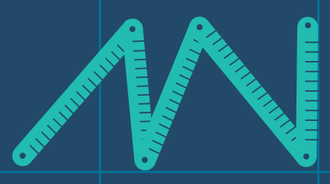
UNITS : INSTRUCTION MANUALS

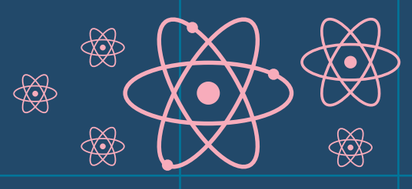
SEVEN INSTRUCTION MANUALS TO UNDERSTAND
THE NEW DEFINITIONS OF UNITS IN PHYSICS.

SECOND



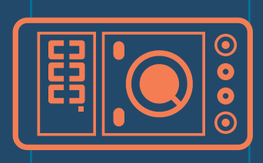
METER

KILOGRAM



MOLE

KELVIN



AMPERE

CANDELA

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In 2018, physicists change the way they define the units.
All of them can now be built using scientific methods relying on fundamental constants and well established theories.
No need for prototypes or human references.

Here are seven instruction manuals on how to build the units in a universal way, using seven fundamental constants established once for all in 2018.

A PROJECT CREATED BY THE “PHYSICS REIMAGINED” TEAM
(LPS, UNIVERSITÉ PARIS-SUD, PARIS-SACLAY, CNRS)
GRAPHIC DESIGN: MARIE JAMON / PHYSICS: JULIEN BOBROFF

THE NEW DEFINITIONS OF UNITS IN PHYSICS

THE (s) SECOND : INSTRUCTION MANUAL

PREREQUISITES

Bohr 1922
Stern 1943 / Rabi 1944
Ramsey 1989

Nobel Prize x4

Quantum physics theory x1

WHAT YOU NEED

Big trash x1

$\Delta\nu(^{133}Cs) = 9\ 192\ 631\ 770$ Hz
Cesium 133 atomic frequency

Fundamental constant x1

55 Cs

Atom x10 000 000

Material to build an atomic fountain

Oscilloscope x1

00:00:0 1,000000000000000

(Very) accurate chronometer x1

1 DISCARD
OLD METHODS

Before 1956 Measure 1/86 400 of a mean solar day.

SORT YOUR WASTE FOR RECYCLING!

METHOD TO AVOID

00:00:0 1,000000000000000

Measure directly the time between 2 oscillations. Use a good chronometer!

2 BUILD
FROM 1967

A Freeze and calm down the cesium atoms using six lasers and form a ball.

B Drop the ball into a cavity full of microwaves (as in a microwave oven).

C Enlight the atoms. If they appear fluorescent, it means they have been excited by the waves.

D Sweep slowly the wave frequency. When you observe fluorescence, measure the wave.
Build the second so that this wave contains 9 192 631 770 oscillations.

= 9 192 631 770
1s

3 SHARE

Duplicate the second you built for the entire world.

03:00:00

03:00

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THE NEW DEFINITIONS OF UNITS IN PHYSICS

THE (m) METER : INSTRUCTION MANUAL

PREREQUISITES

$E = mc^2$

Special relativity theory x1

The invention of lasers x1

WHAT YOU NEED

Big trash x1

$c = 299\ 792\ 458\ m.s^{-1}$
speed of light

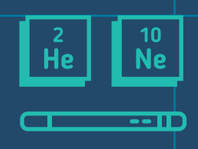
Fundamental constant x1

second

Unit x1

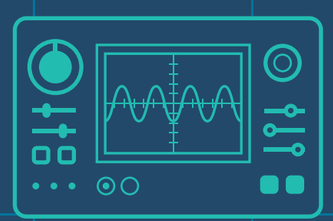
$\lambda = \frac{c}{f}$

Physics formula x1



Laser x1

Material to build a Michelson interferometer



Oscilloscope x1

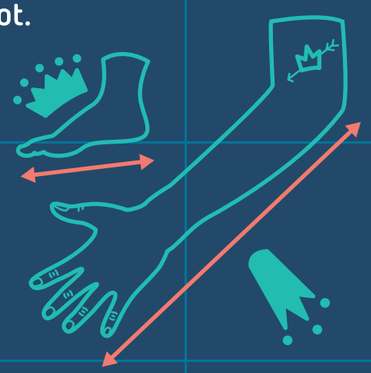
Calculator x1

Ruler x1

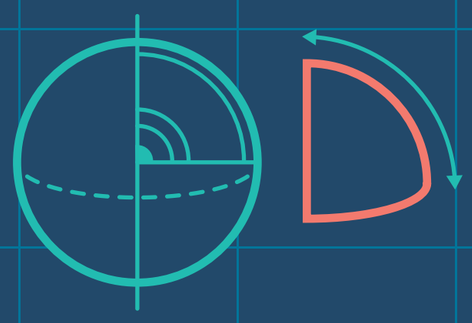
Pencil x1

1 DISCARD
OLD METHODS

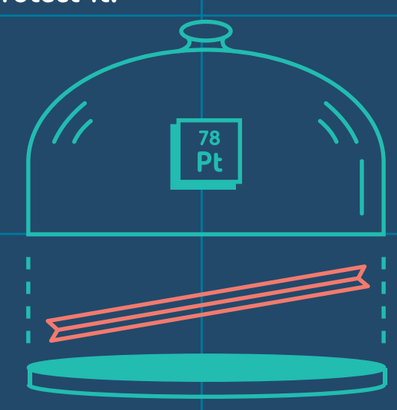
Before 1791 Use the length of the Lord's arm or of the King's foot.

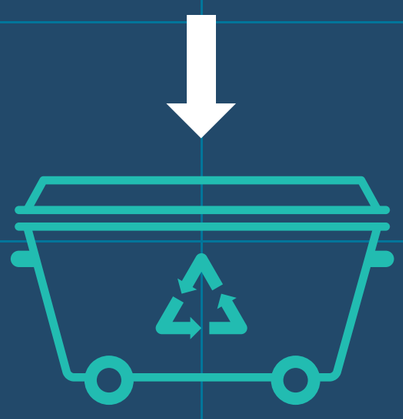


1791 Measure the distance between Barcelona and Dunkirk, deduce the quarter of the terrestrial meridian, then divide by 10 000 000.



With this value, build a prototype meter bar with platinum and protect it.

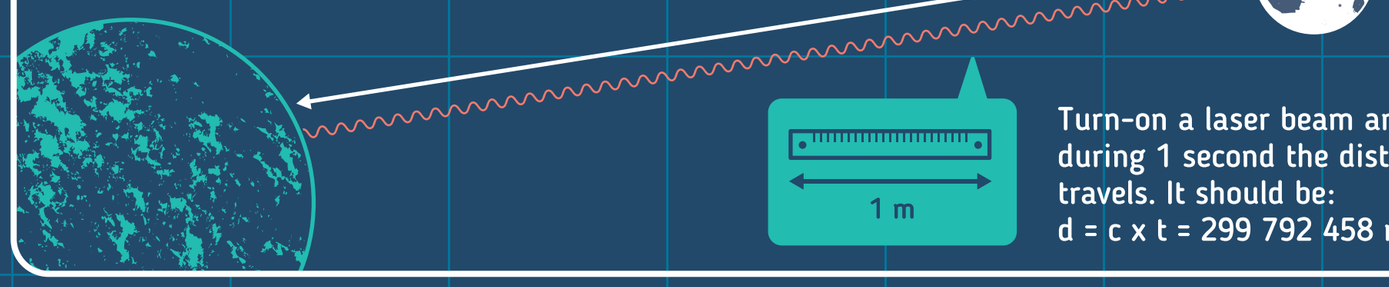




SORT YOUR WASTE FOR RECYCLING!

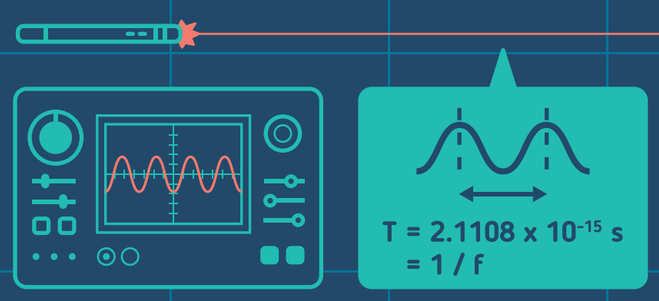
2 BUILD
FROM 1983

METHOD TO AVOID



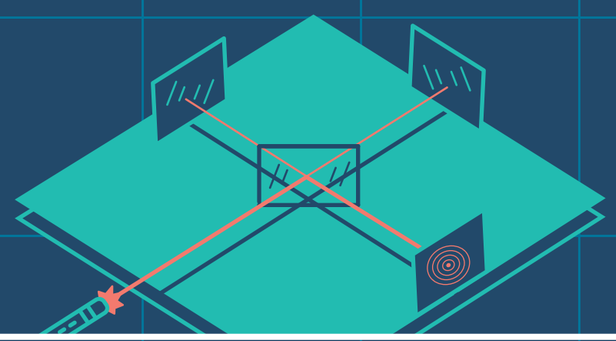
Turn-on a laser beam and measure during 1 second the distance it travels. It should be:
d = c x t = 299 792 458 meters.

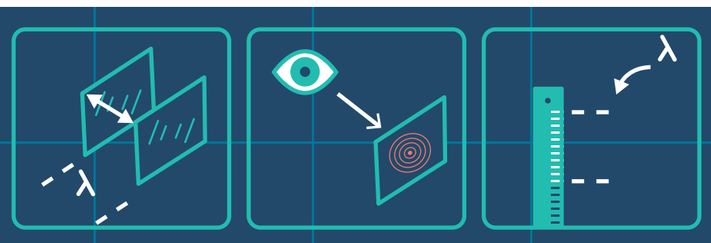
A A more convenient method: measure the period (T) of a helium-neon laser using the second.



B Compute the wavelength in meter by forcing the value for the speed of light (c).

C Send this laser in a Michelson interferometer and observe circular fringes.

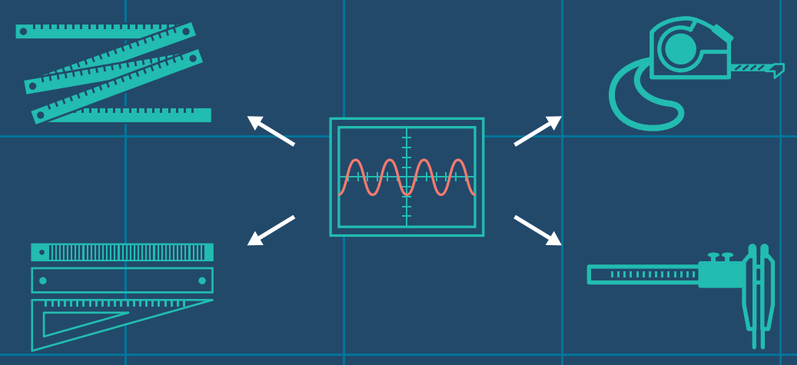




Move one of the mirrors, you'll see the fringes shifting and going back to their position. Do it twice and you'll have moved the mirror by 632.8 nm. Bravo, you just built your meter! (Well, more or less... You still have to multiply).

3 SHARE

Duplicate the meter you built for the entire world.



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THE NEW DEFINITIONS OF UNITS IN PHYSICS

THE KILO (kg) GRAM : INSTRUCTION MANUAL

PREREQUISITES

Classical mechanics theory x1

Quantum physics theory x1

Invention of electricity and induction x1

WHAT YOU NEED

Big trash x1

Unit x2

second

meter

$h = 6.626\ 070\ 15 \times 10^{-34}$ J.s
Planck's constant

Fundamental constant x1

Material to build a Watt balance

voltage

current

Josephson

resistance

magnetic field

Hall

Quantum effect with steps x2

1 DISCARD
OLD METHODS

Between 3rd and 4th millennium BC
Shape stones to create weights (animal shapes authorized).

1799 Measure the mass of a kilogram of distilled water at 4°C.

H_2O

With this value, build a kilogram prototype in platinum and iridium and protect it.

78 Pt

77 Ir

SORT YOUR WASTE FOR RECYCLING!

2 BUILD
FROM 2018

A

2

V

N S

F

1

P

Build a Watt balance
On one side of a scale, put the weight you want to measure. On the other side put an electrical coil and a magnetic field.

1 Cause a current to flow through the coil, this creates a force which counterbalances the weight. Measure the current using two quantum phenomena: Hall effect and Josephson effect (see "The Ampere Manual instruction" for details).

voltage

current

Josephson

resistance

magnetic field

Hall

2 Move the coil vertically at constant speed (v). Measure the induced voltage with Josephson effect.

B The mass is just a function of these two measures and the Planck constant (h). Force the constant value (h). Then deduce the mass: you obtain your new prototype.

$h = 6.626\ 070\ 15 \times 10^{-34}$ J.s

3 SHARE

Duplicate the kilogram you built for the entire world.

58,0

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THE NEW DEFINITIONS OF UNITS IN PHYSICS

THE MOLE (N_A) : INSTRUCTION MANUAL

PREREQUISITES

Crystallography x1

Very clean hands x2
(or wear gloves)

WHAT YOU NEED

Big trash x1

N_A = 6.022 14 076 x 10^{23}
Avogadro number

Fundamental constant x1

$M_{mol} = \frac{m_{TOT}}{\text{Number of moles}}$

Chemistry formula x1

Silicon atoms (sand)

Scale x1

Oven x1

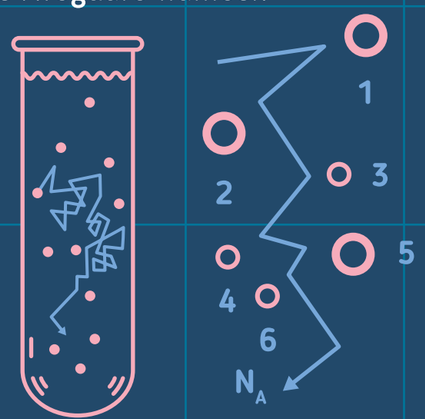
Material to build an optical interferometer

Material to build an X-ray interferometer

The periodic table of elements x1

1 DISCARD
OLD METHODS

Beginning of the XXth century
Observe the movement of small solid particles in a liquid. Deduce how many molecules compose the liquid, and thus the Avogadro number.



1971 A mole corresponds to the number of atoms in 0.012 kg of carbon.

SORT YOUR WASTE FOR RECYCLING!

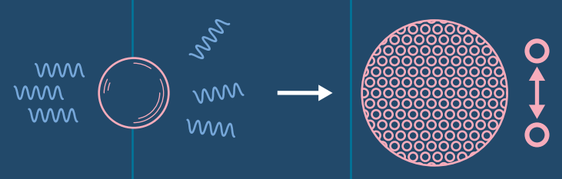
2 BUILD
FROM 2018

A To determine the number of moles in a sample, for example silicon:

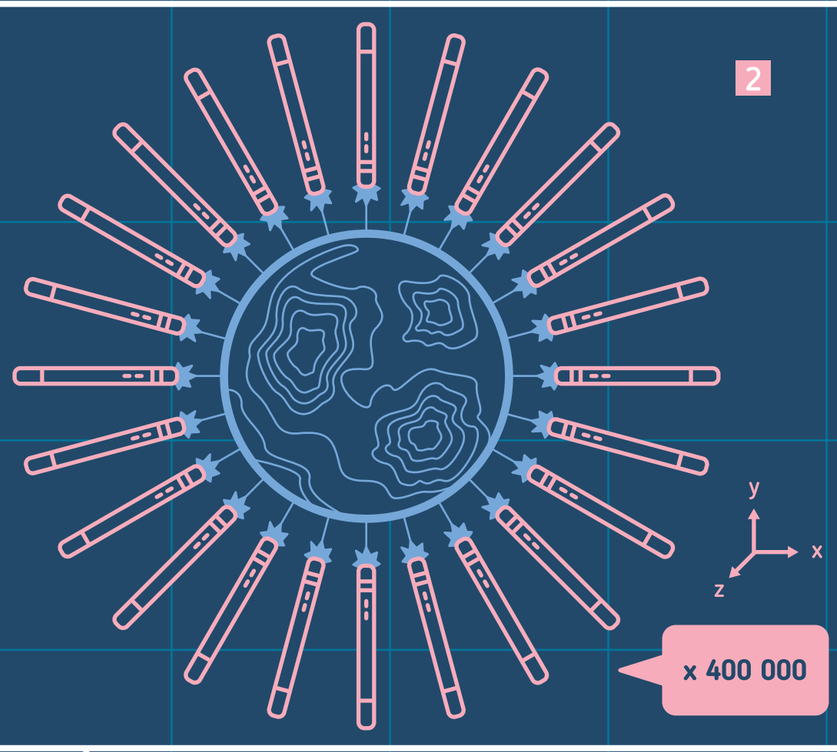
1. Crystallize the purest possible silicon sphere in an oven.
2. Weight it precisely.
3. Polish it for 1 month to get the roundest possible sphere.

B Count the number of atoms in the sphere. This means:

1. Measure the distance between atoms with an X-ray interferometer.



2. Measure the sphere volume by measuring its diameter 400 000 times in all directions with an optical interferometer.
3. Deduce the number of atoms.



C Force the Avogadro constant to be N_A = 6.022 140 76 x 10^{23}.
Deduce the number of moles in the sphere:

$$\text{Number of moles} = \frac{\text{Number of atoms}}{N_A}$$

D From the sphere mass (m_{sphere}), infer the molar mass of a silicon mole (M_{mol}):

$$M_{mol} = \frac{m_{sphere}}{\text{Number of moles}}$$

3 SHARE

Use the definition of the mole and the molar mass of silicon to deduce the molar masses of all atoms. Useful for chemistry!

N_A →

1 H	2 He	3 Li	4 Be	5 B	6 C	7 N	8 O	9 F	10 Ne	11 Na	12 Mg	13 Al	14 Si	15 P	16 S
17 Cl	18 Ar	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge
33 As	34 Se	35 Br	36 Kr	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	41 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	...

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THE NEW DEFINITIONS OF UNITS IN PHYSICS

THE (K) KELVIN : INSTRUCTION MANUAL

PREREQUISITES

Laws of thermodynamics x1

Guitar basics x1

WHAT YOU NEED

Big trash x1

second · meter · kilogram

Unit x3

$k_B = 1.380\ 649 \times 10^{-23}\ J.K^{-1}$
Boltzmann's constant

Fundamental constant x1

Atom x10 000 000 (gas)

Material to build an acoustic thermometer

$v^2 = \frac{\gamma k_B \times T}{m}$

Physics formula x1

1 DISCARD
OLD METHODS

1742 Freeze water, it defines 0°C. Boil it, it defines 100°C.

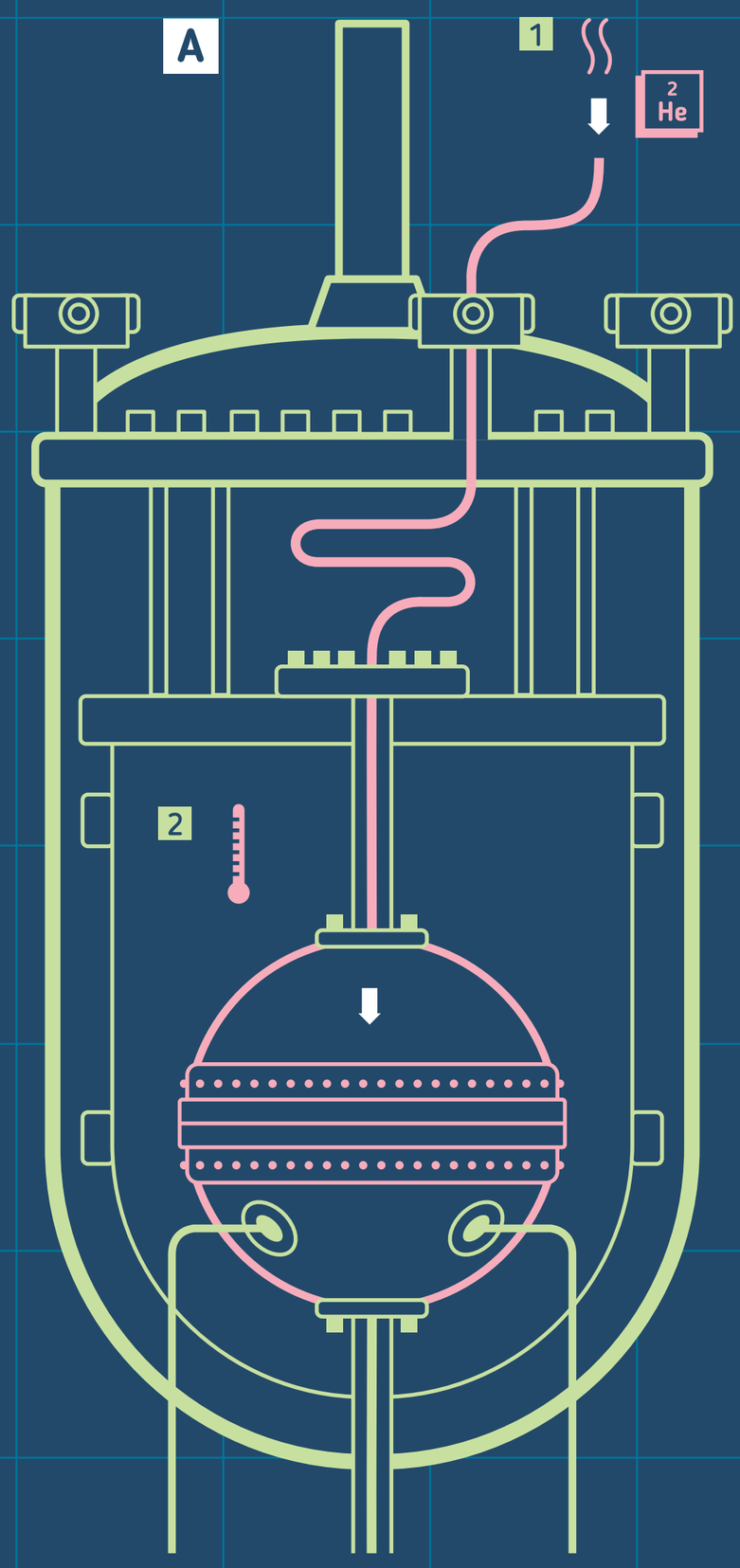
0°C · 100°C

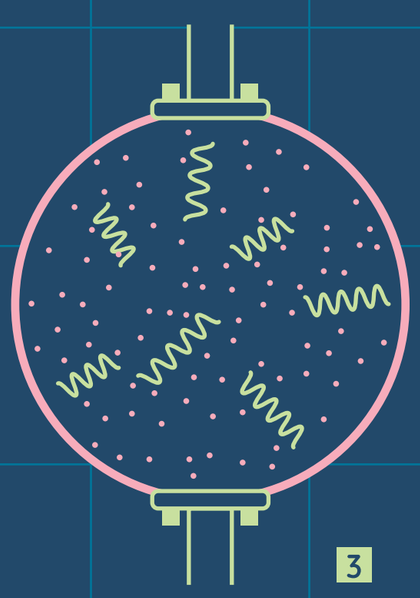
1967 Find the temperature at which water is at the same time a gas, a solid and a liquid: it is the triple point of water, near 0°C. Add 273.16 and divide by 273.16 to get one kelvin.

SORT YOUR WASTE FOR RECYCLING!

2 BUILD
FROM 2018

Property: the speed of sound in a gas depends on temperature. The hotter the gas, the faster the sound moves.





Build an acoustic thermometer

1 Fill a metallic sphere with a rare gas like helium.

2 Put the sphere at a fixed temperature.

3 Excite the sphere and measure at which frequency it vibrates, like a guitar. Deduce the speed of sound (v) in the gas.

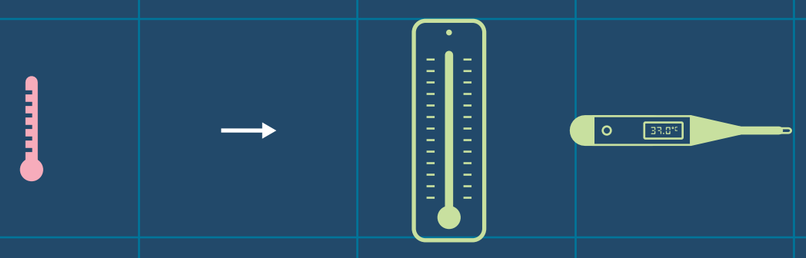
B Force the constant k_B to be $1.380\ 649 \times 10^{-23}\ J.K^{-1}$. Deduce the temperature of the gas (T) with the formula:

$$v^2 = \frac{\gamma k_B \times T}{m}$$

(m: mass of the gas atoms)

3 SHARE

Duplicate the kelvin you built for the entire world.



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THE NEW DEFINITIONS OF UNITS IN PHYSICS

THE (A) AMPERE : INSTRUCTION MANUAL

PREREQUISITES

Quantum Hall effect, Von Klitzing 1985 / Josephson effect, Josephson 1973

Nobel Prize x2

$U = R \times i$

Ohm's law x1

WHAT YOU NEED

Big trash x1

second

Unit x1

$e = 1.602\ 176\ 634\ 10^{-19}$ C
electric charge of the electron

Fundamental constant x1

$R_H = \frac{h}{e^2}$ $V_J = \frac{h\nu}{2e}$

Physics fomula x2

14 Si

A transistor to create a two-dimensional metal x1

41 Nb

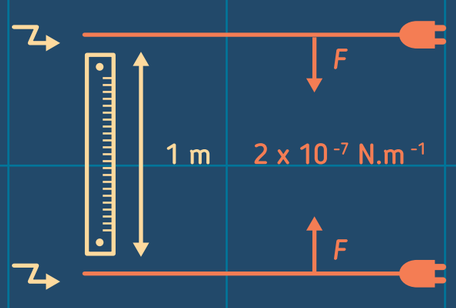
Material to build a superconducting Josephson junction

Electromagnetic waves x1

Magnetic field x1

1 DISCARD
OLD METHODS

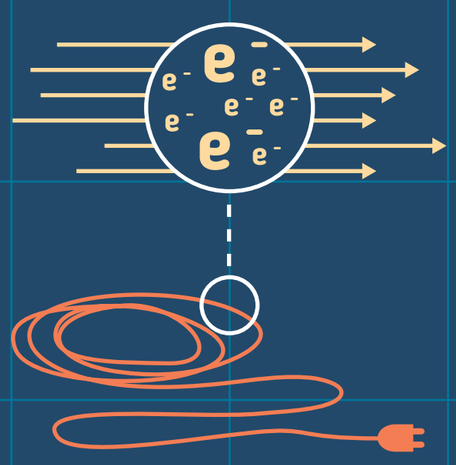
1954 Measure the force acting between two wires set 1 meter apart and carrying a constant electrical current.
When this force equals 2×10^{-7} Newton per meter, the current is worth 1 ampere.



SORT YOUR WASTE FOR RECYCLING!

METHOD UNDER DEVELOPMENT IN NANOPHYSICS LABS

An ampere corresponds to the current due to the flow of $6.241\ 509\ 074 \times 10^{18}$ electrons per second so $1 / 1.602\ 176\ 634 \times 10^{-19}$.

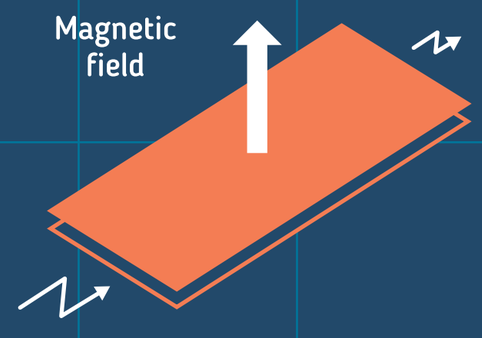


Build a setup capable of counting one by one the number of electrons flowing through an electrical wire. That's it!

2 BUILD
FROM 2018

A

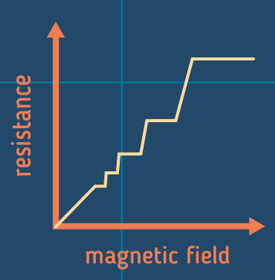
Magnetic field



Measure the Quantum Hall effect

Cause an electrical current to flow through a thin metallic layer, and place this layer in a magnetic field.

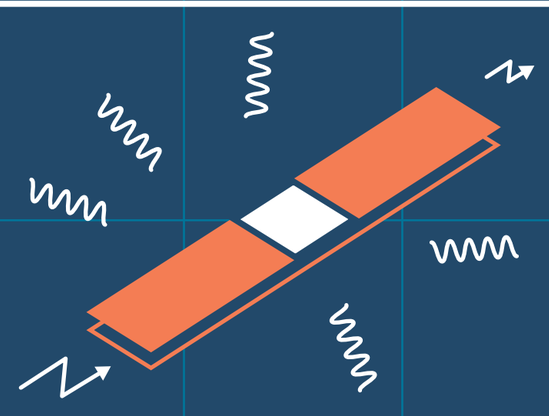
A transversal resistance (R_H) will appear in the shape of steps. Measure the highest one which equals to:



Hall

$$R_H = \frac{h}{e^2}$$

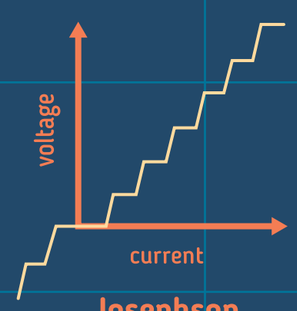
B



Measure the Josephson effect

Take a superconducting-insulating-superconducting sandwich. Add some electromagnetic waves at the frequency (ν) and cause an electric current to flow.

A voltage (V_J) will appear in the shape of steps. Measure any of them which equals to:



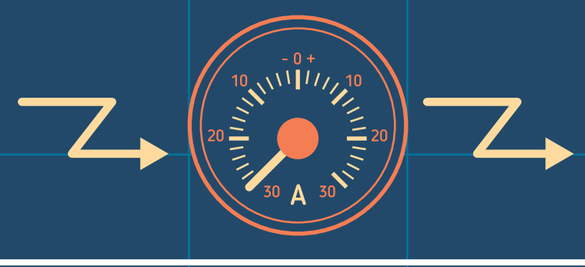
Josephson

$$V_J = \frac{h\nu}{2e}$$

C Deduce the ampere: from your measures, find a current (i) thanks to Ohm's Law.

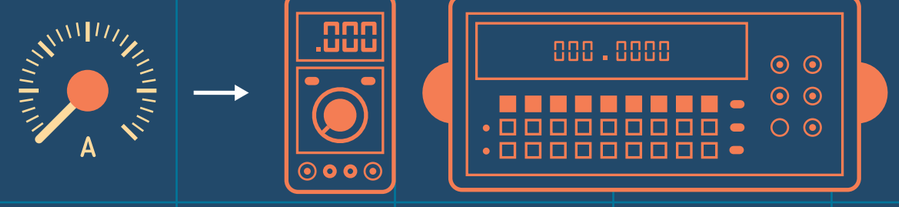
$$i = \frac{V_J}{R_H} = \frac{e\nu}{2}$$

Force the elementary electrical charge of an electron $e = 1.602\ 176\ 634\ 10^{-19}$ C and measure the frequency (ν): you have now a way to measure a current in ampere.



3 SHARE

Duplicate the ampere you built for the entire world.



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THE NEW DEFINITIONS OF UNITS IN PHYSICS

THE (cd) CANDELA : INSTRUCTION MANUAL

PREREQUISITES

The theory of electromagnetism x1

Human eyes x1

WHAT YOU NEED

Big trash x1

second meter kilogram

Unit x3

$Kcd = 683\ lm.W^{-1}$
luminous efficacy

Fundamental constant x1

Material to build
a green light lamp (or use a laser)

Material to build
a light intensity detector

Oscilloscope x1

1 DISCARD
OLD METHODS

1860 Light a candle made from whale sperm, weighing 1/6 the of pound and burning at 7.7 grams per hour.
Measure the light intensity emitted by the flame.

7.7 g / hour

1967 Heat a black body at 1 769°C, the temperature of solidification of platinum.
Measure the luminous intensity emitted in the perpendicular direction of a surface of $1/600\ 000\ m^2$ of this body.

78 Pt

SORT YOUR WASTE FOR RECYCLING!

2 BUILD
FROM 1979

Définition Candela measures the luminous intensity emitted by light in a particular direction, multiplied by a factor which takes into account human eye sensitivity to various colors. Contrary to the other 6 fundamental units, this one is not just linked to a physics phenomenon but chosen arbitrarily in relation with our own vision.

A

Build a monochromatic light
at the specific frequency of 540×10^{12} Hz which corresponds to green color.

Build a light intensity detector

540×10^{12} Hz

B Set the light so that its luminous efficacy is equal to the constant Kcd = 683 lumens per Watt.
The luminous intensity is then worth 1 candela.

C To get the intensity of all other colors, apply a "luminosity function" which models the sensitivity of the human eye to different colors. This function is not universal but linked to the human eye.

Wavelength

3 SHARE

Duplicate the candela you built for the entire world.

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