Measure the Universe: All Units, Constants (v4.1 added volt-amp)

No formulas. Just one unit per phenomenon to be measured. Named fundamental relationships for conceptual understanding of the units. Plus constants, because they are constant like units.

Table of Contents

1: Basic Units

Energy, scalar, conserved in 1st Law of Thermodynamics

$$E\ in\ Joules = J = \mathrm{N} \cdot \mathrm{m} = \mathrm{kg} \cdot \frac{\mathrm{m}^2}{\mathrm{s}^2} = Watt \cdot s = Volts \cdot Amps \cdot seconds$$

$$Energy = force \cdot distance = mass \cdot velocity^2 = power \cdot time = potential \cdot Current \cdot time$$

$$eV = 1.602 \times 10^{-19}\, J \ \ || \ \ BTU = 1055\, J \ \ | \ \ |Calorie = kilocalorie = foodcalorie = 4184\, J$$

Joules are also used to measure total internal energy and enthalpy.

Power, scalar, *also conserved* because Energy must be conserved

$$P\ in\ Watts = W = \frac{J}{s} = \frac{N \cdot m}{s} = \frac{kg \cdot m^2}{s^3} = Volts \cdot Amps = I^2 \cdot R = \frac{U^2}{R} \ \ || \ \ HP = 745.7\, W$$

$$Power = \frac{Energy}{time} = potential \cdot current = current^2 \cdot resistance = \frac{potential^2}{resistance}$$

Efficiency, Ratio of Useful Energy Obtained to Energy Consumed

$$\eta = [\ dimensionless, usually\ \%\ ] = \frac{E_{out}}{E_{in}} = \frac{P_{out}}{P_{in}} = \frac{E_{in} - E_{loss}}{E_{in}} = \frac{P_{out} - P_{loss}}{P_{in}}$$

Efficiency is *the only place* where energy or power – in any form – can be "lost." Even if "lost" in efficiency, energy and power become heat or some other form of energy or power (yeah OK, or $E=mc^2$).

Mass, m, scalar

$$m\ in\ kilograms = kg\ ||\ pound_{on-earth} = lb = 0.4536kg\ |\ Mg = \text{"}tonne\text{"}$$

Length or Distance, scalar

$$meter = m\ ||\ \ inch = 0.0254m\ |\ foot = 0.3048m\ (both\ inch\ and\ foot\ are\ exact, by\ definition)$$

Area, scalar, squared length

$$m^2 = square\ meter = length^2\ ||\ hectare = 10^4 m^2\ ||\ acre = 4046.86m^2|$$

Volume, V, scalar, cubed length

$$m^3 = cubic\ meter = 1000\ liters\ (\sim thousand\ kg\ water)$$

$$gallon = 0.0037854m^3 = 128\ fluid\ ounces$$

Time

$$seconds\ always\ for\ time$$

Force, vector, conserved in Newton's 2nd Law

$$\vec{F}\ in\ Newtons = N = \frac{kg \cdot m}{s^2} = kg \cdot \frac{m}{s^2} \ \ ||\ pound_{force} = lbf = 4.448N$$

Momentum, vector, conserved in Newton's 2nd Law

$$\vec{p} = m \cdot \vec{v} = kg \cdot \frac{m}{s}$$

Frequency, Cycles, or Revolutions per Time or Rotational Speed

$$f\ in\ Hertz = \frac{1}{s}\ for\ cycles\ and\ \frac{rev}{s}\ for\ rotational\ speed\ \ ||\ \boldsymbol{\omega = 2\pi \cdot freq} = 2\pi \cdot \frac{rev}{s}\ radians$$

Angle

$$radian => \frac{2 \cdot \pi\ radians}{full\ circle}\ \ ||\ degree = \frac{\pi}{180} radians$$

"Solid angle" = fractional portion of surface of sphere with radius of one, see Nuclear 5 slide 75…

Torque

$$\tau\ in\ N \cdot m = Newton \cdot meter => [\ Joule\ ]$$

the Energy (or Joule) relationship makes sense when considering the power of a rotating shaft:

$$P_{shaft} = \tau \times \omega\ [\ Watts\ ]$$

Pressure, p or P, scalar (vector is considered normal to the area on which it acts)

$$p\ in\ Pascals = Pa = \frac{N}{m^2} = \frac{kg \cdot m}{s^2} => also\ \frac{J}{m^3}\ ||\ atmosphere = 101325\ Pa\ ||\ PSI = 6895\ Pa$$

$$mmH_2O = 9.81\ Pa\ ||\ mmHg = 133.3\ Pa$$

Temperature, T, scalar

T in Kelvins. Water, at $P_{water} = 1.013 \times 10^5$ Pa, melts at 273.15 Kelvins and boils at 373.15 Kelvins.

E1: Electromagnetism Units

Electric Potential, scalar, energy per charge

$$U\ in\ Volts = V = \frac{E_{potential}}{q} = \frac{J}{C} = \frac{kg \cdot m^2}{s^3 \cdot A} = A \cdot \Omega = \frac{W}{A} = \vec{E} \cdot m$$

Electric Field, vector, potential per distance, and Force, gradient of potential

$$\vec{E} = \frac{Volts}{meter} = \frac{kg \cdot m}{s^3 \cdot A} = \frac{Newtons}{Coulomb} = \frac{N}{C}$$

Electric Flux, vector with scalar, "electric field through a surface"

$$\vec{\Phi}_{electric} = \vec{E} \cdot \vec{S} = E \cdot S \cdot \cos\theta \Rightarrow in\ \ V \cdot m = \frac{V}{m} \cdot m^2 = \frac{N \cdot\ m^2}{C} = \frac{kg \cdot m^3}{s^3 \cdot A}$$

Electric Charge, scalar, energy per potential, quantized

$$q\ in\ Coulombs = C = \frac{Joules}{Volt} = A \cdot s$$

$$e = 1.602 \times 10^{-19}\ C = elementary\ charge\ (proton\ and\ electron\ charge)$$

Electric Current, charge per time

$$I\ in\ Amps = A = \frac{Coulombs}{s} = \frac{C}{s}$$

Current Density, vector, charge per time per area

$$\vec{J}\ \ in\ \frac{Amps}{m^2} \Rightarrow direction\ is\ of\ positive\ charged\ particles$$

Magnetic Field Strength, vector (AKA "Magenetic Field")

$$\vec{H} = \frac{Amps}{meter} = \frac{A}{m} = \frac{\vec{B}}{\mu}$$

Magnetic Flux, vector with scalar

$$\vec{\Phi}_B = \vec{B} \cdot \vec{S} = B \cdot S \cdot \cos\theta \Rightarrow direction\ is\ normal\ to\ the\ surface$$

$$Weber = Wb = \Omega \cdot C = V \cdot s = H \cdot A = T \cdot m^2 = \frac{J}{A} = \frac{kg \cdot m^2}{s^2 \cdot A}$$

Magentic Flux Density, vector (*also* AKA "Magnetic Field")

$$\vec{B} = Tesla = \frac{N}{m \cdot A} = \frac{kg}{s^2 \cdot A} = \mu \cdot \vec{H} \Rightarrow is\ much\ higher\ inside\ magnetic\ material$$

$$Tesla = T = \frac{Wb}{m^2} = \frac{V \cdot s}{m^2} = \frac{N}{A \cdot m} = \frac{H \cdot A}{m^2} = \frac{kg}{C \cdot s} = \frac{N \cdot s}{C \cdot m} = \frac{kg}{A \cdot s^2}$$

E2: Electric Circuit Units

Resistance, R, scalar

$$Ohm = \Omega = \mathrm{R} = \frac{\mathrm{I}}{\mathrm{U}} = \frac{Amps}{Volt} = \frac{A}{V}$$

Impedance, Z, complex phasor, where X is Reactance

$$Z = R + j \cdot X \quad where \quad X = X_L - X_C = X_{inductive} - X_{capacitive}$$

Inductance, scalar: L is inductance, X_L is inductive reactance

$$Henry = H = \frac{V \cdot s}{A} = \frac{kg \cdot m^2}{s^2 \cdot A^2} = \frac{N \cdot m}{A^2} = \frac{kg \cdot m^2}{Coulomb^2} = \frac{J}{A^2} = \frac{T \cdot m^2}{A} = \frac{Weber}{A} = \frac{\Omega}{Hz} = \Omega \cdot s = \frac{s^2}{F}$$

$$v(t) = L \cdot \frac{di}{dt}$$

$$Z_{inductor} = Z_L = \ j \cdot \boldsymbol{X_L} = j \cdot \boldsymbol{\omega} \cdot \boldsymbol{L} = \omega \cdot L \cdot e^{j \cdot \frac{\pi}{2}} = j \cdot 2\pi \cdot freq \cdot L \quad and \quad \boldsymbol{L} = \frac{\boldsymbol{X_L}}{\boldsymbol{2\pi \cdot freq}}$$

Capacitance, scalar: C is capacitance, X_C is capacitive reactance

$$Farad = F = \frac{Coulombs}{Volt} = \frac{A \cdot s}{V} = \frac{J}{V^2} = \frac{N \cdot m}{V^2} = \frac{C^2}{J} = \frac{s}{\Omega} = \frac{1}{\Omega \cdot Hz} = \frac{s^2}{H} = \frac{s^4 \cdot A^2}{m^2 \cdot kg} = \frac{s^2 \cdot C^2}{m^2 \cdot kg}$$

$$i(t) = C \cdot \frac{dv(t)}{dt}$$

$$Z_{capacitor} = Z_C = -j \cdot \boldsymbol{X_C} = -j \frac{\boldsymbol{1}}{\boldsymbol{\omega \cdot C}} = \frac{1}{\omega \cdot C} \cdot e^{j \cdot \left(-\frac{\pi}{2}\right)} = -j \cdot \frac{1}{2\pi \cdot freq \cdot C} \quad and \quad \boldsymbol{C} = \frac{\boldsymbol{1}}{\boldsymbol{2\pi \cdot freq \cdot X_C}}$$

Magnetic Reluctance, opposition to magnetic flux, inverse is Magnetic Permeance

$$\mathcal{R} = \frac{\mathcal{F}}{\Phi_{\mathrm{B}}} = \frac{MMF}{Magnetic\ Flux} = \frac{A \cdot turns}{Weber} = \frac{turns}{Henry} \quad || \quad \mathrm{P} = \frac{1}{\mathcal{R}}$$

Possibly add an image of **IPSE book Table C.1** here. Very useful for magnetic circuits.

Apparent Power, scalar: S is apparent power, P is real power, Q is reactive power

$$volt \cdot amp = VA = V_{RMS} \times I_{RMS} = \ S = \ \sqrt{(real\ power)^2 + (reactive\ power)^2} = \ \sqrt{P^2 + Q^2}$$

$$P = \sqrt{S^2 - Q^2} = S \times power\ factor = S \times \cos\phi = S_{DC}$$

E3: Electrical Properties of Materials and Fluids, and Constants

Resistivity, Conductivity of a material

$$\rho = \Omega \cdot m = R\frac{A}{l} => R = \rho \cdot \frac{l}{A} => resistivity$$

$$\sigma = \rho^{-1} = \frac{1}{\Omega \cdot m} = \frac{l}{R \cdot A} => R = \frac{l}{\sigma \cdot A} => conductivity$$

Permittivity, Vacuum AKA "distributed capacitance of the vacuum"

$$\epsilon_0 = 8.854 \times 10^{-12} \frac{Farads}{meter}$$

Relative Permittivity and Permittivity of a Medium

$$\epsilon_{relative}(\omega) = \frac{\epsilon(\omega)}{\epsilon_0} \;\; || \;\; \epsilon(\omega) = \epsilon_{relative}(\omega) \cdot \epsilon_0 \;\; || \;\; \epsilon_{relative}\; of\; teflon\; is\; 2.1\; [dimensionless] \;||\; also\; \kappa$$

Magnetic Permeability, Vacuum ("Magnetic Permeability" = "Permeability")

$$\mu_0 = 4 \cdot \pi \times 10^{-7} \frac{Henry}{meter} = 1.257 \times 10^{-6} \frac{H}{m} => \frac{H}{m} = \frac{N}{A^2}$$

Relative Permeability and Permeability of a Medium

$$\mu_{relative} = \frac{\mu}{\mu_0} \;||\; \mu = \mu_{relative} \cdot \mu_0 \;\; || \;\; \mu_{relative}\; of\; iron\; is\; {\sim}200{,}000\; [dimensionless]$$

Planck Constant, relates photon frequency to photon energy

$$h = 6.626 \times 10^{-34}\, J \cdot s \;\; || \;\; E_{photon} = h \cdot f_{photon}$$

Speed of Light

$$c_0 = 3.0 \times 10^8 \;\frac{m}{s} = \frac{1}{\sqrt{\mu_0 \cdot \epsilon_0}}$$

E4: Electromagnetism, Named Laws and Equations

Maxwell's equations go here.

Lorentz Force Law

$$\vec{F}_{electromagnetic} = \vec{F}_{electric} + \vec{F}_{magnetic} = q \cdot (\vec{E} + \vec{v} \times \vec{B})$$

Coulomb's Law

$$F_{Coulomb\ Law} = \frac{1}{4 \cdot \pi \cdot \epsilon_0} \frac{q_1 \cdot q_2}{r^2}$$

F1: Fluids, Properties of Fluids and Materials

Density, mass per volume:

$$\rho = \frac{kg}{m^3}$$

Density inverse is specific volume:

$$\nu = \rho^{-1} = \frac{m^3}{kg}$$

Speed of Sound, c, in Ideal Gases and Air

$$c = \sqrt{\frac{K_S}{\rho}} = \sqrt{\lambda \cdot \frac{P}{\rho}} \quad => \quad c_{air} = 20.05 \cdot \sqrt{T}\ \frac{m}{s}$$

Viscosity (dynamic viscosity and kinematic viscosity)

$$\mu = Pa \cdot s = \frac{N \cdot s}{m^2} = \frac{kg}{m \cdot s} => dynamic\ viscosity\ \boldsymbol{\mu = \rho \cdot \nu}$$

$$\nu = \frac{m^2}{s} => kinematic\ viscosity\ \boldsymbol{\nu} = \frac{\boldsymbol{\mu}}{\boldsymbol{\rho}}\ \ ||\ \ stokes = \frac{cm^2}{s} = 0.0001\frac{m^2}{s}$$

Bulk Modulous, K: Resistance to Compression of a substance.

$$K = -V \cdot \frac{dP}{dV} = \rho \frac{dP}{d\rho}$$

$$K_S = \lambda \cdot P\ (isentropic)\ \ ||\ \ K_T = P\ (isothermal)$$

F2: Fluids, Named Laws and Equations

Need Navier-Stokes etc. here

T1: Thermodynamics, Materials, Fluids, Constants

Heat Energy

$Q \text{ in Joules}$

Heat Energy Flow

$\dot{Q} \text{ in } \frac{Joules}{s} = Watts$

Enthalpy, internal energy plus "work required to establish the system's physical dimensions"

$H \text{ in Joules} = U + p \cdot V$

Internal Energy, energy contained within the system excluding kinetic and potential energy

$U \text{ in Joules}$

Heat Flux, heat flow per area

$$q = \frac{\dot{Q}}{Area} \text{ in} \frac{Watts}{m^2} \Rightarrow \text{in this reference, always } \dot{Q} \text{ in Watts or } Q \text{ in Joules. No "little } q." $$

Specific heat (often given for either constant pressure or constant volume)

$c_P \text{ and } c_V \text{ are both measured in } \frac{J}{kg \cdot K}$

$c_P = c_V + R_{specific}$

$\lambda = \frac{c_P}{c_V} = \text{heat capacity ratio}$

c_P is always larger [almost always larger, water?] than c_V conceptually because "constant volume" means the pressure increases as energy is added and "helps" heat the substance. "Constant *pressure*" implies the gas is allowed to expand while energy is added and expanding materials cool. Thus constant pressure requires more energy per temperature to make up for the cooling that *would have* happened.

Thermal Conductivity, heat transfer of a material

$$\kappa = \frac{\dot{Q}}{Area} \cdot \frac{thickness}{\Delta T} \text{ in } \frac{Watts}{m \cdot K} = \frac{Watts}{m^2} \cdot \frac{m}{\Delta T} \Rightarrow \text{ sometimes } \lambda \text{ or } k \Rightarrow \dot{Q} = \kappa \cdot \frac{Area \cdot \Delta T}{thickness}$$

Heat Transfer Coefficient, of a surface

$$h = \frac{\dot{Q}}{A} \cdot \frac{1}{\Delta T} = \frac{Watts}{m^2 \cdot K} \Rightarrow \dot{Q} = h \cdot A \cdot \Delta T \text{ and } h_{surface} = \kappa_{surface\ material} \cdot thickness$$

Steffan-Boltzmann Constant, radiant heat of a black body

$\sigma = 5.670 \times 10^{-8} \frac{W}{m^2 \cdot K^4}$

can also be directly related to the Boltzmann constant, Planck constant, and c_0 (= speed of light)

Boltzmann Constant, relates average kinetic energy of particles in a gas to thermodynamic temperature

$$k_B = 1.381 \times 10^{-23} \frac{J}{K}$$

Gas Constant and Specific Gas Constant

$$R = R_{molar} = 8.314 \frac{J}{K \cdot mol}$$

$$R_{specific} = \frac{R}{M} \; unit\ is\ \frac{J}{kg \cdot K} \left(note{:}\ M\ usually\ given\ in \frac{g}{mol}\ so\ must\ convert\ to \frac{kg}{mol} \right)$$

Ideal Gas

$$PV = nRT \ \boldsymbol{and}\ PV = m \cdot R_{specific} \cdot T$$

T2: Thermodynamics, Named Laws and Equations

1. **Conservation of Energy**. The energy gained (or lost) by a system is equal to the energy lost (or gained) by its surroundings. Cannot produce work without energy input.
2. In a natural thermodynamic process, the sum of the entropies of the interacting thermodynamic systems never decreases. Heat does not spontaneously pass from a colder body to a warmer body. Cannot spontaneously convert thermal energy into mechanical work.
3. A system's entropy approaches a constant value as the temperature approaches absolute zero. With the exception of non-crystalline solids (glasses) the entropy of a system at absolute zero is typically close to zero.

named thermodynamics equations here

N1: Nuclear Units

Nuclear

Energy

$MeV = 1.602 \times 10^{-13}$

Area, Tiny

$barn = 10^{-28} m^2$

Radioactivity, various forms

$becquerel = Bq = \frac{1\ decay}{second} = \frac{1}{s} => one\ 70kg\ human\ emits\ 8000\ Bq\ normally\ from\ \_\_\_$

$Curie\ Ci = 3.7 \times 10^{10} Bq = 37\ GBq\ \ ||\ \ Rutherford\ Rd = 10^6 Bq = 1\ MBq$

$Gray = Gy = \frac{Joule}{kg}\ absorbed\ radiation\ energy\ = \frac{m^2}{s^2}$

$Sievert = Sv = \frac{Joule}{kg} => is\ Gray\ adjusted\ for\ stochastic\ health\ risk, LNT\ is$ "linear no threshold"

$Normal\ in\ Belgium\ is\ 0.005 \frac{Sv}{year}\ from\ \_\_\_$

Geez, how many v's are there? Volume, velocity, volts, Greek nu for viscosity. Some form of v for specific volume.