the volume of a gas at constant pressure
- the electrical resistance of a conductor
- the colour of an object...

Operating a thermometer needs : - calibration
 - a temperature scale

The Celsius scale (centigrade scale)

- 0°C → the freezing temperature of pure water; the temperature of a mixture water/ice
- 100°C → the boiling temperature of water at p=1atm.

then, we divide in 100 equal intervals called degrees.
 Negative temperatures are below the frozen point of water.

Obs. The Celsius scale is the most common used in everyday life

The Fahrenheit scale (used in USA)

- 32°F : the frozen point of water
 - 212°F : the boiling point of water at p=1atm
- ⇒ 180°F between freezing - boiling point

Conversion:

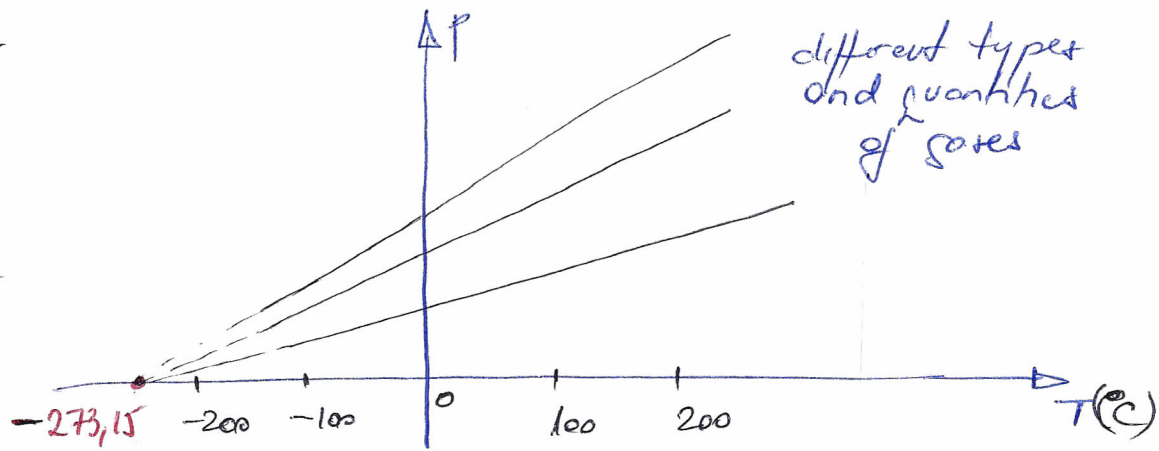
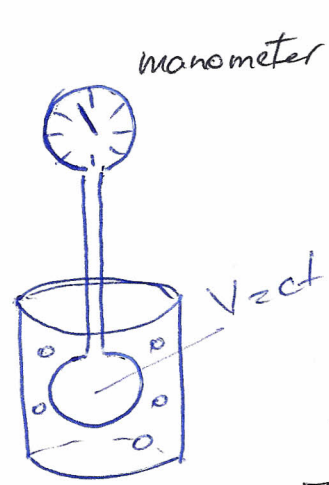
$$T_F = \frac{9}{5} T_C + 32^\circ$$

$$T_C = \frac{5}{9} (T_F - 32^\circ)$$

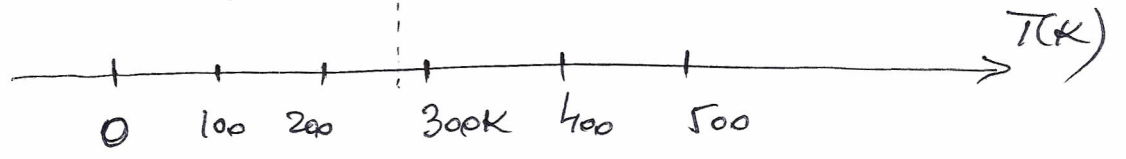
The absolute Kelvin scale

Because the previously defined scales depend on some specific material (water) properties, one would like to define a temperature scale which should be not dependant on any material properties.

⇒ We discuss a thermometer that comes close to the ideal, the gas thermometer. His working principle exploits the increase with the temperature of the gas pressure at constant volume.



The extrapolated plots all reach zero pressure at same temperature $-273,15^{\circ}\text{C}$



$$T_K = T_C + 273,15$$

$T = 0\text{K} = -273,15^{\circ}\text{C}$ (este numere si zero absolut) is called ABSOLUTE ZERO

At this temperature a system composed by atoms/molecules would have a minimum of its kinetic + potential energy. (The total energy is not zero). This will be later discussed when covering the 3rd principle of thermodynamics

③ Thermal expansion

Most materials expand when their temperature increase.

→ linear expansion

$$\Delta L = L - l_0 = \alpha l_0 \Delta T \quad \Rightarrow \boxed{L = l_0 (1 + \alpha \Delta T)}$$

$\alpha = \text{coeff of linear expansion}$ $[\alpha] = \text{K}^{-1}$ (or $^{\circ}\text{C}^{-1}$)

→ volume expansion

$$\Delta V = \beta V_0 \Delta T$$

$$\Rightarrow \boxed{V = V_0 (1 + \beta \Delta T)}$$

β = coeff of volume expansion

$$[\beta] = K^{-1} (^\circ C^{-1})$$

for solid materials $\boxed{\beta \approx \alpha^2}$

Examples

Al	$\alpha = 2,4 \cdot 10^{-5} K^{-1}$	$\beta = 7,2 \cdot 10^{-5} K^{-1}$
glass	$\alpha = 0,4 - 0,9 \cdot 10^{-5} K^{-1}$	$\beta = 1,2 - 2,7 \cdot 10^{-5} K^{-1}$
quartz	$\alpha = 0,06 \cdot 10^{-5} K^{-1}$	$\beta = 0,12 \cdot 10^{-5} K^{-1}$

water

0-4°C anomaly: the volume decreases with increasing T $\Rightarrow \beta < 0$

above 4°C classical behaviour

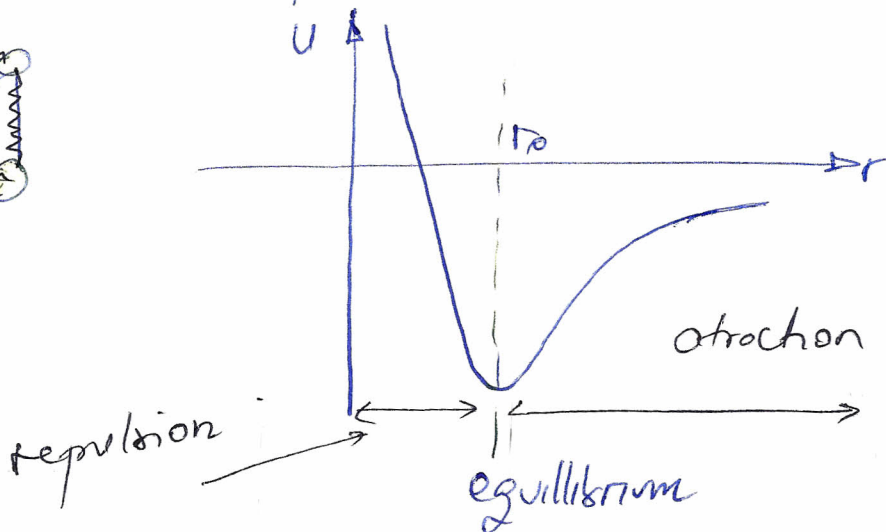
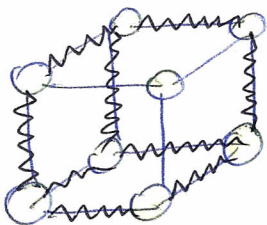
$$V = V_0 (1 + \beta \Delta T) ; \beta > 0$$

From $\rho = \frac{m}{V} \Rightarrow$ the water has a maximum density at 4°C.

Moreover, the volume of water increases when freezing, whereas for most of materials the volume decreases by freezing.

Dilatation microscopic explanation

The interatomic potential in a solid structure is:



atoms oscillate around the equilibrium position at finite T.
 • amplitude $\propto T$

When the temperature increases, the energy and the amplitude of vibration increase. The interatomic spring forces are not identical / symmetrical with respect to the equilibrium; they usually behave as a spring which is easier to stretch than to compress. As consequence, to minimize repulsion energy, when the T increases and the vibration amplitude increases, the equilibrium distance r_0 will also increase. \Rightarrow dilatation.

Obs.: Thermal dilatation has a lot of applications and consequences in technics, especially when composite materials with different thermal coefficients of constituent materials are involved.

2 HEAT AND INTERNAL ENERGY.

Internal energy: represents the total energy of a system associated to its microscopic components (atoms, molecules) as analysed from a referential in rest with respect to the center of mass of the system.

U

ex.: translational, rotational, vibrational kinetic energy of molecules in a gas, potential interaction energy of and between molecules, ...

Heat: is defined as the energy transferred to or from a system due to different temperature of the system with respect to its environment.

Q

ex.: we warm a body by energy transfer to it from another body with higher temperature.

Specific heat

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The heat required to increase the temperature by ΔT to a system with the mass m is:

$$Q = mc\Delta T$$

c = specific heat (material dependent)

$$c_{H_2O} = 4180 \text{ J/kgK} = 1 \text{ cal/g}^\circ\text{C} = 1 \text{ BTU} / 16^\circ\text{F}$$

ex: overheating electronics

an electronic circuit element made by 23 μg of silicon. The electric current through it adds energy at the rate of $7.4 \text{ mW} = 7.4 \cdot 10^{-3} \text{ J/s}$. If the design does not allow any heat flow towards other element at what rate the temperature increases? ($c_{Si} = 705 \text{ J/kgK}$)

$$Q = mc\Delta T$$

$$\frac{dQ}{dt} = mc \frac{\Delta T}{dt} \Rightarrow \frac{\Delta T}{dt} = \frac{dQ/dt}{mc} = \frac{7.4 \cdot 10^{-3}}{23 \cdot 10^{-6} \cdot 705} =$$

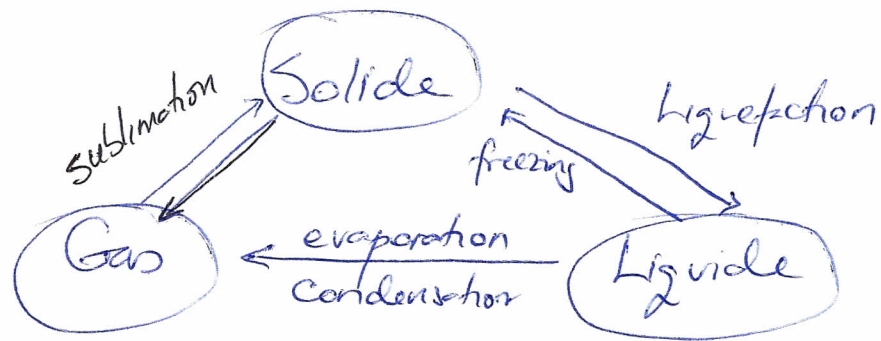
$$= 0.46 \text{ K/s}$$

$$= 27 \text{ K/min}$$

At this rate, the circuit will self-destruct soon \Rightarrow special radiators to allow heat transfer required.

Phase changes \rightarrow occur at given constant T

melting (solid \leftrightarrow liquid) \leftarrow freezing (L \rightarrow S)
evaporation (liquid \rightarrow gas) condensation (G \rightarrow L)
sublimation (S \rightarrow G)
solid gas



$$Q = \pm m \lambda$$

$\lambda =$ latent heat

- + melting (absorption of heat)
- freezing (release of heat)

The fundamental equation of calorimetry

$$Q_{\text{given}} = Q_{\text{received}}$$

< 0

> 0

convention

↳ issues from energy conservation principle

3] Mechanisms of heat transfer

There are materials that permit or prevent heat transfer between bodies. These are conductors and insulators (thermal).

Three main mechanisms are involved in the heat transfer:

- conduction
- convection
- radiation

Conduction: occurs within a body or between two bodies in contact

Convection: depends on the motion of mass from one region of the space to another.

Radiation is the heat transfer by electromagnetic radiation, such as sunshine, with no need of matter to be present in the space between bodies. -9-

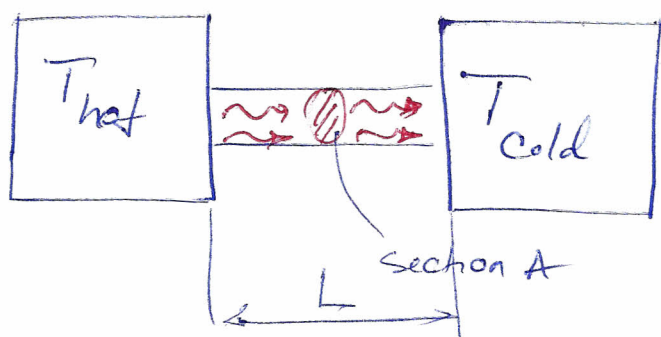
(A) Conduction

If one holds one end of a copper rod and place the other on a flame, the end holded gets hotter and hotter even if it is not in direct contact with the flame. Heat is transferred by conduction through the metal.

At atomic level the atoms in hotter region have more kinetic energy than their cooler neighbours. This energy is transferred from place to place up to the colder region to the colder atoms. The atoms themselves do not move but their energy does.

In metals, the free electrons provide a more efficient mechanism for heat transfer, carrying more rapidly the energy from hotter to colder places. \rightarrow metals are good heat conductors.

The heat transfer ALWAYS takes place from hotter places to colder places



One can define:
 \rightarrow the heat current

$$H = \frac{dQ}{dt}$$

One can see that

$$H \propto A \quad (\text{unit area})$$

$$\propto \frac{1}{L} \quad (\text{conductor length})$$

$$\Rightarrow H = \frac{dq}{dt} = kA \frac{T_H - T_C}{L}$$

heat current

thermal conductivity

temperature gradient $\frac{\Delta T}{L} = \frac{dT}{dx}$

$$\Rightarrow \frac{H}{A} = \vec{j}_q = -k \frac{\partial T}{\partial x}$$

density of heat current

minus sign shows that heat always flows in the direction of decreasing the temperature

If T varies along x, y and z

$$\nabla T = \text{grad } T = \frac{\partial T}{\partial x} \vec{i} + \frac{\partial T}{\partial y} \vec{j} + \frac{\partial T}{\partial z} \vec{k}$$

$$\Rightarrow \vec{j}_q = -k \nabla T$$

Fourier Law for thermal conduction

see equivalence with the Ohm's law in electricity (2nd term)

$$\vec{j} = \sigma \vec{E} = -\sigma \nabla V$$

electric charge current density

electric conductivity

$$j = \frac{1}{A} \frac{dq}{dt} = \frac{i}{A}$$

Thermal Conductivities

Substance	k ($W/m \cdot K$)
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Metals:

Al	205
brass	109
Cu	385
Hg	813
Ag	406
steel	50,2
Pb	34,7

Solids

Brick, insulating	0,15
Brick, red	0,6
concrete	0,8
Cork	0,04
glass	0,8
wood	0,12 - 0,04
rock wool	0,04
polystyrene	0,027 - 0,05
BCA	0,27

Gases:

air	0,024
Ar	0,016
He	0,14
H	0,14
oxygen	0,023

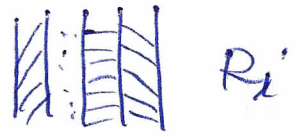
For thermal isolation of buildings one uses the thermal resistance

$$R = \frac{L}{k}$$

$$[R]_{SI} = \frac{1 \text{ m}^2 \text{ K}}{\text{W}}$$

For stratified materials:

$$R = \sum_x R_i$$



$$L = 20 \text{ cm brick} \quad R_c = 1,33 \frac{\text{m}^2 \text{K}}{\text{W}}$$

$$L = 20 \text{ cm polystyrene} \quad R_c = 4 \frac{\text{m}^2 \text{K}}{\text{W}}$$

$$L = 20 \text{ cm concrete} \quad R_c = 0,21 \frac{\text{m}^2 \text{K}}{\text{W}}$$

ok: 10 cm polystyrene \Rightarrow 11 cm concrete !

$\rightarrow R_{\text{min}} = 1,4 \frac{\text{m}^2 \text{K}}{\text{W}}$ (indicative C107/2005)
minimum thermal resistance
required for house isolation

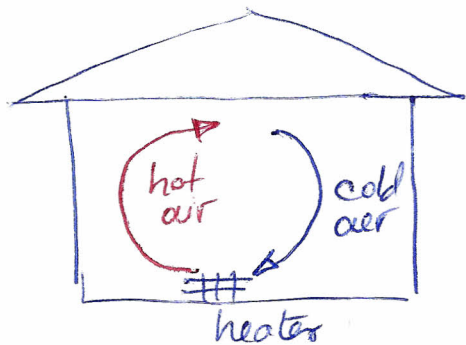
(B) CONVECTION

Convection is the transfer of heat by mass motion of a fluid from one region of space to another.

Examples: hot-air and hot-water home heating system, cooling system of car's engine, flow of blood in the body.

• If the fluid is circulated by a blower or a pump the process is called forced convection

• If the flow is caused by differences in density due to thermal expansion, such as hot air rising, the process is called natural or free convection



The most important mechanism through the human body needed to maintain constant temperature in different circumstances is the forced convection of blood with heart serving as pump.

Convective heat transfer is a very complex process and there is no simple equation to describe it. However there are some experimental features:

- (1) The heat current due to the convection is proportional to the surface area. This is why we use large area radiators.
- (2) Viscosity of fluids slows natural convection near stationary surface, giving rise to a thin insulating film with $R = 0.7$. Forced convection reduces the thickness of this insulating film increasing the rate of heat transfer. This is the reason of the "wind chilling factor" you feel colder weather in windy days.
- (3) The current of heat due to the convection is found to be approximately proportional to the $5/4$ power of the temperature difference between the surface and the main body of fluid.

(c) Radiation

Radiation is the transfer of heat by electromagnetic waves such as visible light, UV, IR radiation.

Every body, even at ordinary temperatures, emits energy in the form of electromagnetic radiation.

→ around 20°C , nearly all the energy is carried by infrared (IR) waves with wavelength λ longer than the one of visible light.

→ as the temperature rises, the wavelength shifts to shorter values (frequency increases). $f = \frac{c}{\lambda}$; ($c = 3 \cdot 10^8 \text{ m/s}$).

At 800°C a body emits enough visible radiation to appear as red-hot. At 3000°C the temperature of an incandescent lamp filament contains enough visible radiation to appear as white-hot.

The power in watt radiated by the surface of an object heated at a temperature T is given by:

$$H = Ae\sigma T^4$$

Stefen - Boltzmann Law

σ = fundamental constant called Stefen - Boltzmann constant

$$\sigma = 5,67 \cdot 10^{-8} \text{ W/m}^2\text{K}^4$$

e = emissivity (0-1) often larger for darker surfaces than light ones

A = surface of radiating body

Radiation and absorption

While a body at temperature T is radiating its surroundings at temperature T_s are also radiating and the body absorbs a part of this radiation. If it is in thermal equilibrium with its surroundings, $T = T_s$ the rates of emitted and absorbed radiation have to be equal. Then the net rate of radiation from a body at a finite temperature T with respect to surrounding at T_s is:

$$H_{\text{net}} = Ae\sigma (T^4 - T_s^4)$$

$H_{\text{net}} > 0 \Rightarrow$ net flux of radiation out of the body

This equation shows that for radiation, as for the conduction and the convection, the heat current depends on the temperature difference between bodies.

Particular cases

- ideal absorber = body that absorbs all the radiation arriving on it.

$$\boxed{e = 1}$$

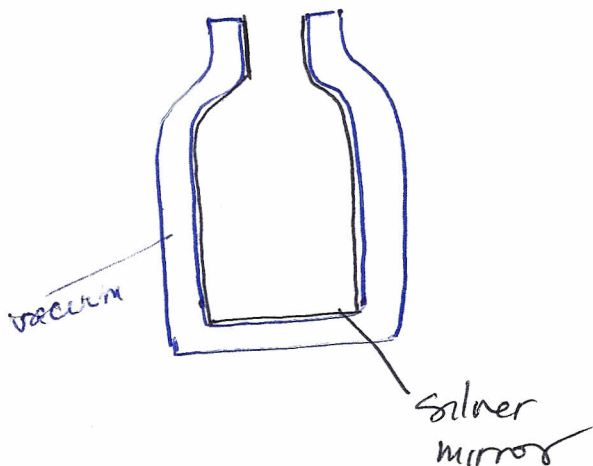
This is also called BLACK-BODY

- Ideal reflector = reflects all the electromagnetic energy incident on it. (zero absorption)

$$\boxed{e = 0}$$

ex: The Dewar ("thermos") : invented by Sir James Dewar 1842-1923

vacuum bottle with double glass walls



pump out the air in the space
eliminates heat transfer by:

→ conduction

→ convection

The silver coating on inner wall reflects the electromagnetic radiation back into the container ⇒ poor emitter.

Therefore one can keep warm or cold food or liquefied gases (i.e. liquid N_2 ; $T = 70K$).

For liquid He ($T = 4.2K$) one uses a double Dewar system with intermediate space filled with liquid N_2 .

PRINCIPLES OF THERMODYNAMICS

A thermodynamic system is any collection of objects that is convenient to regard as a unit that have the potential to exchange energy with its surroundings.

A process in which there are changes in the state of a thermodynamic system is called a thermodynamic process.

A state of a thermodynamic system is specified by the state variables:

- temperature (T)
- pressure (p)
- volume (V)
- composition n

In some cases the relationship $T-p-V-n$ is simple enough that we can express it in an equation of state. For an ideal gas, the equation of state is:

$$pV = nRT$$

pressure of the gas volume of the gas number of moles temperature

$R = 8310 \text{ J/molK}$
is the perfect gases constant

1) The first law of thermodynamics

→ states a conservation law (energy conservation) for a thermodynamic system.

When heat Q is added or extracted from a system while the system does or receives the work W , the total internal energy of the system U changes by the amount $Q - W$.

$$\Delta U = Q - W$$

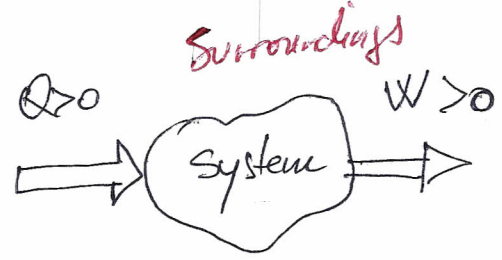
$$\Rightarrow Q = \Delta U + W$$

or in an infinitesimal process
 $dU = dQ - dW$

The internal energy of a thermodynamic system depends only on its state \Rightarrow the change of U in any process depends only on initial and final state, not on the evolution path. The internal energy of an isolated system is constant.

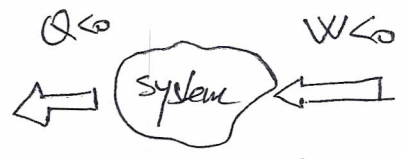
Sign convention

$Q > 0 \Rightarrow$ heat flow INTO the system (received)



$Q < 0 \Rightarrow$ heat flow OUT OF the system (released)

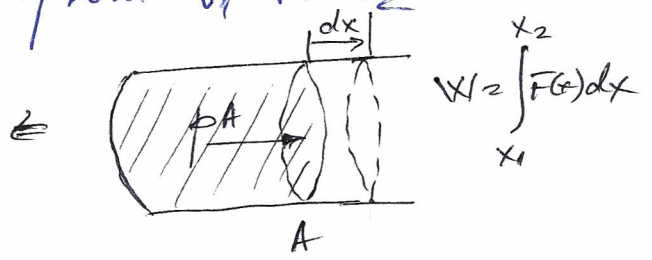
$W > 0 \Rightarrow$ work done by the system against surroundings (e.g. expanding gas)



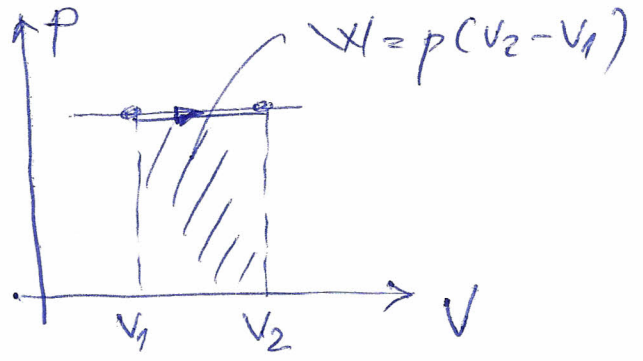
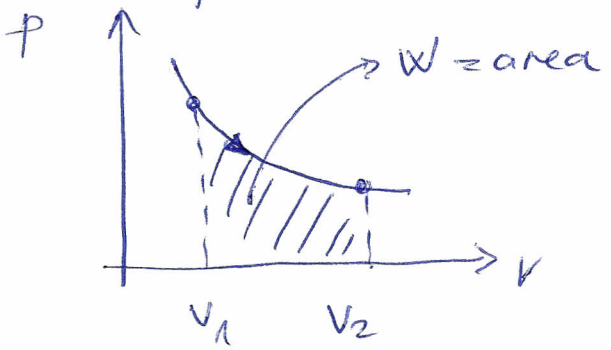
$W < 0 \Rightarrow$ work done by surroundings on the system (e.g. compression of a gas)

In a finite change of volume from V_1 to V_2

$$W = \int_{V_1}^{V_2} p \, dV$$



In a p - V diagram:



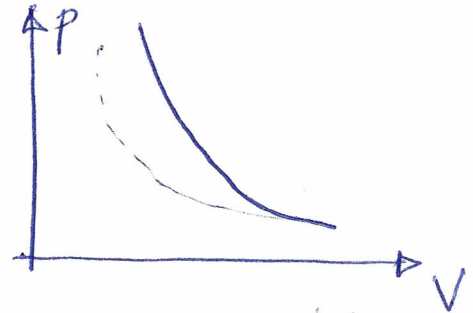
work done in a volume change at constant pressure

Important types of thermodynamic processes

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① Adiabatic : No heat transfer into or out of the system
 $Q=0$

$$\Rightarrow U_2 - U_1 = \Delta U = -W$$



Clepyron representation

$$pV^\gamma = \text{const}$$

$$\gamma = \frac{C_p}{C_v}$$

C_p = heat capacity of the gas at constant pressure

ratio of heat capacities

C_v = heat capacity of the gas at constant volume

monatomic gas $\left\{ \begin{array}{l} C_v = \frac{3}{2} R \\ C_p = \frac{5}{2} R \end{array} \right.$

$$C_p = C_v + R$$

Robert-Mayer relation

diatomic gas $\left\{ \begin{array}{l} C_v = \frac{5}{2} R \\ C_p = \frac{7}{2} R \end{array} \right.$

$$\Delta U = n C_v (T_2 - T_1)$$

$$\Rightarrow W = -\Delta U = n C_v (T_1 - T_2)$$

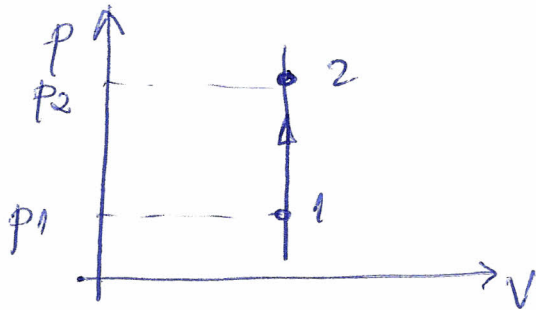
adiabatic process.

if we use $pV = nRT$

$$W = \frac{C_v}{R} (p_1 V_1 - p_2 V_2) = \frac{1}{\gamma - 1} (p_1 V_1 - p_2 V_2)$$

② Isochoric process

constant volume $V = \text{const}$



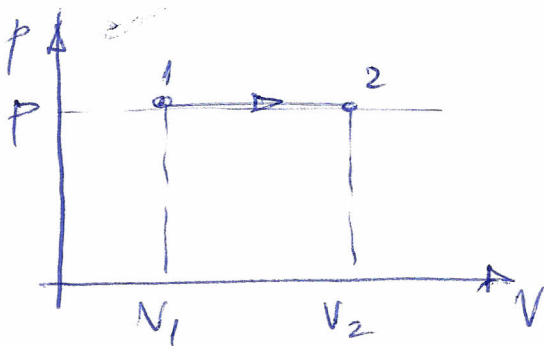
Clapeyron representation

$$W = \int_{V_1}^{V_2} p dV = 0$$

$$\Rightarrow Q = \Delta U = nC_v(T_2 - T_1)$$

③ Isoobaric process

constant pressure $p = \text{const}$



$$W = p(V_2 - V_1)$$

$$\Delta U = nC_v(T_2 - T_1)$$

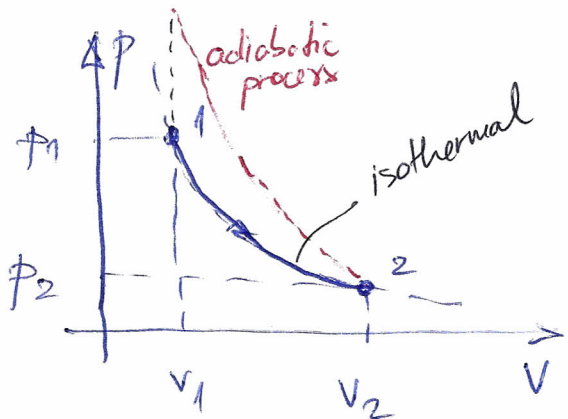
$$Q = \Delta U + W = \left. \begin{aligned} & \\ & pV = nRT \end{aligned} \right\} \Rightarrow$$

$$Q = (C_v + R)n(T_2 - T_1) = nC_p(T_2 - T_1)$$

$$Q = nC_p(T_2 - T_1)$$

④ Isothermal process

constant temperature $T = \text{const}$



$$\Rightarrow \Delta U = 0$$

$$Q = W = \int_{V_1}^{V_2} p dV$$

$$pV = nRT \Rightarrow p = \frac{nRT}{V}$$

$$Q = W = nRT \int_{V_1}^{V_2} \frac{dV}{V} = nRT \ln \frac{V_2}{V_1}$$

$$= nRT \ln \frac{p_1}{p_2}$$

[2] The second law of thermodynamics

The first principle of thermodynamics does not indicate the direction of a thermodynamic process. Many thermodynamic processes proceed naturally in one direction but not the opposite:

→ heat by itself always flows from a hot body to a cold one, never vice-versa

→ a drop of ink always spreads and mixes to a cup of water. One never observes the opposite

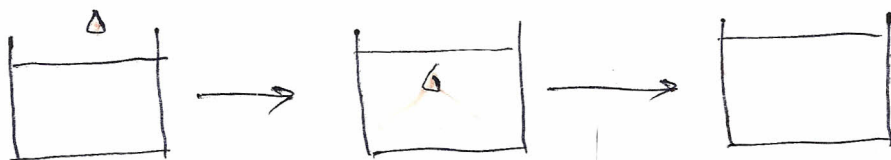
→ it is easy to convert totally mechanic energy into heat (ie stopping a moving car by braking). In the reverse direction one can only partially convert heat to mechanical energy (work), e.g. engines.

The answer to these questions has to do with the directions of a thermodynamic process stated by the second law of thermodynamics. This law places fundamental limitations to the efficiency of an engine or a power plant, or a refrigerator.

We can also state the second law in terms of a concept called ENTROPY, a quantitative measure of the degree of disorder or randomness of a system. The entropy helps us to explain why ink mixed into water never unmixes spontaneously!

In a natural thermodynamic process the total energy always increases.

$$dS = \frac{dQ}{T} \quad \Rightarrow \quad \Delta S = \int \frac{dQ}{T} > 0$$



mixing of ink
disorder increases
 $\Delta S > 0$

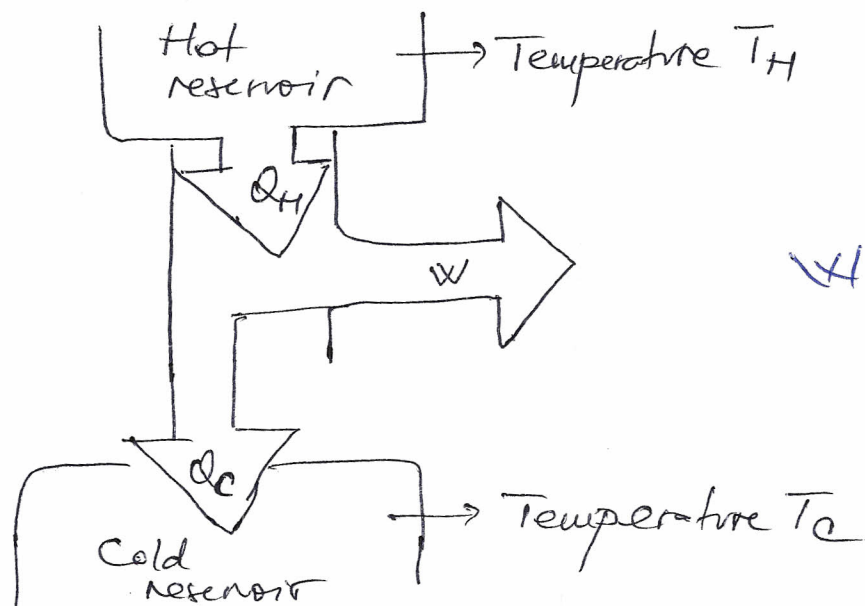
Heat engines and refrigerator

Any device that transforms heat partially into work or mechanical energy is a heat-engine using cyclic or non-cyclic processes.

Hot and cold reservoirs

All heat engines absorb heat from a source at high temperature

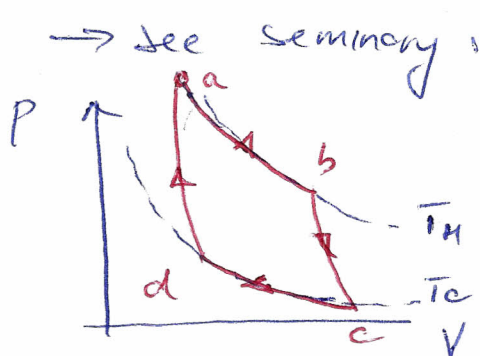
- perform work
- discard / reject some heat at lower temperature



$$W = |Q_H| - |Q_C|$$

Thermal efficiency of the engine:

$$e = \frac{W}{Q_H} = 1 - \frac{|Q_C|}{|Q_H|} < 1$$

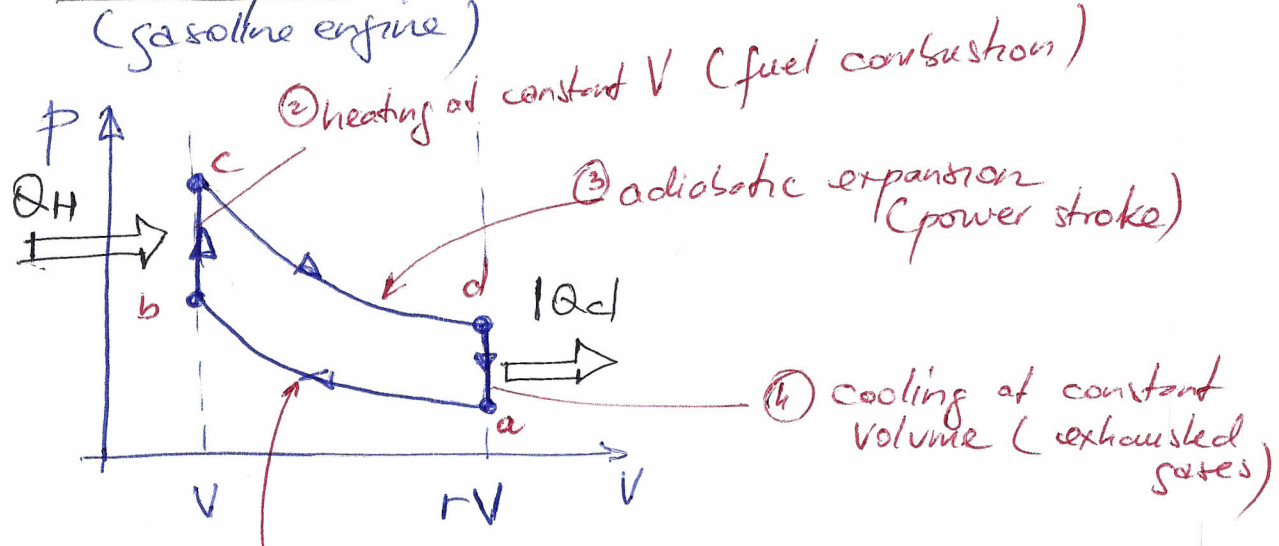


Carnot cycle (ideal engine) giving maximum efficiency when working between T_C & T_H

- 2 adiabatic trans bc, da
- 2 isochores ab, cd

$$e = 1 - \frac{T_C}{T_H}$$

Otto cycle (gasoline engine)



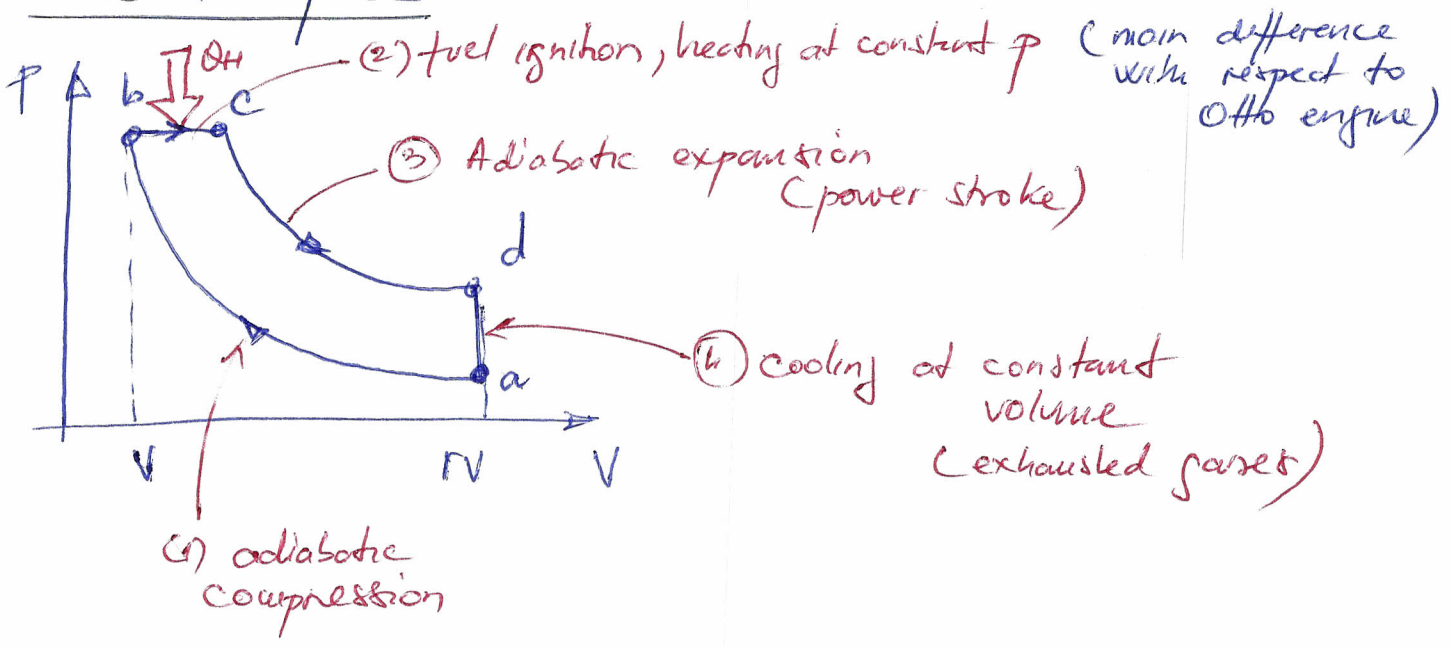
① adiabatic compression

$$e = 1 - \frac{1}{r^{\gamma-1}}$$

$r =$ compression ratio

$r = 8, \gamma = 1.4 \Rightarrow e = 0.56$ (56%)
(theoretically)
in practice $e \approx 35\%$

Diesel cycle



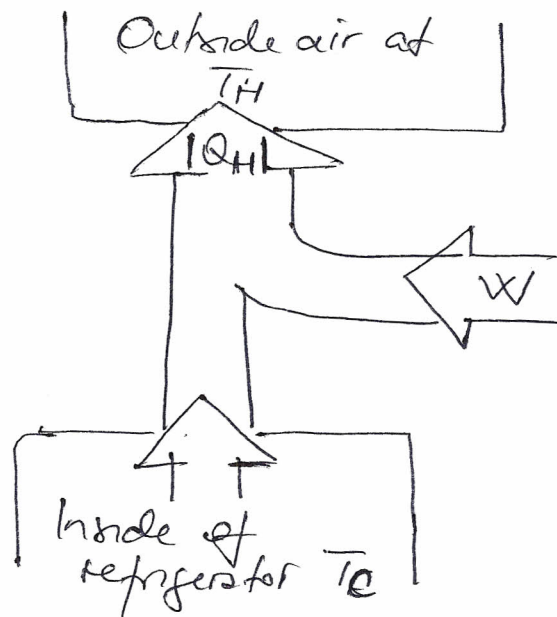
① adiabatic compression

④ cooling at constant volume (exhausted gases)

Refrigerator

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A refrigerator is a heat engine operating in reverse: it takes heat from a cold place and gives it off to a warmer place, using a work done on it.



$$|Q_H| = Q_C + |W|$$

One can define the coefficient of performance

$$K = \frac{|Q_C|}{|W|} = \frac{|Q_C|}{|Q_H| - |Q_C|}$$

Enunciation for the 2nd law of thermodynamics

It is impossible for any system to undergo a cyclical process in which it absorbs heat from a reservoir at a single temperature and converts the heat completely into mechanical work
(Kelvin-Planck statement)

It is impossible for any process to have its sole result the transfer of heat from a cooler to a hotter body

(Clausius statement)

Ob: a refrigerator does this but its operation requires an input of mechanical energy of work.

③ Third law

Also called the principle of Nernst
has different formulations:

(1) Planck: the entropy of a system approaches to an absolute constant which can be considered as zero when the temperature approaches the absolute zero.

(2) At $T = 0K$ the system has to be in a state with minimum thermal energy

If one defines the entropy by

$$S = k_B \ln \Omega \quad k_B = \text{Boltzmann constant}$$

Ω = number of microstates (possible configurations of atoms constituent of the system)

at $T = 0K$ $\Omega = 1$ (fixed atoms)

$$\Rightarrow S = 0$$

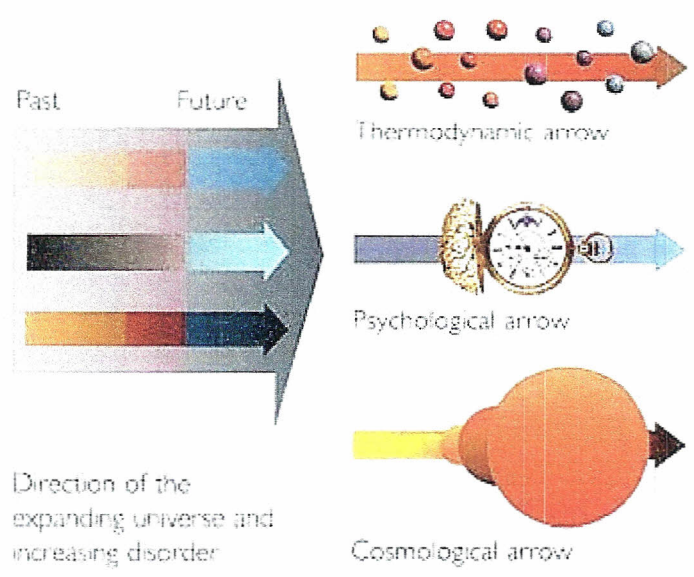
At $T = 0K$ any system goes in its fundamental quantum states.

(3) It is impossible, via a finite number of thermodynamic processes, to decrease the temperature of a system to absolute zero.

Entropy and time arrow

The arrow of time expresses the fact that in the world about us the past is distinctly different from the future. Milk spills but doesn't unspill; eggs splatter but do not unsplatter; waves break but do not unbreak; we always grow older, never younger. These processes all move in one direction in time - they are called "time-irreversible" and define the arrow of time. It is therefore very surprising that the relevant fundamental laws of nature make no such distinction between the past and the future. This in turn leads to a great puzzle - if the laws of nature permit all processes to be run backwards in time, why don't we observe them doing so? Why does a video of an egg splattering run backwards look ridiculous? Put another way: how can time-reversible motions of atoms and molecules, the microscopic components of material systems, give rise to the observed time-irreversible behavior of our everyday world? The resolution of this apparent paradox is due to Maxwell, Thomson and (particularly) Boltzmann. These ideas also explain most other arrows of time - in particular; why do we remember the past but not the future?

The arrow of time in various phenomena



All phenomena that behave differently in one time direction can ultimately be linked to the Second Law of Thermodynamics. This includes the fact that ice cubes melt in hot coffee rather than assembling themselves out of the coffee, that a block sliding on a rough surface slows down rather than speeding up, and that we can remember the past rather than the future. This last phenomenon, called the "psychological arrow of time", has deep connections with Maxwell's demon and the physics of information; In fact, it is easy to understand its link to the Second Law of Thermodynamics if one views memory as correlation between brain cells (or computer bits) and the outer world. Since the Second Law of Thermodynamics is

equivalent to the growth with time of such correlations, then it states that memory is created as we move towards the future (rather than towards the past).

The thermodynamic arrow of time

The thermodynamic arrow of time is provided by the Second Law of Thermodynamics, which says that in an isolated system, entropy tends to increase with time.

The cosmological arrow of time

The cosmological arrow of time points in the direction of the universe's expansion.

The radiative arrow of time

Waves, from radio waves to sound waves to those on a pond from throwing a stone, expand outward from their source, even though the wave equations allow for solutions of convergent waves as well as radiative ones.

This arrow probably follows from the thermodynamic arrow in that meeting the conditions to produce a convergent wave requires more order than the conditions for a radiative wave.

The causal arrow of time

A cause precedes its effect: the causal event occurs before the event it affects. Birth, for example, follows a successful conception and not vice versa. Thus causality is intimately bound up with time's arrow.

The quantum arrow of time

According to the Copenhagen interpretation of quantum mechanics, quantum evolution is governed by the Schrödinger equation, which is time-symmetric, and by wave function collapse, which is time irreversible.

The psychological/perceptual arrow of time

A related mental arrow arises because one has the sense that one's perception is a continuous movement from the known (past) to the unknown (future).

Why is Time a One-Way Street?

Leonard Susskind

https://www.youtube.com/watch?v=jhnKBKZvb_U

Anyone can see that the past is different from the future. Anyone, that is, but theoretical physicists, whose equations do not seem to distinguish the past from the future. How, then, do physicists understand the "arrow of time" — the fact that the past and future are so different? Leonard Susskind will discuss the paradox of time's arrow and how physicists and cosmologists view it today. Leonard Susskind is Felix Bloch Professor of Theoretical Physics at Stanford University and Director of the Stanford Institute for Theoretical Physics