TERMODINAMIKAREN ZERO PRINTZIPIOA
TENPERATURA

1.5 * OREKA TERMIKOA

- (SISTEMA , HORMA , INGURUNEA) HIRUKOTEAREN KASU BEREZIA
  ADIABATIKOA ISOLAMENDUA
  DIATERMANOA

1.5 * TERMODINAMIKAREN ZERO PRINTZIPIOA

1.6 * TENPERATURA KONTZEPTUA

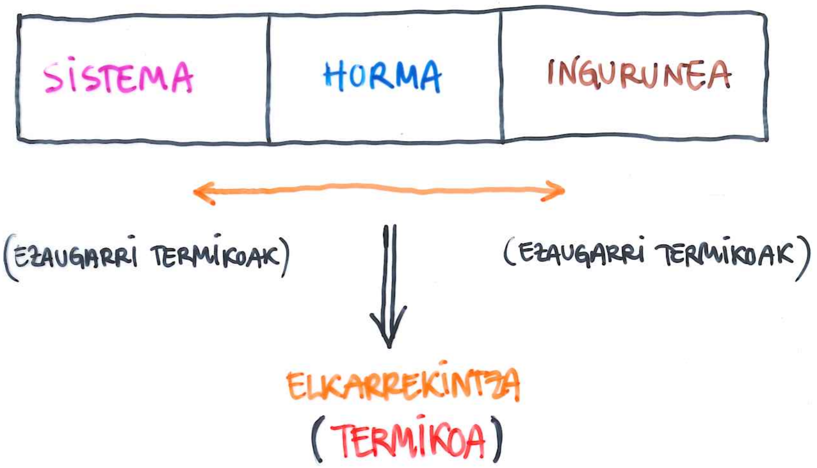
- ESPERIENTZIAN OINARRITURIKO METODOA : PROPIETATE KOMUNA
- MATEMATIKAN OINARRITURIKO METODOA : BALIO KOMUNA
  - LERRO ISOTERMANOAK
  - LERRO ISOTERMANO KORRESPONDENTEAK
  - TENPERATURA :

1.7 * SISTEMEN TENPERATURA
[illegible]
1.9
1.10
1.11

- TENPERATURA ESKALA
  - TERMOMETROA
    - SISTEMA-MOTA
    - SISTEMA KONKRETUA
  - ALDAGAI TERMOMETRIKOA
  - FUNTZIO TERMOMETRIKOA
  - PROPORTZIONALTASUN-KONSTANTEA : PUNTU FINKOAK
- TENPERATURAREN NEURKETA
  - TERMOMETRO-MOTAK
- TENPERATURA-ESKALAK
  - GAS IDEALAREN TENPERATURA-ESKALA
  - CELSIUS ESKALA
  - KELVIN ESKALA

⋮

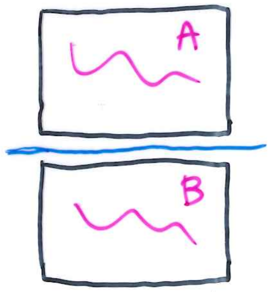
OREKA TERMIKOA



BAI

HORMA DIATERMANOA

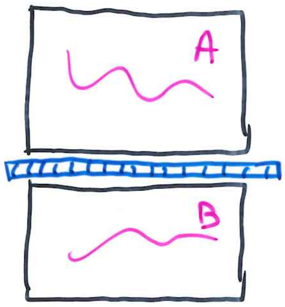
ISOLAMENDU EZA TERMIKOA



EZ

HORMA ADIABATIKOA

ISOLAMENDUA TERMIKOA



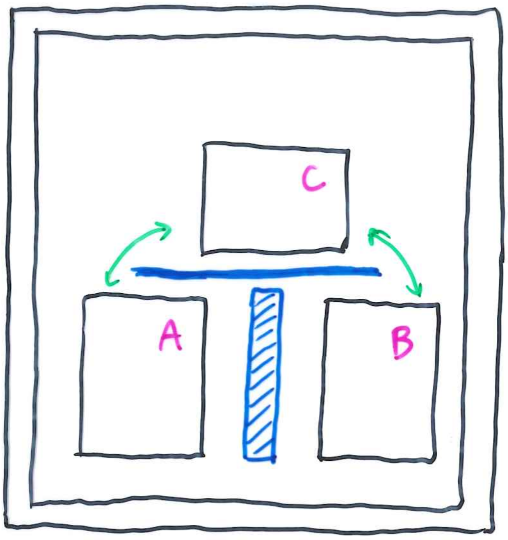
OREKA TERMIKOA:

HORMA DIATERMIKOAREN BIDEZ 'LOTURIKO' BI SISTEMEK LORTUKO DUTEN EGOERA ALDAEZINA (HOTS; OREKA-EGOERA)

- Aldagai termodinamikoak aipatu; $\{X, Y, Z, \ldots\}$ ez dute beren balioak aldatuko; edo, bai.

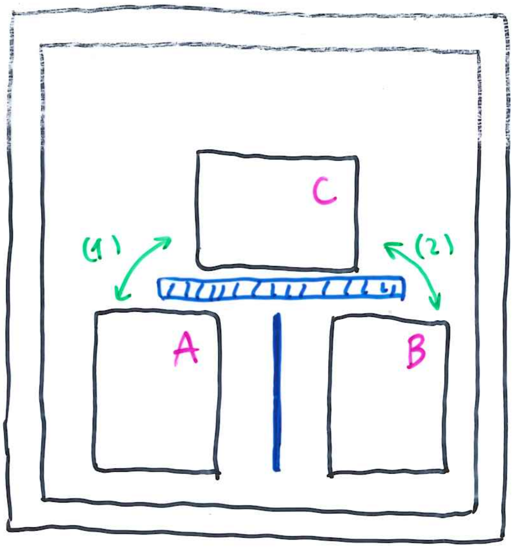
TERMODINAMIKAREN ZERO PRINTZIPIOA (7,8 orr.)

(a)



BIAK ALDIBEREAN

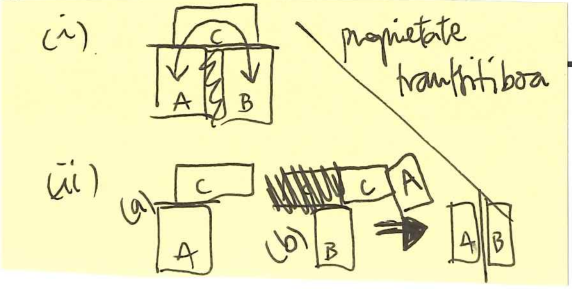
(b)



LEHENENGO BAT,
GERO BESTEA

TERMODINAMIKAREN ZERO PRINTZIPIOA :

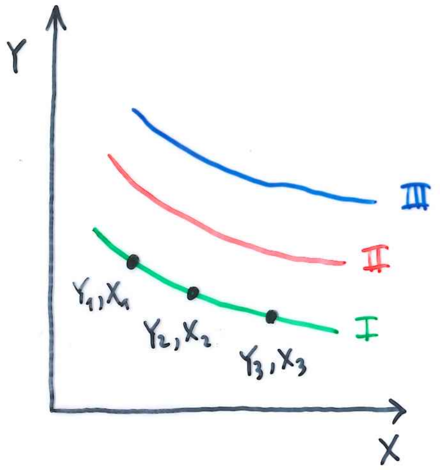
ESKU ARTEAN DITUGUN A ETA B SISTEMAK, C SISTEMAREKIN OREKA TERMIKOAN BADAUDE (BAKOITZA BERE ALDETIK), ELKARREN ARTEKO OREKA TERMIKOAN DAUDE



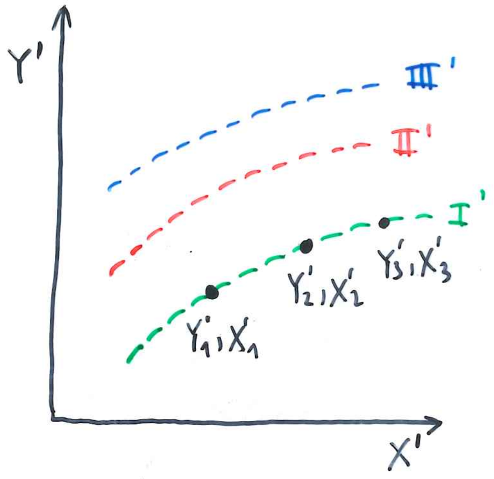
propietate trantsitiboa

TENPERATURA

(a) ESPERIENTZIAN OINARRITUTAKO "METODOA" TENPERATURA DEFINITZEKO



A SISTEMA



B SISTEMA

"LERRO" ISOTERMANOA

LERRO ISOTERMANO KORRESPONDENTEAK

TENPERATURA: PROPIETATE KOMUNA

(b) MATEMATIKAN OINARRITUTAKO "METODOA" TENPERATURA DEFINITZEKO

$\{A, B, C\}$ SISTEMAK

$\{A, C\}$ OREKA TERMIKOA

$$f_{AC}(X_A, Y_A; X_C, Y_C) = 0$$

$\{B, C\}$ OREKA TERMIKOA

$$f_{BC}(X_B, Y_B; X_C, Y_C) = 0$$

$$f_{AC}(X_A, Y_A; X_C, Y_C) = 0 \Rightarrow Y_C = g_{AC}(X_A, Y_A; X_C)$$

$$f_{BC}(X_B, Y_B; X_C, Y_C) = 0 \Rightarrow Y_C = g_{BC}(X_B, Y_B; X_C)$$

$$g_{AC}(X_A, Y_A; X_C) = g_{BC}(X_B, Y_B; X_C)$$

$\{A, B\}$ OREKA TERMIKOA

$$\left.\begin{aligned} f_{AB}(X_A, Y_A; X_B, Y_B) &= 0 \\ g_{ABC}(X_A, Y_A; X_B, Y_B; X_C) &= 0 \end{aligned}\right\} X_C \text{ SOBERAN}$$

$$h_A(X_A, Y_A) = h_B(X_B, Y_B)$$

$$h_A(X_A, Y_A) = h_B(X_B, Y_B) = h_C(X_C, Y_C)$$

$$\boxed{\text{TENPERATURA}: t = h_A(X_A, Y_A) = h_B(X_B, Y_B) = h_C(X_C, Y_C)}$$

ORUKORTUZ . . .

$$h_i = h_i\,(x_i, y_i, z_i, \dots)$$

$$i = A, B, C \dots$$

$$\boxed{t = h_A(X_A, Y_A, Z_A, \dots) = \dots = h_i(X_i, Y_i, Z_i, \dots) = \dots}$$

$$\left.\begin{array}{l}\text{SISTEMAK}\\ \text{ALDAGAIAK}\\ \text{FUNTZIOAK}\end{array}\right\}\ \text{DESBERDINAK}$$

(SISTEMA-MOTA ERE DESBERDINA IZAN DAITE)

OREKA TERMIKOAN BADAUDE

"TENPERATURA BEREAN DAUDE"

FUNTZIOAK BALIO BAKARRA DU (BALIO KOMUNA DU)

HAUXE DA LERRO ISOTERMANOAREN SORTARI BALIOA

ZEIN BALIO DA HORI ? (ZEIN ZENBAKI DA HORI ?)

BALIOAK FINKATZEKO TENPERATURA-ESKALA DEFINITU BEHAR DA

TENPERATURA-ESKALA / TENPERATURAREN NEURKETA

- BALIOA FINKATZEKO PROZEDURA OROKORRA

1 - SISTEMA-MOTA
2 - SISTEMA KONKRETUA
3 - ALDAGAI TERMOMETRIKOA
4 - FUNTZIO TERMOMETRIKOA
5 - PUNTU FINKOAK

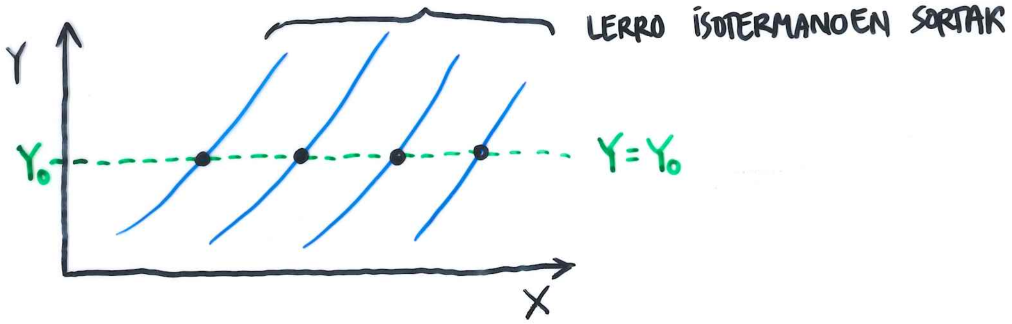
} FINKATU

} TERMOMETROA (PATROIA)

1 - S SISTEMA-MOTA $S = S(X, Y, Z, \dots)$ $\{X, Y, Z, \dots\}$

2 - SISTEMA KONKRETUA $S(X, Y)$

3 -



X DA ALDAGAI TERMUMETRIKOA $\{X ; Y_0\}$
(HAUXE DA TENPERATURAREKIN BATERA ALDATUKO DENA)

4 - $\theta(X) = aX$ FUNTZIO TERMOMETRIKOA a ?

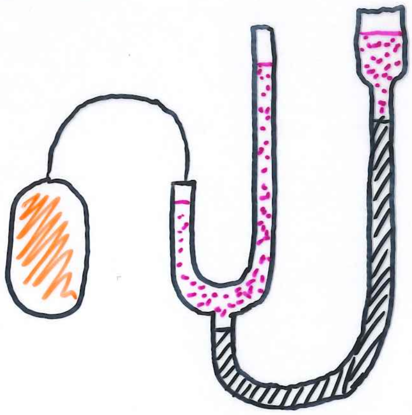
5 - PUNTU FINKOAK ARBITRARIOKI

$$\left.\begin{array}{l}\text{FINKATU } X_0 \\ \text{FINKATU } \theta_0 = \theta(X_0)\end{array}\right\} a \text{ FINKATU} \quad a = \frac{\theta_0}{X_0}$$

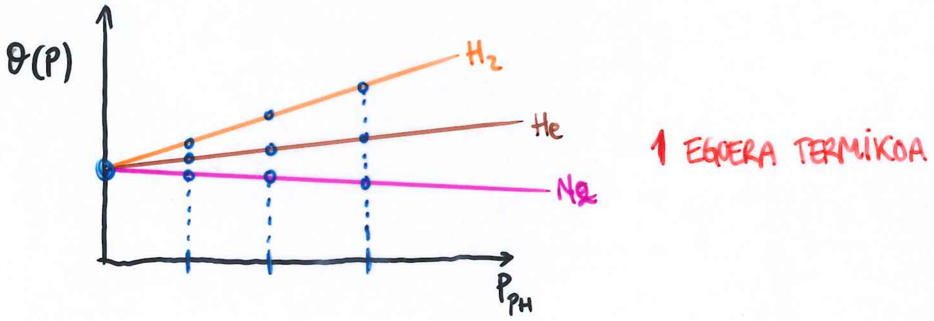
$$\boxed{\theta = \left[\frac{\theta_0}{X_0}\right] X}$$

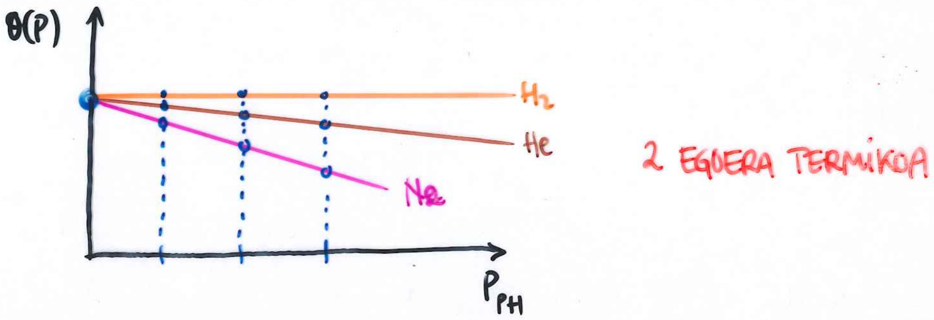
GAS IDEALAREN TENPERATURA-ESKALA

(a) TRESNA

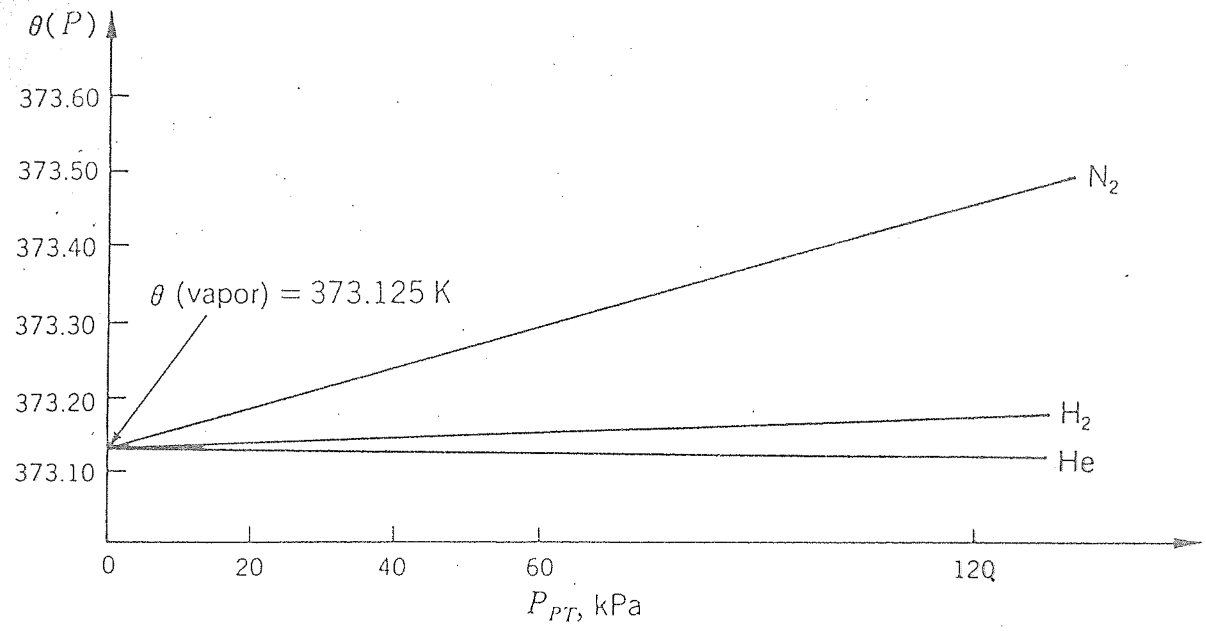


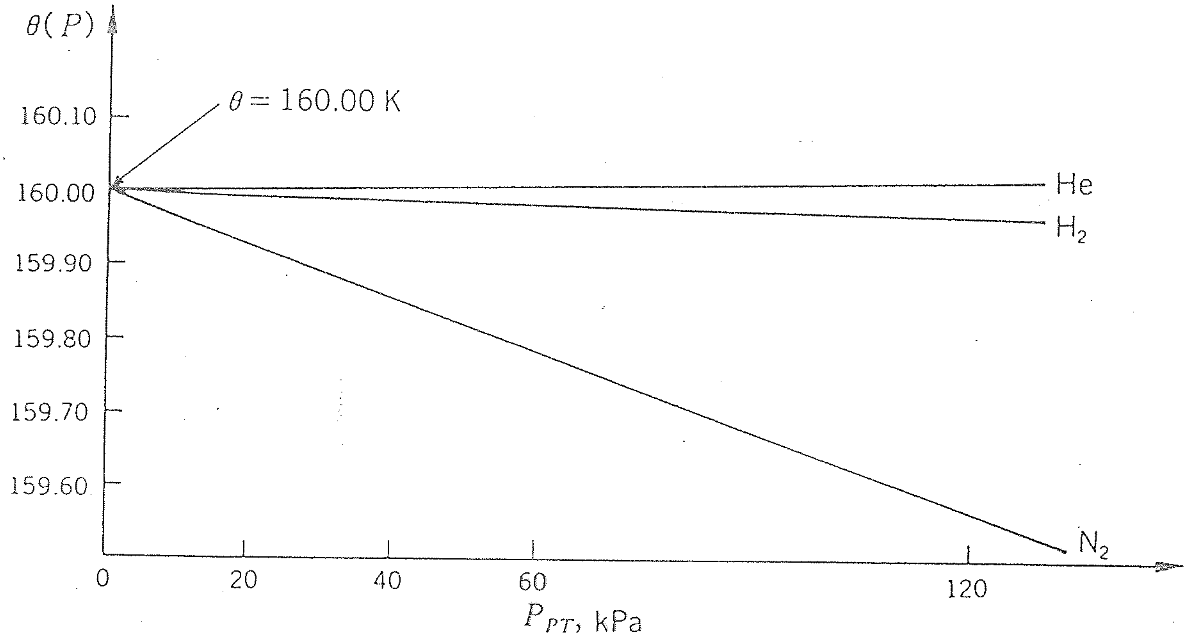
(b) PROZEDURA





$$\boxed{\theta = 273.16 \lim_{P_{PH}\to 0}\left(\frac{P}{P_{PH}}\right) \quad V = Kte}$$


θ(P)
373.60
373.50
373.40
373.30
373.20
373.10
θ (vapor) = 373.125 K
N₂
H₂
He
0
20
40
60
120
P_PT, kPa


θ(P)
160.10
160.00
159.90
159.80
159.70
159.60
θ = 160.00 K
He
H₂
N₂
0
20
40
60
120
P_PT, kPa

En segundo lugar, β es un parámetro más natural para expresar la temperatura que la propia T. Según veremos más tarde, el cero absoluto de temperatura ($T = 0$) no puede alcanzarse en un número finito de pasos, lo que puede resultar confuso; es menos sorprendente que un valor infinito de β (el que tiene β cuando $T = 0$) no sea alcanzable en un número finito de pasos. Sin embargo, aunque β sea la manera más natural de expresar temperaturas, tal terminología es incómoda en su uso diario. No resulta fácil decir que el agua, que se congela a 0 °C (273 K), lo hace cuando $\beta = 2{,}65 \times 10^{20}\ \mathrm{J}^{-1}$, o que el punto de ebullición, a 100 °C (373 K), se alcanza cuando $\beta = 2{,}47 \times 10^{20}\ \mathrm{J}^{-1}$. Como tampoco lo son los valores que caracterizan un día frío (10 °C, esto es, $\beta = 2{,}56 \times 10^{20}\ \mathrm{J}^{-1}$) u otro más cálido (20 °C, es decir, $\beta = 2{,}47 \times 10^{20}\ \mathrm{J}^{-1}$).

En tercer lugar, la existencia y el valor de la constante fundamental k es mera consecuencia de que insistamos en utilizar una escala convencional de temperaturas en vez de la más fundamental basada en β. Las escalas Fahrenheit, Celsius y Kelvin no van bien encaminadas: el inverso de la temperatura, esencialmente β, es una medida de la temperatura con mayor significado, más natural. No debe esperarse, sin embargo, que sea aceptada como tal, por motivos históricos y por el poder que en nuestra cultura tienen los números simples, como 0 y 100, e incluso 32 y 212, mucho más apropiados, además, para el día a día.

Aunque la constante de Boltzmann k suele incluirse en la lista de constantes fundamentales, esto no es más que una consecuencia de una mala elección histórica. Si Ludwig Boltzmann hubiera llevado a cabo sus trabajos antes que Fahrenheit y Celsius los suyos, se habría visto que β era la medida natural para la temperatura, y podríamos habernos acostumbrado a expresar la temperatura en unidades del inverso del Julio, con valores bajos de β para sistemas calientes y altos para sistemas fríos. Sin embargo, la convención estaba ya establecida con los sistemas calientes a temperaturas más altas que los fríos, y se introdujo k, mediante la relación $k\beta = 1/T$, para hacer corresponder la escala natural de temperaturas basada en β con la escala basada en T, convencional y profundamente arraigada. Esto es, la constante de Boltzmann no es más que un factor de conversión entre una escala convencional y bien establecida y la escala que, visto con perspectiva, la sociedad podría haber adoptado. La constante de Boltzmann no habría sido necesaria si β hubiera sido adoptada como medida de la temperatura.

Terminaremos esta sección con un detalle positivo. Hemos establecido que la temperatura, y concretamente β, es un parámetro que da cuenta de la distribución en el equilibrio de las moléculas de un sistema entre los estados disponibles de energía. Uno de los sistemas más fáciles de imaginar en este contexto es un gas perfecto (o «ideal»), en el que imaginamos las moléculas como integrantes de un enjambre caótico, algunas de ellas moviéndose rápidamente, otras despacio, viajando en línea recta hasta chocar entre sí, rebotando en direcciones diferentes y a velocidades distintas, y golpeando contra las paredes en una tormenta de impactos, dando lugar así a lo que interpretamos como presión. Un gas es un conjunto caótico de moléculas (de hecho, las palabras «gas» y «caos» provienen de la misma raíz), caótico en la distribución espacial y en la distribución de velocidades moleculares. Cada velocidad se corresponde con una energía cinética dada, y se puede utilizar la distribución de Boltzmann para expresar la distribución de velocidades, a través de la distribución de moléculas entre los estados posibles de energía de traslación; y relacionar esa distribución de velocidades con la temperatura. La expresión resultante se denomina *distribución de velocidades de Maxwell–Boltzmann,* ya que fue James Clerk Maxwell (1831-1879) el primero que la dedujo, de una forma ligeramente diferente. Cuando se lleva a cabo el cálculo,

The Meaning of Temperature

Ralph Baierlein

Wesleyan University, Middletown, CT 06457

The summer of 1988 found me working with a dozen high-school teachers on the subject "Atoms in Motion." One of our classes was devoted to "the meaning of temperature." The topic may seem simple, but it can be deceptive. Misconceptions are propagated in many textbooks, and there are several surprises. What follows is an expanded version of the notes I handed out following our class.

The Essence

Among the many things that I learned from Professor Eric Rogers was a simple, clear meaning for temperature: temperature is hotness measured on some definite scale.[1] In turn, "hotness" is the tendency to transfer energy in irregular, microscopic fashion. (It is the tendency to transfer energy "as heat.")

We can order objects according to their hotness. A red-hot piece of iron is hotter than iron we can hold in our hands; it is not as hot as white-hot iron. If we place the three pieces in contact, as sketched in Fig. 1, then energy is transferred from "red hot" to "can be handled" and to "red hot" from "white hot." "Temperature" provides such an ordering on a convenient numerical scale. In our illustration, the temperatures might be these

$$T_{\textit{can be handled}} = 300\ \mathrm{K} \qquad (1)$$

$$T_{\textit{red hot}} = 1000\ \mathrm{K} \qquad (2)$$

$$T_{\textit{white hot}} = 1700\ \mathrm{K} \qquad (3)$$

To say that object A is "hotter" than object B is to say that if A and B are placed together, then energy flows from A to B.

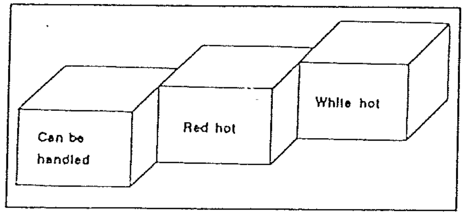


Fig. 1. Among the three objects, energy is transferred from right to left. That sequence provides an ordering of the objects according to their "hotness."

As time goes on, the rates of energy transfer between our blocks decrease toward zero. When the rates become zero, we have "thermal equilibrium." The three blocks now have equal hotnesses, that is, equal tendencies to transfer energy, which cancel out one another's effects. Equal hotnesses imply equal temperatures. In short, mutual thermal equilibrium implies equality of temperatures and vice versa.

While correct, this presentation of what temperature means is austere and can leave one with a desire for a more intuitive grasp. The attempt to provide a more intuitive view, however, may lead to error, as we will see.

A Common Misconception

For a dilute gas, the empirical gas law gives the pressure p as

$$p = \frac{N}{V}kT \qquad (4)$$

where N is the total number of molecules, V is the container's volume, k is Boltzmann's constant, and T is the absolute temperature.

The kinetic theory of gases provides its own expression for the pressure

$$p = \frac{1}{3}\frac{N}{V}mv^2 \qquad (5)$$

where m is the molecular mass and v is the molecular speed (specifically, the root mean square speed).

We can equate the two expressions for the pressure and then rearrange factors to isolate the kinetic energy

$$\frac{1}{2}mv^2 = \frac{3}{2}kT \qquad (6)$$

While a true statement, the equation does *not* provide us with a *meaning* for temperature. We may not take the equation to imply that "absolute temperature means the average kinetic energy (within a constant factor)." There are at least two reasons why the equation does not provide an acceptable meaning for temperature.

① Equation (6) is strictly a classical result. When the gas is no longer dilute or the temperature is low, quantum physics becomes essential to a correct description. (Intermolecular forces become significant, too, but that is a separate issue.) When quantum physics just begins to be important, Eq. (6) must be replaced by

$$\frac{1}{2}mv^2 = \frac{3}{2}kT\left[1 + C\frac{N}{V}\frac{h^3}{(2\pi mkT)^{3/2}}\right] \qquad (7)$$

Here h denotes Planck's constant, and the constant C depends on the species of gas.[2,3] For example, for ^{4}He, the usual helium isotope with two neutrons, the constant C is $-\left(2^{-5/2}\right)$; for ^{3}He, the rare isotope with only one neutron, the constant is $+\left(2^{-7/2}\right)$. The average kinetic energy depends on number density N/V as well as on temperature, and the dependence on T is complicated. (*Editor's Note:* For 1 mole of ^{4}He, compressed to 1 liter at 10 K, the correction factor is 0.2 percent.) We would not be tempted to use this more exact equation to ascribe a meaning to temperature based on average kinetic energy. (Moreover, note this: in a mixture of ^{3}He and ^{4}He gases, with each gas specified to have the same number density N/V and certainly having the same temperature, the average kinetic energies would differ between the two isotopes because the constants C differ in sign. At the same temperature, you can have different average kinetic energies – surely temperature cannot mean average kinetic energy.)

② When a kitchen oven is baking brownies, it is filled with radiation, mostly infrared radiation. The energy density of that radiation grows as the fourth power of the absolute temperature

$$\begin{pmatrix}\text{energy per unit volume}\\ \text{of radiation}\end{pmatrix} = \begin{pmatrix}\text{universal}\\ \text{constant}\end{pmatrix} T^4 \qquad (8)$$

We can solve this equation for T

$$T = \left(\frac{\text{energy density}}{\text{universal constant}}\right)^{1/4} \qquad (9)$$

But we would not be tempted to say, "Oh, now I know what temperature means. It is the fourth root of the radiant energy density."

Just as we do not use Eq. (8) or (9) to give a meaning to temperature, so we should not use Eq. (6) to try to give a meaning. All three equations are valid instances in which temperature plays a role in determining physical properties related to energy, but we should not push the equations beyond that.

Some Thermal Surprises

Negative absolute temperatures. Experiments can produce temperatures below absolute zero: negative absolute temperatures. The first such experiment was performed by Edward Purcell and Robert Pound in 1951; their physical system was the assembly of nuclei in a crystal of lithium fluoride.[4,5] (In more detail, the system was the nuclei acting as though they were tiny spinning bar magnets. That aspect of the nuclei was adequately decoupled from the nuclei acting as though they were vibrating masses, having ordinary kinetic energy; the latter aspect cannot exhibit a negative temperature.) By swiftly reversing an external magnetic field and achieving internal magnetic thermal equilibrium before a second reversal occurred, Purcell and Pound produced a final temperature of −350 K.

(*A technical aside.* One would like some microscopic picture of how the negative temperature was achieved. The interactions of the magnetic moments among themselves are crucial. In a crystal, a magnetic moment interacts not only with an external magnetic field but also with the neighboring magnetic moments. Following convention, we call the energy associated with the latter interaction the *spin-spin energy*. Initially, the spin system is at a positive temperature, with the nuclear magnetic moments predominantly parallel to the external field, an orientation of negative potential energy. The first field reversal is so fast that the spins cannot respond; they cannot change their orientation during the reversal. Consequently, the spins find themselves pointed predominantly antiparallel to the reversed field, an orientation of positive potential energy. In a short time some of this energy is transferred, by mutual interactions, to spin-spin energy. The energy associated with the mutual interactions becomes relatively large. In fact, that energy becomes larger than what one would predict at any positive temperature.

Since the interaction between the spin system and the lattice vibrations is weak, the spin system holds onto that relatively large amount of energy, even as the crystal is transferred for observation from the small external field to a large magnetic field. There is, in fact, so much spin-spin energy around that the magnetic moments "prefer" to line up antiparallel to the new external field, a position of positive potential energy, rather than line up in the usual parallel position, the position of negative potential energy. There is enough energy around so that a spin can easily line up in what is ordinarily an energetically unfavored orientation. This occurs no matter how the crystal, as a macroscopic object, is rotated during the physical transfer from one magnetic field in the laboratory to the other.

Indeed, the examination of the crystal in the large field was quite directly a test for the amount of energy possessed by the nuclear spin system. Purcell and Pound applied electromagnetic radiation at a frequency chosen so that lithium-7 nuclei could flip from an orientation of low to high potential energy by the absorption of a photon. Instead of absorption, they found – as they had hoped – stimulated *emission* of radiation at that frequency. The spin system had so much energy that spins predominantly flipped to low potential energy orientations and simultaneously emitted a photon. From the direct observation of stimulated emission of radiation – rather than absorption – one infers both that the total magnetic moment is antiparallel to the external field and that the nuclear spin system is at a negative temperature.)

Negative T is hotter than positive T. At $T = -350$ K, Purcell and Pound's system of nuclei was hotter than anything at a positive temperature. That is, it would transfer energy to anything at a positive temperature. The experimental test for a negative temperature relied on that property: the nuclei now emitted energy when probed with radio-frequency waves. At ordinary room temperature, they had absorbed such waves. Indeed, all negative temperatures are hotter than all positive temperatures.[6,7]

You cannot get to zero from either side. As their system cooled down, its temperature went from −350 K to −1000 K to −∞, which is physically equivalent to +∞, and continued through +1000 K to +300 K, ordinary room temperature. The system did not pass through absolute zero.

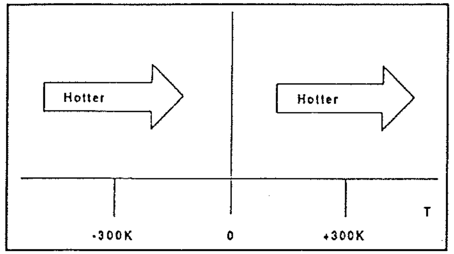


Fig. 2. A depiction of hotness as a function of the absolute temperature. The vertical line at $T = 0$ represents both a barrier for the arrows and an unattainable value. One cannot cool a system to absolute zero from above nor heat it to zero from below.

So far as one knows, one may not achieve absolute zero by approaching it from either side. Figure 2 offers a picture.

The coldest temperatures are just above 0 K on the positive side. The hottest temperatures are just below 0 K on the negative side.

Bizarre results, indeed, and there is yet another surprise.

Compression: Maybe Hotter, Maybe Colder

Imagine mechanically compressing a physical system. (A bicycle pump provides an example wherein the air is compressed by the plunger.) Specify that no heating (as with a Bunsen burner or electric current) accompanies the compression. (Thus, in technical language, we are examining adiabatic compression.) The mechanical work associated with the compression increases the physical system's energy. As a consequence of all of this, does the temperature increase? Most often the temperature does increase, but—amazingly—sometimes it decreases.

If the system is any dilute gas, then the temperature certainly increases. If, however, the system is the isotope ^{3}He in the form of coexisting liquid and solid at temperatures below 0.3 K, then the temperature decreases.

[*Another technical aside.* The nuclei in the solid phase of ^{3}He are located at specific lattice sites, and so in some respects the nuclei act independently of each other. Their spins need not be correlated by the Pauli exclusion principle. Nuclei in the liquid phase do not enjoy this quasi-independence, and so the Pauli principle (or antisymmetry for a total wave function) causes the spins to be correlated and reduces their contribution to the entropy.

Because of the correlations, the spin contribution to the entropy per atom is less for the liquid than for the solid. At very low temperatures, the spin contribution dominates over motional and positional contributions. Thus the entropy per atom of the liquid is less than that of the solid. (This inequality holds when the temperature is 0.3 K or less.)

The solid phase has a smaller volume per atom than does the liquid phase. Thus, when a coexisting mixture of liquid and solid is compressed adiabatically, solid is formed at the expense of liquid. The adiabatic (and reversible) compression leaves the total entropy constant. Yet the phase of higher entropy per atom (the solid) is being formed at the expense of the phase of lower entropy. Consistency is possible if the entropy per atom of both phases is simultaneously decreasing (slightly), and that common decrease can occur if the temperature decreases. (The Clausius-Clapeyron equation offers a rigorous route to the conclusion that the temperature decreases.)

Although this description does not provide all the microscopic explanation that one would like to see, it does outline the logic of why the reversible, adiabatic compression of coexisting phases of ^{3}He causes the temperature to decrease.]

In the case of ^{3}He, theory preceded experiment. The decrease in temperature was predicted by Soviet physicist I. Pomeranchuk in 1950, but the effect was realized experimentally only in the late 1960s. Research "refrigerators" based on the effect work in the temperature range of 0.3 to 0.002 K.[8,9] While the system's energy increases, its temperature decreases, but this need not be a paradox.

Recapitulation

Many texts, including some of the very best, contain statements like this: Temperature "is a measure of the average kinetic energy of the molecules or atoms in a substance."[10] Such a statement is misleading, if not downright wrong. The function of temperature is not to tell us about a physical system's *amount* of energy. Rather, it is to tell us about a system's *tendency to transfer* energy (as heat). To be sure, a quantitative knowledge of the tendency to transfer, together with some statistical reasoning, sometimes enables us to infer the amount of energy. Equations (6), (7), and (8) are cases in point. We reason from temperature to energy. None of those equations, however, captures the essential meaning of temperature. For that we must return to "temperature is hotness measured on some definite scale."◆

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meno. De la misma manc. xiste un movimiento browniano, un movimiento irregular, del gas alrededor de las aspas, sea cual fuere el material con el que está construido el aparato, éste, al ir calentándose, empezará a moverse de manera más irregular. Llegará un momento en que la rueda estará tan caliente que el retén se moverá debido simplemente al movimiento de las moléculas de su interior, es decir, debido a lo mismo que hace mover las aspas. El retén saltará sobre la rueda hacia arriba y hacia abajo y como estará tanto tiempo bajado como levantado, los dientes de la rueda se moverán tanto en un sentido como en otro. Con lo cual el instrumento dejará de ir solamente en una dirección. ¡En realidad el aparato puede llegar a moverse únicamente en sentido opuesto! Si la rueda está caliente y las aspas frías, la rueda que nosotros creíamos giraba en un sentido, empezará a girar en el otro, porque cada vez que el retén caiga, resbalará sobre el plano inclinado de un diente de la rueda y la empujará "hacia atrás". Saltará luego el retén hacia arriba para volver a caer sobre el plano inclinado siguiente y así sucesivamente. De manera que si la rueda está más caliente que las aspas girará en sentido opuesto.

¿Qué tiene esto que ver con la temperatura del gas que rodea las aspas? Supongamos por un momento que el mecanismo carece de aspas. La rueda será empujada por el retén al caer éste sobre el plano inclinado pero, acto seguido, la rueda chocará con el retén y rebotará hacia atrás. Con el fin de evitar que la rueda rebote ponemos un amortiguador en forma de aspas frenadas por el aire, que impedirá el rebote de la rueda. De esta manera la rueda sólo girará en un sentido, pero en sentido opuesto al previsto. Así pues, sea cual sea el diseño del aparato, una rueda de este tipo girará en un sentido cuando una de las partes sea la más caliente y en el otro sentido en el caso contrario. Pero una vez haya tenido lugar un intercambio térmico entre las dos partes y ambas posean la misma temperatura, la rueda no se moverá por término medio, ni en un sentido ni en el otro. Ésta es la forma técnica que tienen los fenómenos de la naturaleza de seguir en una dirección única mientras se hallen en desequilibrio, es decir, mientras un lado esté más caliente que el otro, o mientras un lado sea más azul que el otro.

Podría parecer como si el principio de conservación de la energía indicara que disponemos de toda la energía que queramos. La naturaleza ni gana ni pierde energía. Sin embargo, la energía del mar, por poner un ejemplo, el movimiento térmico de todos los átomos del mar, está prácticamente fuera de nuestro alcance. Con el fin de organizar y dominar esta energía, de poder utilizarla, tenemos que poseer una

diferencia de temperatura, porque si no resulta que aunque la energía está allí, permanece inutilizable.

El principio de conservación de la energía indica que la energía total del mundo se mantiene constante. Pero debido a los movimientos erráticos de las partículas, esta energía puede distribuirse de manera tan uniforme que, en determinadas circunstancias, no sea posible extraer más energía de la que se añade, es decir, que no haya forma de controlarla.

Creo que mediante una analogía podré dar cuenta mejor de cuál es la dificultad. No sé si alguno de ustedes habrá pasado por la experiencia, que yo conozco bien, de estar sentado en la playa con varias toallas cuando de pronto empieza a caer una tormenta. Rápidamente agarramos las toallas y corremos a ponernos a cubierto. Una vez protegidos de la lluvia empezamos a secarnos y descubrimos que una toalla está un poco húmeda, pero relativamente más seca que nuestro cuerpo, con lo que vamos secándonos con ella hasta que llega un momento en que está demasiado empapada, es decir, que nos seca tanto como nos moja. Probamos con la siguiente toalla y muy pronto descubrimos algo terrible, que todas las toallas están tan mojadas como nuestro cuerpo. Ya no hay, pues, manera de secarse un poco más a pesar de poseer varias toallas, porque en algún sentido ya no hay diferencia entre lo mojados que estamos nosotros y lo mojadas que están las toallas. Podría inventar una expresión de cantidad y llamarla "facilidad de secar el agua". La toalla posee la misma facilidad de secar el agua que nosotros, con lo cual cada vez que paso la toalla por encima de mi cuerpo tanta agua pasa de la toalla a mi piel como de mi piel a la toalla.

Esto no significa que haya la misma cantidad de agua en la toalla que sobre mi cuerpo — una toalla grande contendrá más agua que una pequeña — pero tienen la misma humedad. Cuando todo adquiere el mismo grado de humedad ya no hay nada que hacer.

El agua es como la energía, porque la cantidad total de agua no cambia. (Si de pronto aparece el sol y nos podemos secar o si encontramos otra toalla, entonces estamos salvados, pero suponemos que estamos en un lugar cerrado y no hay forma de conseguir nuevas toallas.) De manera análoga, si imaginamos una parte del mundo como cerrada y esperamos el tiempo suficiente, la energía, como el agua, acabará distribuida de manera uniforme (desaparecerá el movimiento en sentido único), hasta el punto de que el mundo perderá todo su interés.

Así pues, en el caso de la rueda de trinquete con aspas, que es un

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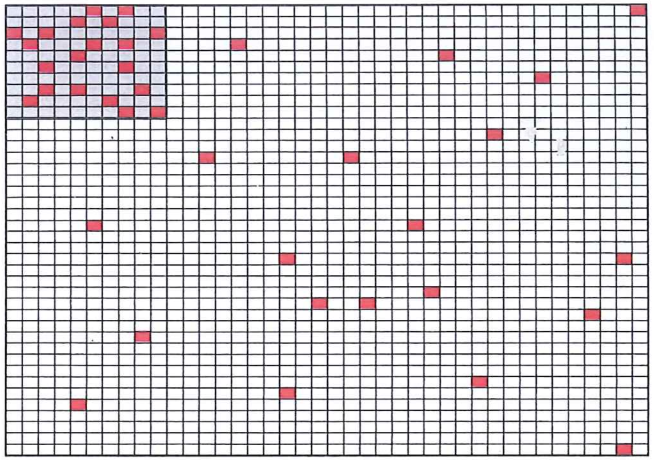
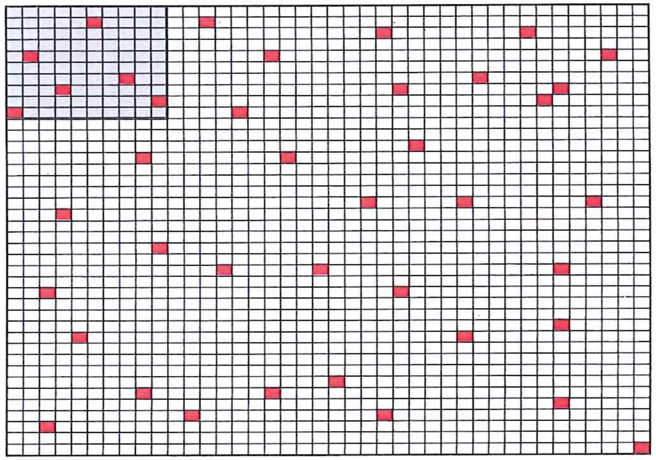
"El caracter de la ley física", Richard Feynman
CONJETURAS, Antoni Bosch Editor, 1983

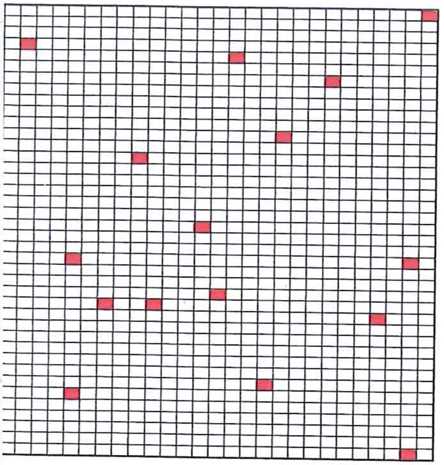


Some time after the initial stage, the energy is spread more uniformly over all the atoms as a result of their jostling each other. The small block still has a higher proportion of its atoms ON than the bigger block, and so it is still hotter. The temperature of System 1 is now 0.72 and that of System 2 is 0.23.

What is the final state of the universe? There is *no* final state for the careful observer, for the ON-ness jostles and migrates forever (there is no rule that brings it to an end). But there is an *apparent* final state for an observer who stands so far back that the behavior of the individual atoms cannot be discerned. There is a final state for the *thermodynamic observer,* not for the atomic individualist. This *apparent* end of change occurs when there is a *uniform distribution of ON-ness,* as in the figure below.



Later, the jostling of the atoms results in a uniform distribution of the energy. There will be small accumulations here and there (there are fluctuations*), but on average the proportion of atoms ON in the smaller block is equal to the proportion ON in the larger. The temperatures of the blocks are now the same, at 0.27, and they are at* thermal equilibrium.



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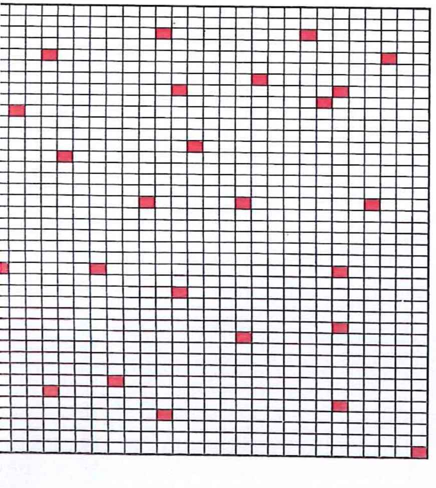

The sequence of illustrations on the two preceding pages shows how the universe attains not so much a final state as a *steady state*. In this state the individual atoms turn ON and OFF as they have always done, but, to the casual observer of averages, the redistribution of energy leaves the universe apparently unchanged. We see that the jostling, random migration of energy disperses it. When it is uniformly dispersed over the available universe, it remains dispersed.

That last remark is not quite true, because the random wandering of ON-ness may lead it to accumulate, by chance, in System 1 and leave Sytem 2 completely OFF. However, even with a universe of 1,600 atoms this chance is slight (as may be tested by using one of the programs), and in a real Universe, where each system is a block of Avogadro's numbers of atoms, the chance is so remote that it is negligible. *Lack of rules allied with vastness of domain accounts for the virtual irreversibility of the process of dispersal.*

Temperature

Before we wrap this observation into a neat package, let us notice that we are also closing in on the significance of *temperature*. We have just seen that System 1 heats System 2 as a natural consequence of the dispersal of energy, and that the net transfer of energy continues until, on average, the energy is evenly dispersed over all the available atoms. Now note the following important distinction. When the ON-ness is evenly distributed, there is more *energy* in System 2 than in System 1 (because the former contains more atoms, and therefore more are ON when the ON-ness is uniformly distributed), but the *ratio* of the numbers ON and OFF is the same in both.

All this conforms with common sense about hot and cold so long as we interpret the ratio of the numbers of atoms ON and OFF as indicating *temperature*. First, we know that energy flows as heat from high temperatures to low, and we have seen that System 1 (which initially has a higher "temperature" than System 2) heats System 2. Second, the steady state, when there is no net flow of energy between the two systems, corresponds to their having equal "temperatures," not equal total energies. Finally, "temperature" measures the *incoherent* motion, not the coherent motion, of particles; it is intrinsically a thermodynamic (as distinct from a dynamic) property of systems of many particles. It would be absurd to refer to the temperature of a single particle. When we say that a baseball is warm, we are referring to the excitation of its component particles, not to the whole baseball regarded as a single particle.