

About orders of magnitude

Un ordre de grandeur, c'est **zero** chiffre significatif !

Si on veut raffiner, on peut mettre choisir une mantisse entière ou bien ajouter une virgule à l'exposant (ex: $2 \cdot 10^2$ ou bien $10^{2.3}$). Toute tentative d'aller plus loin se heurte au principe fondamental de l'OdG, qui est d'accepter l'imprécision.

En log, $[1-3.3] = 1$ et $[3.3-10] = 10$

In black: lots of useful orders of magnitude that it is interesting to learn by heart

In grey, the bonus: fancy orders of magnitude which are less often useful.

Constants

Fundamental constants

- $G = 6.67 \cdot 10^{-11}$ SI
- $e = 1.19 \cdot 10^{-19}$ C
- $k_B \approx 1.38 \cdot 10^{-23}$ J/K
- $h \approx 6.63 \cdot 10^{-34}$ J·s
- $c = 3.00 \cdot 10^8$ m/s
- $m_e \approx 9.11 \cdot 10^{-31}$ kg

Conversion factors

- Avogadro number $\mathcal{N}_a = 6.02 \cdot 10^{23}$
- Electronvolt $1 \text{ eV} = 1.6 \cdot 10^{19}$ C

Mechanics

Celestial mechanics

Sun Distance to earth 1 a.u. = 8 light-minutes ($150 \cdot 10^6$ km)

- Mass $2 \cdot 10^{30}$ kg
- Temperature 6000 K
- Radius 10^6 km
- $\lambda_{\max} \approx 530$ nm
- Gravity $28 g$

Earth

- Mass $6 \cdot 10^{24}$ kg
- Liberation speed 11 km/s
- Asphericity $\Delta R/R \approx 1/300$
- Mean density 5.5
- Radius 6400 km
- Geostationarity 36 000 km
- $\Delta g/g$ (asphericity) $6 \cdot 10^{-3}$
- Core density 12
- Gravity $1 g \approx 10 \text{ m/s}^2$
- $\Delta g/g$ (earth rotation) $3 \cdot 10^{-3}$
- Crust density 3

Moon Distance to earth 1 light-second

- Mass $7 \cdot 10^{22}$ kg
- $T_{\text{rev}} = T_{\text{spin}} = 28$ days
- Radius 1700 km
- Recessition rate 3.8 cm/yr
- Gravity $g/6$

Mars

- Mass $6 \cdot 10^{23}$ kg
- Travel time ≈ 6 months
- Radius 3400 km
- $T_{\text{rev}} \approx 1.8$ yr
- Gravity $g/2.5$

Bigger scales 1 parsec (pc) = 1 parallax / arcsecond ≈ 3 lightyears (ly)

- 1 ly $\approx 10^{16}$ m
- Galaxy size 10^5 ly
- Local supercluster 10^8 ly

Classical mechanics

Solid friction

- Steel/ice : $\mu_D \approx \mu_S = 0.02$
- Tire on road : $\mu_D = 0.5, \mu_S = 0.8$

Condensed matter

Diffusion

Molecular diffusion In a solid, $D \propto D_0 \exp(-E_0/kT)$ with $E_0 \approx 1$ eV — in a gaz, $D \propto T^{3/2}$

- Solid : $D \approx 10^{-20}$ m²/s
- Liquid : $D \approx 10^{-9}$ m²/s
- Gases : $D \approx 10^{-5}$ m²/s

Thermal diffusion $D_{th} = \lambda/(\rho c_v)$

- Metals $\lambda \approx 100$ W/m/K
- Liquids $\lambda \approx 1$ W/m/K
- Gases $\lambda \approx 0.01$ W/m/K

Solids

Density of solids $\approx 10^{30}$ atoms/ m³ — Density of metals (steel) 8000 kg/m³

Elasticity Young modulus of steel: 200 GPa

Liquids

Statics 1 atm = 1013.15 hPa = 760 mmHg

- 1 Pa = 1 N/m²
- 1 bar = 10⁵ Pa
- 1 atm \approx 1 bar

Dynamic viscosity η often given in Poiseuille (1 Pl = 1 Pa·s)

- Air $\eta = 10^{-5}$ Pa·s
- Mineral oil $\eta = 0.1$ Pa·s
- Honey $\eta = 10$ Pa·s
- Water $\eta = 10^{-3}$ Pa·s
- Glycerol $\eta = 1.5$ Pa·s
- Pulmonary mucus $\eta = 50$ Pa·s

Momentum diffusivity (kinematic viscosity) ν often given in centistokes 1 cSt = 1 mm²/s = 10⁻⁶ m²/s

- Air 10⁻⁵ m²/s
- Water 10⁻⁶ m²/s
- Mineral oil 10⁻³ m²/s

Surface tension Surface tension coefficient γ in N/m or W/m² often given in dyns/cm = erg/cm² = mN/m

- Octane/air 22 mN/m
- Pure water/air 73 mN/m
- Mercury/air 490 mN/m

Capillary length (capillarity/gravity competition scale) $\ell_c = \sqrt{\frac{\gamma}{\rho g}} \approx 3$ mm for most liquids

Laplace overpressure γ/R_c with R_c the radius of curvature

Reynolds number Typically a flow is laminar at low Re, and turbulent if $Re > 2000$

$$Re = \frac{UL}{\nu}$$

Typical boundary layer size: L/Re

Wind speed

- Breeze 10 km/h
- Windy day 50 km/h
- Tempest 80 km/h
- Typhoon 120 km/h

Drag force

- $Re \ll 1$: $6\pi\eta RV$ ($\propto 1/Re$)
- $Re \gg 1$: $\frac{1}{2}C_x SV^2$ (indep. of Re)

The dimensionless drag coefficient C_D and lift coefficient C_L depend on the shape

- Sphere $C_D \approx 0.3$
- Bullet $C_D \approx 0.03$

Wings (airfoils) (NACA 4412) $C_D \approx 0.01$, $C_L \approx 1.5$

Thermodynamics

- $R = 8.34 \text{ J/K/mol}$
- Stefan constant $\sigma \approx 5.67 \times 10^{-8} \text{ (} P = \sigma T^4 \text{)}$

Perfect gases

For perfect gases : $C_{v,m} \approx C_{p,m} \approx R$

	Monoatomic	Diatomic
$C_{v,m}$	$3R/2$	$5R/2$
$C_{p,m}$	$5R/2$	$7R/2$
γ	$5/3$	$7/5$

Air

Pour l'air (80% de N_2 , 20% d' O_2) à 20 deg C à 1 atm

- Masse molaire 29 g/mol
- Masse volumique 1.3 kg/m^3
- Vitesse quadratique moyenne 500 m/s
- Libre parcours moyen 100 nm
- Compressibility $\xi_T = 10^{-5} \text{ Pa}^{-1}$
- Volume molaire 24 L/mol

Eau

Pour l'eau pure

- Masse volumique 10^3 kg/m^3
- Temperature de fusion à 1 atm : $273 \text{ K} = 0 \text{ C}$
- Triple point 0 C 612 Pa
- Critical point $T_c = 274 \text{ deg}$ $P_c = 221 \text{ bar}$
- Capacite thermique eau liquide $c = 4.18 \text{ kJ/K/kg}$
- Capacite thermique glace $c = 2.1 \text{ kJ/K/kg}$
- Chaleur latente de fusion 330 kJ/kg
- Chaleur latente de vaporisation 2500 kJ/kg

Electromagnetism

- Rydberg constant: $Ry \approx 13.6 \text{ eV}$
- Bohr radius: $a_0 = 53 \text{ pm}$
- $\mu_0 = 4\pi 10^{-7} \text{ H/m}$
- $\epsilon_0 \approx 8.85 \cdot 10^{-12} \text{ F/m}$

Electrostatics

Electric field

- Radio wave 0.1 V/m
- Dry weather 150 V/m
- Thunderstorm 10^4 V/m
- In an atom 10^{11} V/m

Champ disruptif de l'air 1000 kV/m (air humide) — air sec: 3600 kV/m .

Relative dielectric permittivity ϵ_r at 0 Hz

- Air $5 \cdot 10^{-3}$
- Glass 5
- Water 80

Dipolar moment of water: 2 D

Magnetostatics

1 G (Gauss) = $100 \mu\text{T}$

Magnetic field

- Earth 0.5 G
- Brain 10^{-11} G
- NdFeB magnet 0.1 T
- Neutron star 10^8 T
- MRI $1\text{-}10 \text{ T}$
- Magnetar 10^{11} T

Bohr magneton $\mu_B \approx 10^{-23} \text{ A} \cdot \text{m}^2$

Magnetic moment of a good magnet $\approx N_a \mu_B$

Curie temperature $\approx 100^\circ\text{C}$ (typical NdFeB magnets)

Relative magnetic susceptibility χ_r at 0 Hz

- N_2 (dia) -10^{-8}
- H_2O (dia) -10^{-5}
- O_2 (para) $5 \cdot 10^{-6}$
- FeCl_3 (para) $3 \cdot 10^{-3}$

Electronics

Conductivity

- Conductor (Cu) $6 \cdot 10^7$ S/m
- Semiconducteur (Si) 10^4 S/m
- Isolant (Paraffine) 10^{-8} S/m

Speed of an electron in a 1 mm diameter copper cable with a 1 A current : 1 mm/s.

Electric current

- In the lab 1 – 10 mA
- Danger threshold 30 mA
- Thunder 10 – 100 kA
- Nervous signal 20 μ A
- 1 kW heater 5 A
- High voltage line 1 kA

Voltage

- In the lab 1 – 10 V
- In Europe 230 V
- High voltage line 100 kV

The voltage is often given in valeur efficace: $\sqrt{2}$ factor. e.g. in Europe, voltage go as high as 325 V.

Components

Resistors

- In the lab 1 – 100 k Ω
- GBF (interne) 50 Ω
- Voltmètre (entry) 1 M Ω
- Human body 1 k Ω
- Wire 0.1 Ω
- Ampèremètre (entry) 100 m Ω

Coils

- In the lab 10 – 100 mH
- Main MRI coil 100 H

Condensators

- In the lab 1 – 10 nF
- Oscillo (entrée) 10 pF

Operational amplifier	Idéal	μ A741	TL081
Paramètres linéaires			
Résistance d'entrée R_e	∞	$2 \times 10^6 \Omega$	$10^{12} \Omega$
Résistance de sortie R_s	0Ω	100 Ω	100 Ω
Courant de polarisation d'entrée $I_p = (i_+ + i_-)/2$	0 A	80 nA	30 pA
Paramètres non-linéaires			
Tension maximum de sortie	V_{cc}	15 V	15 V
Courant maximum de sortie	∞	10 mA	10 mA
Vitesse de balayage σ	∞	0.5 V/ μ m	13 V/ μ m

Electromagnetic waves

Impédance du vide $Z_0 = 377 \Omega$

Loi de Wien $\lambda_{\max} T \approx 2900 \mu\text{m} \cdot \text{K}$

Fréquence plasma ionosphère 3 MHz ($n \approx 10^{11} \text{ e}^-/\text{m}^3$)

< pm	pm - nm	nm - μ m	μ m - mm	mm - m	m- km	> km
γ	X	UV	IR	radar	TV	radio

- Radio AM : $f \sim 100$ kHz
- Radio FM / télévision : $f \sim 100$ MHz
- Téléphonie mobile : 2,4-5 Ghz
- Four à 'micro ondes' : $f = 2,45$ GHz (ondes centimétriques)
- Wi-fi : 2.5 GHz

Wave propagation

Optics

Visible light range ('magic numbers': 39 & 77): $[3,9 \times 10^{14}; 7,7 \times 10^{14}]$ Hz \iff [390; 770] nm

Refractive index

- Void $n = 1$
- Air $n = 1 + 3 \cdot 10^{-4}$
- Water $n = 1.33$
- Glass $n \approx 1.6 \pm 0.1$
- Diamond $n = 2.4$
- Mineral oil $n \approx 1.5$

Cauchy law $n(\lambda) = A + B/\lambda^2$ with $B \sim 10^{-3} \mu\text{m}^3$

Optique géométrique

Pouvoir séparateur de l'oeil $\epsilon \approx 1' \approx 10^{-4}$ rad

Human eye

- Punctum proximum 25 cm
- Sensibilité maximale 560 nm
- Résolution angulaire $1' \approx 10^{-4}$ rad

Source	λ_0 (nm)	$\Delta\lambda$ (nm)	$\Delta\nu$ (Hz)	τ (s)	$\ell_c = c\tau$
Lumière blanche	550	300	10^{14}	10^{-15}	1 μ m
Lampe spectrale Na	589,3	0.01	10^{10}	10^{-10}	3 cm
Laser He-Ne	633	10^{-3}	10^9	10^{-9}	30 cm
Laser stabilisé	633	10^{-6}	10^6	10^{-6}	300 m

Doublet jaune du sodium : $\Delta\lambda = 0,6$ nm

Doublet jaune du mercure : $\lambda_m = 578$ nm, $\Delta\lambda = 2$ nm

Laser for a typical He-Ne laser (laser de TP)

- $\lambda = 633$ nm
- waist 1 mm
- $\Delta\mathcal{E} \approx 2$ eV
- $\ell_c \approx 1$ m
- $E \approx 100$ V/m
- $\mathcal{P} \approx 1$ mW

Smallest laser impulsion : a few femtoseconds (but we can go below using nonlinear optics technics).

Acoustics

In general, $c = \sqrt{1/\rho\xi_s}$ with ρ volumic mass and ξ_s the isentropic compressibility
Speed of sound in

- Steel $c = \sqrt{E/\mu} \approx 5$ km/s
- Water $c \approx 1.5$ km/s
- Air $c = \sqrt{\gamma RT/M} \approx 340$ m/s

Hearing Typical hearing bandwidth 20 Hz — 20 kHz

Power level in dB $P = 10 \log(I/I_{\text{ref}})$

- 0 dB $I_{\text{ref}} = 10^{-12}$ W/m² hearing threshold
- 50 dB Rain
- 60 dB Normal conversation
- 105 dB Techno concert
- 120 dB (pain threshold) 100m from plane lift-off
- 140 dB (burst eardrum) gunshot

Perturbation amplitude For a sound wave of 35 dB in air

- $\delta P = 1$ mPa
- $\delta v = 1$ μ m/s
- $\delta T = 1$ μ K

Displacement of air molecules: $\delta v/f \approx 1$ nm at 400 Hz.

Music la_3 : 440 Hz. Octave = $\cdot 2$, ton = $\cdot 2^{1/12}$

Microscopic physics

- Rydberg constant $Ry \approx 13.6$ eV
- Bohr radius 53 pm
- Reduced Planck constant $\hbar \approx 10^{-34}$ J·s
- $\alpha \approx 1/137$

Constituants de la matière

Electron

- Mass $m_e = 9.1 \cdot 10^{-31}$ kg = 511 keV
- Classical radius 10^{-15} m

Nucleon

- Mass 10^{-27} kg $\approx 1000 m_e$
- Classical radius 1 fm

Énergies d'interaction

- Covalente 100 kJ/mol ≈ 1 eV
- Liaison H 20 kJ/mol
- VdW 1kJ/mol
- Électron-noyau 1 eV
- Nucléons 100 MeV

Typical thermal noise $kT = 0.03$ eV ≈ 3 kJ/mol at 300 K
Photon at 532 nm $h\nu = 2.3$ eV

Life, Humans & Environment

Life

Size of a bacteria: $10 \mu\text{m}$

Size of a cell: $1 \mu\text{m}$

Humans

- Thermal power at rest: 100 W
- Heart mechanical power: 3 W

BPM coeur humain : 80 to 100

Temperature 37 deg C

- Brain consumption: 15 W

Power

Power consumption 1 horsepower (hp) = 735 W

- Heater 1 kW

- Car 100 kW (135 hp)

Human (to maintain body heat) ~ 100 W

Power generation

- Solar panel: 1 kW/m^2 (clear weather, noon)
- Wind turbine: 1 MW (windy weather)

- Nuclear reactor: 1 GW
- Total electrical power on Earth: 10 TW

Efficiency

- Electric motor: 99 %

- Thermal motor: 60 %

Energy

- 1 cal = 4.18 J

- 1 tep (tonne équivalent pétrole) = 42 GJ

Environment

Concentration en CO_2 dans l'atmosphère 0.05%

Typical astmospheric height $\frac{RT_0}{Mg} = 8 \text{ km}$

CO_2 emissions (kg / km)

- Voiture

- Avion

Flow rates

Typical showerhead: 20 L/min WC flush: 10 L Fleuve (big river): $500 \text{ m}^3/\text{s}$ (Seine)