AETD MINI-COURSE 115:

UNITS OF MEASUREMENT

COURSE HANDOUTS

D.G. SIMPSON

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

Contents

Chapter 1

Metric Prefixes

1.1 SI Prefixes

Prefix	Symbol	Definition	English
yotta-	Y	10^{24}	septillion
zetta-	Z	10^{21}	sextillion
exa-	E	10^{18}	quintillion
peta-	P	10^{15}	quadrillion
tera-	T	10^{12}	trillion
giga-	G	10^{9}	billion
mega-	M	10^{6}	million
kilo-	k	10^{3}	thousand
hecto-	h	10^{2}	hundred
deka-	da	10^{1}	ten
deci-	d	10^{-1}	tenth
centi-	c	10^{-2}	hundredth
milli-	m	10^{-3}	thousandth
micro-	μ	10^{-6}	millionth
nano-	n	10^{-9}	billionth
pico-	p	10^{-12}	trillionth
femto-	f	10^{-15}	quadrillionth
atto-	a	10^{-18}	quintillionth
zepto-	z	10^{-21}	sextillionth
yocto-	y	10^{-24}	septillionth

1.2 Computer Prefixes

Prefix	Symbol		Definition
yobi-	Yi	2^{80}	$= 1024^8 =$ 1,208,925,819,614,629,174,706,176
zebi-	Zi	2^{70}	$= 1024^7 =$ 1,180,591,620,717,411,303,424
exbi-	Ei	2^{60}	$= 1024^6 =$ 1,152,921,504,606,846,976
pebi-	Pi	2^{50}	$= 1024^5 =$ 1,125,899,906,842,624
tebi-	Ti	2^{40}	$= 1024^4 =$ 1,099,511,627,776
gibi-	Gi	2^{30}	$= 1024^3 =$ 1,073,741,824
mebi-	Mi	2^{20}	$= 1024^2 =$ 1,048,576
kibi-	Ki	2^{10}	$= 1024^1 =$ 1,024

Chapter 2

SI Units

2.1 SI Base Units

Name	Symbol	Quantity
meter	m	length
kilogram	kg	mass
second	s	time
ampere	A	electric current
kelvin	K	temperature
mole	mol	amount of substance
candela	cd	luminous intensity

2.2 SI Derived Units (Standard MKSA Base Units)

This table shows each of the SI derived units expressed in terms of base units.

Name	Symbol	Definition	Base Units	Quantity
radian	rad	m / m	—	plane angle
steradian	sr	m^2 / m^2	—	solid angle
newton	N	kg m s^{-2}	kg m s^{-2}	force
joule	J	N m	kg m^2 s^{-2}	energy
watt	W	J / s	kg m^2 s^{-3}	power
pascal	Pa	N / m^2	kg m^{-1} s^{-2}	pressure
hertz	Hz	s^{-1}	s^{-1}	frequency
coulomb	C	A s	A s	electric charge
volt	V	J / C	kg m^2 A^{-1} s^{-3}	electric potential
ohm	Ω	V / A	kg m^2 A^{-2} s^{-3}	electrical resistance
siemens	S	A / V	kg^{-1} m^{-2} A^2 s^3	electrical conductance
farad	F	C / V	kg^{-1} m^{-2} A^2 s^4	capacitance
weber	Wb	V s	kg m^2 A^{-1} s^{-2}	magnetic flux
tesla	T	Wb / m^2	kg A^{-1} s^{-2}	magnetic induction
henry	H	Wb / A	kg m^2 A^{-2} s^{-2}	induction
lumen	lm	cd sr	cd sr	luminous flux
lux	lx	lm / m^2	cd sr m^{-2}	illuminance
becquerel	Bq	s^{-1}	s^{-1}	radioactivity
gray	Gy	J / kg	m^2 s^{-2}	absorbed dose
sievert	Sv	J / kg	m^2 s^{-2}	dose equivalent
katal	kat	mol / s	mol s^{-1}	catalytic activity

2.3 SI Derived Units (MVSA Base Units)

This is an unofficial system in which the *volt* replaces the kilogram as an SI base unit. This system simplifies the expression of electromagnetic derived units in terms of base units.

Name	Symbol	Definition	MVSA Base Units	Quantity
kilogram	kg		V A s^3 m^{-2}	mass
radian	rad	m / m	—	plane angle
steradian	sr	m^2 / m^2	—	solid angle
newton	N	kg m s^{-2}	V A s m^{-1}	force
joule	J	N m	V A s	energy
watt	W	J / s	V A	power
pascal	Pa	N / m^2	V A s m^{-3}	pressure
hertz	Hz	s^{-1}	s^{-1}	frequency
coulomb	C	A s	A s	electric charge
ohm	Ω	V / A	V A^{-1}	electrical resistance
siemens	S	A / V	A V^{-1}	electrical conductance
farad	F	C / V	A s V^{-1}	capacitance
weber	Wb	V s	V s	magnetic flux
tesla	T	Wb / m^2	V s m^{-2}	magnetic induction
henry	H	Wb / A	V s A^{-1}	induction
lumen	lm	cd sr	cd sr	luminous flux
lux	lx	lm / m^2	cd sr m^{-2}	illuminance
becquerel	Bq	s^{-1}	s^{-1}	radioactivity
gray	Gy	J / kg	m^2 s^{-2}	absorbed dose
sievert	Sv	J / kg	m^2 s^{-2}	dose equivalent
katal	kat	mol / s	mol s^{-1}	catalytic activity

2.4 SI Equations of Electromagnetism

Maxwell's Equations

Both the differential (left column) and integral (right column) forms of Maxwell's equations are shown. Here **D** is the electric displacement vector; **B** is the magnetic induction vector; **E** is the electric field vector; **H** is the magnetic intensity vector; **J** is the current density vector; ρ is the electric charge density; q is the electric charge; Φ_B is the magnetic induction flux; and Φ_D is the electric displacement flux.

$$\nabla \cdot \mathbf{D} = \rho \qquad \oint_S \mathbf{D} \cdot d\mathbf{A} = q$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \oint_S \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \qquad \oint_C \mathbf{H} \cdot d\mathbf{l} = I + \frac{d\Phi_D}{dt}$$

Coulomb's Law

This gives the force F between two point charges q_1 and q_2, separated by a distance r.

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$$

Lorentz Force

The first equation is the conventional Lorentz force on an electric charge q in electric and magnetic fields; the second equation is the analogous force on a magnetic monopole of pole strength q^*.

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad \mathbf{F} = q^* \left(\mathbf{B} - \frac{\mathbf{v}}{c^2} \times \mathbf{E}\right)$$

Constitutive Relations

$$\mathbf{E} = \frac{1}{\varepsilon_0}(\mathbf{D} - \mathbf{P})$$

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

Chapter 3

Electrostatic Units

3.1 Electrostatic Base Units

Name	Symbol	Quantity
centimeter	cm	length
gram	g	mass
second	s	time
kelvin	K	temperature
mole	mol	amount of substance
candela	cd	luminous intensity

3.2 Electrostatic Derived Units

This table shows each of the electrostatic derived units expressed in terms of base units.

Name	Symbol	Definition	Base Units	Quantity
radian	rad	m / m	—	plane angle
steradian	sr	m^2 / m^2	—	solid angle
dyne	dyn	g cm s^{-2}	g cm s^{-2}	force
erg	erg	dyn cm	g cm^2 s^{-2}	energy
statwatt	statW	erg / s	g cm^2 s^{-3}	power
barye	ba	dyn / cm^2	g cm^{-1} s^{-2}	pressure
galileo	Gal	cm / s^2	cm s^{-2}	acceleration
poise	P	g / (cm s)	g cm^{-1} s^{-1}	dynamic viscosity
stokes	St	cm^2 / s	cm^2 s^{-1}	kinematic viscosity
hertz	Hz	s^{-1}	s^{-1}	frequency
statcoulomb	statC		$g^{1/2}$ $cm^{3/2}$ s^{-1}	electric charge
franklin	Fr	statC	$g^{1/2}$ $cm^{3/2}$ s^{-1}	electric charge
statampere	statA	statC / s	$g^{1/2}$ $cm^{3/2}$ s^{-2}	electric current
statvolt	statV	erg / statC	$g^{1/2}$ $cm^{1/2}$ s^{-1}	electric potential
statohm	statΩ	statV / statA	s cm^{-1}	electrical resistance
statfarad	statF	statC / statV	cm	capacitance
statweber	statWb	statV cm	$g^{1/2}$ $cm^{1/2}$	magnetic flux
unit pole	pole	dyn / Oe	$g^{1/2}$ $cm^{3/2}$ s^{-1}	magnetic pole strength
stathenry	statH	erg / $statA^2$	s^2 cm^{-1}	induction
lumen	lm	cd sr	cd sr	luminous flux
phot	ph	lm / cm^2	cd sr cm^{-2}	illuminance
stilb	sb	cd / cm^2	cd cm^{-2}	luminance
lambert	Lb	$1/\pi$ cd / cm^2	cd cm^{-2}	luminance
kayser	K	1 / cm	cm^{-1}	wave number
becquerel	Bq	s^{-1}	s^{-1}	radioactivity
katal	kat	mol / s	mol s^{-1}	catalytic activity

3.3 Electrostatic Equations of Electromagnetism

Maxwell's Equations

Both the differential (left column) and integral (right column) forms of Maxwell's equations are shown. Here $\mathbf{D}$ is the electric displacement vector; $\mathbf{B}$ is the magnetic induction vector; $\mathbf{E}$ is the electric field vector; $\mathbf{H}$ is the magnetic intensity vector; $\mathbf{J}$ is the current density vector; ρ is the electric charge density; q is the electric charge; Φ_B is the magnetic induction flux; and Φ_D is the electric displacement flux.

$$\nabla \cdot \mathbf{D} = 4\pi\rho \qquad \oint_S \mathbf{D} \cdot d\mathbf{A} = 4\pi q$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \oint_S \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt}$$

$$\nabla \times \mathbf{H} = 4\pi\mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \qquad \oint_C \mathbf{H} \cdot d\mathbf{l} = 4\pi I + \frac{d\Phi_D}{dt}$$

Coulomb's Law

This gives the force F between two point charges q_1 and q_2, separated by a distance r.

$$F = \frac{q_1 q_2}{r^2}$$

Lorentz Force

The first equation is the conventional Lorentz force on an electric charge q in electric and magnetic fields; the second equation is the analogous force on a magnetic monopole of pole strength q^*.

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad \mathbf{F} = q^*(\mathbf{B} - \frac{\mathbf{v}}{c^2} \times \mathbf{E})$$

Constitutive Relations

$$\mathbf{E} = \mathbf{D} - 4\pi\mathbf{P}$$

$$\mathbf{B} = \frac{1}{c^2}(\mathbf{H} + 4\pi\mathbf{M})$$

Chapter 4

Electromagnetic Units

4.1 Electromagnetic Base Units

Name	Symbol	Quantity
centimeter	cm	length
gram	g	mass
second	s	time
kelvin	K	temperature
mole	mol	amount of substance
candela	cd	luminous intensity

4.2 Electromagnetic Derived Units

This table shows each of the electromagnetic derived units expressed in terms of base units.

Name	Symbol	Definition	Base Units	Quantity
radian	rad	m / m	—	plane angle
steradian	sr	m^2 / m^2	—	solid angle
dyne	dyn	g cm s^{-2}	g cm s^{-2}	force
erg	erg	dyn cm	g cm^2 s^{-2}	energy
abwatt	abW	erg / s	g cm^2 s^{-3}	power
barye	ba	dyn / cm^2	g cm^{-1} s^{-2}	pressure
galileo	Gal	cm / s^2	cm s^{-2}	acceleration
poise	P	g / (cm s)	g cm^{-1} s^{-1}	dynamic viscosity
stokes	St	cm^2 / s	cm^2 s^{-1}	kinematic viscosity
hertz	Hz	s^{-1}	s^{-1}	frequency
abcoulomb	abC		$g^{1/2}$ $cm^{1/2}$	electric charge
abampere	abA	abC / s	$g^{1/2}$ $cm^{1/2}$ s^{-1}	electric current
biot	Bi	abA	$g^{1/2}$ $cm^{1/2}$ s^{-1}	electric current
abvolt	abV	erg / abC	$g^{1/2}$ $cm^{3/2}$ s^{-2}	electric potential
abohm	abΩ	abV / abA	cm s^{-1}	electrical resistance
abfarad	abF	abC / abV	s^2 cm^{-1}	capacitance
maxwell	Mx	statV cm	$g^{1/2}$ $cm^{3/2}$ s^{-1}	magnetic flux
gauss	G	Mx / cm^2	$g^{1/2}$ $cm^{-1/2}$ s^{-1}	magnetic induction
oersted	Oe	abA / cm	$g^{1/2}$ $cm^{-1/2}$ s^{-1}	magnetic intensity
gilbert	Gb	abA	$g^{1/2}$ $cm^{3/2}$ s^{-2}	magnetomotive force
unit pole	pole	dyn / Oe	$g^{1/2}$ $cm^{3/2}$ s^{-1}	magnetic pole strength
abhenry	abH	erg / $statA^2$	cm	induction
lumen	lm	cd sr	cd sr	luminous flux
phot	ph	lm / cm^2	cd sr cm^{-2}	illuminance
stilb	sb	cd / cm^2	cd cm^{-2}	luminance
lambert	Lb	$1/\pi$ cd / cm^2	cd cm^{-2}	luminance
kayser	K	1 / cm	cm^{-1}	wave number
becquerel	Bq	s^{-1}	s^{-1}	radioactivity
katal	kat	mol / s	mol s^{-1}	catalytic activity

4.3 Electromagnetic Equations of Electromagnetism

Maxwell's Equations

Both the differential (left column) and integral (right column) forms of Maxwell's equations are shown. Here **D** is the electric displacement vector; **B** is the magnetic induction vector; **E** is the electric field vector; **H** is the magnetic intensity vector; **J** is the current density vector; ρ is the electric charge density; q is the electric charge; Φ_B is the magnetic induction flux; and Φ_D is the electric displacement flux.

$$\nabla \cdot \mathbf{D} = 4\pi\rho \qquad \oint_S \mathbf{D} \cdot d\mathbf{A} = 4\pi q$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \oint_S \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d\Phi_B}{dt}$$

$$\nabla \times \mathbf{H} = 4\pi \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \qquad \oint_C \mathbf{H} \cdot d\mathbf{l} = 4\pi I + \frac{d\Phi_D}{dt}$$

Coulomb's Law

This gives the force F between two point charges q_1 and q_2, separated by a distance r.

$$F = c^2 \frac{q_1 q_2}{r^2}$$

Lorentz Force

The first equation is the conventional Lorentz force on an electric charge q in electric and magnetic fields; the second equation is the analogous force on a magnetic monopole of pole strength q^*.

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \qquad \mathbf{F} = q^*(\mathbf{B} - \frac{\mathbf{v}}{c^2} \times \mathbf{E})$$

Constitutive Relations

$$\mathbf{E} = c^2(\mathbf{D} - 4\pi \mathbf{P})$$

$$\mathbf{B} = \mathbf{H} + 4\pi \mathbf{M}$$

Chapter 5

Gaussian Units

5.1 Gaussian Base Units

Name	Symbol	Quantity
centimeter	cm	length
gram	g	mass
second	s	time
kelvin	K	temperature
mole	mol	amount of substance
candela	cd	luminous intensity

5.2 Gaussian Derived Units

This table shows each of the Gaussian derived units expressed in terms of base units.

Name	Symbol	Definition	Base Units	Quantity
radian	rad	m / m	—	plane angle
steradian	sr	m^2 / m^2	—	solid angle
dyne	dyn	g cm s^{-2}	g cm s^{-2}	force
erg	erg	dyn cm	g cm^2 s^{-2}	energy
statwatt	statW	erg / s	g cm^2 s^{-3}	power
barye	ba	dyn / cm^2	g cm^{-1} s^{-2}	pressure
galileo	Gal	cm / s^2	cm s^{-2}	acceleration
poise	P	g / (cm s)	g cm^{-1} s^{-1}	dynamic viscosity
stokes	St	cm^2 / s	cm^2 s^{-1}	kinematic viscosity
hertz	Hz	s^{-1}	s^{-1}	frequency
statcoulomb	statC		$g^{1/2}$ $cm^{3/2}$ s^{-1}	electric charge
franklin	Fr	statC	$g^{1/2}$ $cm^{3/2}$ s^{-1}	electric charge
statampere	statA	statC / s	$g^{1/2}$ $cm^{3/2}$ s^{-2}	electric current
statvolt	statV	erg / statC	$g^{1/2}$ $cm^{1/2}$ s^{-1}	electric potential
statohm	statΩ	statV / statA	s cm^{-1}	electrical resistance
statfarad	statF	statC / statV	cm	capacitance
maxwell	Mx	statV cm	$g^{1/2}$ $cm^{3/2}$ s^{-1}	magnetic flux
gauss	G	Mx / cm^2	$g^{1/2}$ $cm^{-1/2}$ s^{-1}	magnetic induction
oersted	Oe	statA s / cm^2	$g^{1/2}$ $cm^{-1/2}$ s^{-1}	magnetic intensity
gilbert	Gb	statA	$g^{1/2}$ $cm^{3/2}$ s^{-2}	magnetomotive force
unit pole	pole	dyn / Oe	$g^{1/2}$ $cm^{3/2}$ s^{-1}	magnetic pole strength
stathenry	statH	erg / $statA^2$	s^2 cm^{-1}	induction
lumen	lm	cd sr	cd sr	luminous flux
phot	ph	lm / cm^2	cd sr cm^{-2}	illuminance
stilb	sb	cd / cm^2	cd cm^{-2}	luminance
lambert	Lb	$1/\pi$ cd / cm^2	cd cm^{-2}	luminance
kayser	K	1 / cm	cm^{-1}	wave number
becquerel	Bq	s^{-1}	s^{-1}	radioactivity
katal	kat	mol / s	mol s^{-1}	catalytic activity

5.3 Gaussian Equations of Electromagnetism

Both the differential (left column) and integral (right column) forms of Maxwell's equations are shown. Here **D** is the electric displacement vector; **B** is the magnetic induction vector; **E** is the electric field vector; **H** is the magnetic intensity vector; **J** is the current density vector; ρ is the electric charge density; q is the electric charge; Φ_B is the magnetic induction flux; and Φ_D is the electric displacement flux.

Maxwell's Equations

$$\nabla \cdot \mathbf{D} = 4\pi\rho \qquad \oint_S \mathbf{D} \cdot d\mathbf{A} = 4\pi q$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \oint_S \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \qquad \oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{1}{c}\frac{d\Phi_B}{dt}$$

$$\nabla \times \mathbf{H} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} \qquad \oint_C \mathbf{H} \cdot d\mathbf{l} = \frac{4\pi}{c}I + \frac{1}{c}\frac{d\Phi_D}{dt}$$

Coulomb's Law

This gives the force F between two point charges q_1 and q_2, separated by a distance r.

$$F = \frac{q_1 q_2}{r^2}$$

Lorentz Force

The first equation is the conventional Lorentz force on an electric charge q in electric and magnetic fields; the second equation is the analogous force on a magnetic monopole of pole strength q^*.

$$\mathbf{F} = q\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right) \qquad \mathbf{F} = q^*\left(\mathbf{B} - \frac{\mathbf{v}}{c}\times\mathbf{E}\right)$$

Constitutive Relations

$$\mathbf{E} = \mathbf{D} - 4\pi\mathbf{P}$$

$$\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$$

Chapter 6

Heaviside-Lorentz Units

6.1 Heaviside-Lorentz Base Units

Name	Symbol	Quantity
centimeter	cm	length
gram	g	mass
second	s	time
kelvin	K	temperature
mole	mol	amount of substance
candela	cd	luminous intensity

6.2 Heaviside-Lorentz Derived Units

This table shows each of the Heaviside-Lorentz derived units expressed in terms of base units. Heaviside-Lorentz units do not appear to have ever been given proper names; they are indicated here with the prefix *hlu-* replacing the *stat-* or *ab-* prefix in the corresponding Gaussian unit name.

Name	Symbol	Definition	Base Units	Quantity
radian	rad	m / m	—	plane angle
steradian	sr	m^2 / m^2	—	solid angle
dyne	dyn	g cm s^{-2}	g cm s^{-2}	force
erg	erg	dyn cm	g cm^2 s^{-2}	energy
hlu watt	hluW	erg / s	g cm^2 s^{-3}	power
barye	ba	dyn / cm^2	g cm^{-1} s^{-2}	pressure
galileo	Gal	cm / s^2	cm s^{-2}	acceleration
poise	P	g / (cm s)	g cm^{-1} s^{-1}	dynamic viscosity
stokes	St	cm^2 / s	cm^2 s^{-1}	kinematic viscosity
hertz	Hz	s^{-1}	s^{-1}	frequency
hlu coulomb	hluC		$g^{1/2}$ $cm^{3/2}$ s^{-1}	electric charge
hlu ampere	hluA	hluC / s	$g^{1/2}$ $cm^{3/2}$ s^{-2}	electric current
hlu volt	hluV	erg / hluC	$g^{1/2}$ $cm^{1/2}$ s^{-1}	electric potential
hlu ohm	hluΩ	hluV / hluA	s cm^{-1}	electrical resistance
hlu farad	hluF	hluC / hluV	cm	capacitance
hlu maxwell	hluMx	hluV cm	$g^{1/2}$ $cm^{3/2}$ s^{-1}	magnetic flux
hlu gauss	hluG	hluMx / cm^2	$g^{1/2}$ $cm^{-1/2}$ s^{-1}	magnetic induction
hu oersted	hluOe	hluA s / cm^2	$g^{1/2}$ $cm^{-1/2}$ s^{-1}	magnetic intensity
hlu gilbert	hluGb	hluA	$g^{1/2}$ $cm^{3/2}$ s^{-2}	magnetomotive force
hlu unit pole	hlupole	dyn / hluOe	$g^{1/2}$ $cm^{3/2}$ s^{-1}	magnetic pole strength
hlu henry	hluH	erg / $hluA^2$	s^2 cm^{-1}	induction
lumen	lm	cd sr	cd sr	luminous flux
phot	ph	lm / cm^2	cd sr cm^{-2}	illuminance
stilb	sb	cd / cm^2	cd cm^{-2}	luminance
lambert	Lb	$1/\pi$ cd / cm^2	cd cm^{-2}	luminance
kayser	K	1 / cm	cm^{-1}	wave number
becquerel	Bq	s^{-1}	s^{-1}	radioactivity
katal	kat	mol / s	mol s^{-1}	catalytic activity

6.3 Heaviside-Lorentz Equations of Electromagnetism

Maxwell's Equations

Both the differential (left column) and integral (right column) forms of Maxwell's equations are shown. Here $\mathbf{D}$ is the electric displacement vector; $\mathbf{B}$ is the magnetic induction vector; $\mathbf{E}$ is the electric field vector; $\mathbf{H}$ is the magnetic intensity vector; $\mathbf{J}$ is the current density vector; ρ is the electric charge density; q is the electric charge; Φ_B is the magnetic induction flux; and Φ_D is the electric displacement flux.

$$\nabla \cdot \mathbf{D} = \rho \qquad \oint_S \mathbf{D} \cdot d\mathbf{A} = q$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \oint_S \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \qquad \oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{1}{c}\frac{d\Phi_B}{dt}$$

$$\nabla \times \mathbf{H} = \frac{1}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{D}}{\partial t} \qquad \oint_C \mathbf{H} \cdot d\mathbf{l} = \frac{1}{c}I + \frac{1}{c}\frac{d\Phi_D}{dt}$$

Coulomb's Law

This gives the force F between two point charges q_1 and q_2, separated by a distance r.

$$F = \frac{1}{4\pi}\frac{q_1 q_2}{r^2}$$

Lorentz Force

The first equation is the conventional Lorentz force on an electric charge q in electric and magnetic fields; the second equation is the analogous force on a magnetic monopole of pole strength q^*.

$$\mathbf{F} = q(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}) \qquad \mathbf{F} = q^*(\mathbf{B} - \frac{\mathbf{v}}{c} \times \mathbf{E})$$

Constitutive Relations

$$\mathbf{E} = \mathbf{D} - \mathbf{P}$$

$$\mathbf{B} = \mathbf{H} + \mathbf{M}$$

Chapter 7

Units of Physical Quantities

Table 7-1. Units of physical quantities.

Quantity	SI	Gaussian	Electrostatic	Electromagnetic	Heaviside-Lorentz
Absorbed dose	Gy	erg g^{-1}	erg g^{-1}	erg g^{-1}	erg g^{-1}
Acceleration	m s^{-2}	cm s^{-2}	cm s^{-2}	cm s^{-2}	cm s^{-2}
Amount of substance	mol	mol	mol	mol	mol
Angle (plane)	rad	rad	rad	rad	rad
Angle (solid)	sr	sr	sr	sr	sr
Angular acceleration	rad s^{-2}	rad s^{-2}	rad s^{-2}	rad s^{-2}	rad s^{-2}
Angular momentum	N m s	dyn cm s	dyn cm s	dyn cm s	dyn cm s
Angular velocity	rad s^{-1}	rad s^{-1}	rad s^{-1}	rad s^{-1}	rad s^{-1}
Area	m^2	cm^2	cm^2	cm^2	cm^2
Bulk modulus	Pa	ba	ba	ba	ba
Catalytic activity	kat	kat	kat	kat	kat
Coercivity	A m^{-1}	Oe	statA cm^{-1}	Oe	hluOe
Crackle	m s^{-5}	cm s^{-5}	cm s^{-5}	cm s^{-5}	cm s^{-5}
Density	kg m^{-3}	g cm^{-3}	g cm^{-3}	g cm^{-3}	g cm^{-3}
Distance	m	cm	cm	cm	cm
Dose equivalent	Sv	erg g^{-1}	erg g^{-1}	erg g^{-1}	erg g^{-1}
Elastic modulus	N m^{-2}	dyn cm^{-2}	dyn cm^{-2}	dyn cm^{-2}	dyn cm^{-2}
Electric capacitance	F	statF	statF	abF	hluF
Electric charge	C	statC	statC	abC	hluC
Electric conductance	S	statΩ^{-1}	statΩ^{-1}	abΩ^{-1}	hluΩ^{-1}
Electric conductivity	S m^{-1}	statΩ^{-1} cm^{-1}	statΩ^{-1} cm^{-1}	abΩ^{-1} cm^{-1}	statΩ^{-1} cm^{-1}
Electric current	A	statA	statA	abA	hluA
Electric dipole moment	C m	statC cm	statC cm	abA cm	hluC cm
Electric displacement (D)	C m^{-2}	statC cm^{-2}	statC cm^{-2}	abC cm^{-2}	
Electric elastance	F^{-1}	statF^{-1}	statF^{-1}	abF^{-1}	hluF^{-1}
Electric field (E)	V m^{-1}	statV cm^{-1}	statV cm^{-1}	abV cm^{-1}	hluV cm^{-1}
Electric flux	V m	statV cm	statV cm	abV cm	hluV cm
Electric permittivity	F m^{-1}	—	statF cm^{-1}	abF cm^{-1}	—
Electric polarization (P)	C m^{-2}	statC cm^{-2}	statC cm^{-2}	abC cm^{-2}	hluC cm^{-2}
Electric potential	V	statV	statV	abV	hluV
Electric resistance	Ω	statΩ	statΩ	abΩ	hluΩ
Electric resistivity	Ω m	statΩ cm	statΩ cm	abΩ cm	hluΩ cm

Table 7-1 (cont'd). Units of physical quantities.

Quantity	SI	Gaussian	Electrostatic	Electromagnetic	Heaviside-Lorentz
Energy	J	erg	erg	erg	erg
Enthalpy	J	erg	erg	erg	erg
Entropy	J K^{-1}	erg K^{-1}	erg K^{-1}	erg K^{-1}	erg K^{-1}
Force	N	dyn	dyn	dyn	dyn
Frequency	Hz	Hz	Hz	Hz	Hz
Heat	J	erg	erg	erg	erg
Heat capacity	J K^{-1}	erg K^{-1}	erg K^{-1}	erg K^{-1}	erg K^{-1}
Illuminance	lx	ph	ph	ph	ph
Impulse	N s	dyn s	dyn s	dyn s	dyn s
Inductance	H	statH	statH	abH	hluH
Jerk	m s^{-3}	cm s^{-3}	cm s^{-3}	cm s^{-3}	cm s^{-3}
Jounce	m s^{-4}	cm s^{-4}	cm s^{-4}	cm s^{-4}	cm s^{-4}
Latent heat	J kg^{-1}	erg g^{-1}	erg g^{-1}	erg g^{-1}	erg g^{-1}
Length	m	cm	cm	cm	cm
Luminance	cd m^{-2}	sb	sb	sb	sb
Luminous flux	lm	lm	lm	lm	lm
Luminous intensity	cd	cd	cd	cd	cd
Magnetic flux	Wb	Mx	statWb	Mx	hluMx
Magnetic induction (B)	T	G	statWb cm^{-2}	G	hluG
Magnetic intensity (H)	A m^{-1}	Oe	statA cm^{-1}	Oe	hluOe
Magnetic dipole moment (B conv.)	A m^2	pole cm		pole cm	hlupole cm
Magnetic dipole moment (H conv.)	Wb m	pole cm		pole cm	hlupole cm
Magnetic permeability	H m^{-1}	—	statH cm^{-1}	abH cm^{-1}	—
Magnetic permeance	H	s	statH	abH	
Magnetic pole strength (B conv.)	A m	unit pole		unit pole	hlupole
Magnetic pole strength (H conv.)	Wb	unit pole	statWb	unit pole	hlupole
Magnetic potential (scalar)	A	abA	statA	abA	hluA
Magnetic potential (vector)	T m	G cm	statWb cm^{-1}	G cm	hluG cm
Magnetic reluctance	H^{-1}	s^{-1}	statA $statWb^{-1}$	abA Mx^{-1}	
Magnetization (M)	A m^{-1}	Mx cm^{-2}			hluMx cm^{-2}
Magnetomotive force	A	Gb	statA	Gb	hluGb
Mass	kg	g	g	g	g
Memristance	Ω	statΩ	statΩ	abΩ	hluΩ
Molality	mol kg^{-1}	mol g^{-1}	mol g^{-1}	mol g^{-1}	mol g^{-1}
Molarity	mol m^{-3}	mol cm^{-3}	mol cm^{-3}	mol cm^{-3}	mol cm^{-3}
Moment of inertia	kg m^2	g cm^2	g cm^2	g cm^2	g cm^2
Momentum	N s	dyn s	dyn s	dyn s	dyn s
Pop	m s^{-6}	cm s^{-6}	cm s^{-6}	cm s^{-6}	cm s^{-6}
Power	W	statW	statW	statW	hluW
Pressure	Pa	ba	ba	ba	ba
Radioactivity	Bq	Bq	Bq	Bq	Bq
Remanence	T	G	statWb cm^{-2}	G	hluG
Retentivity	T	G	statWb cm^{-2}	G	hluG

Table 7-1 (cont'd). Units of physical quantities.

Quantity	SI	Gaussian	Electrostatic	Electromagnetic	Heaviside-Lorentz
Shear modulus	N m^{-2}	dyn cm^{-2}	dyn cm^{-2}	dyn cm^{-2}	dyn cm^{-2}
Snap	m s^{-4}	cm s^{-4}	cm s^{-4}	cm s^{-4}	cm s^{-4}
Specific heat	J K^{-1} kg^{-1}	erg K^{-1} g^{-1}	erg K^{-1} g^{-1}	erg K^{-1} g^{-1}	erg K^{-1} g^{-1}
Strain	—	—	—	—	—
Stress	N m^{-2}	dyn cm^{-2}	dyn cm^{-2}	dyn cm^{-2}	dyn cm^{-2}
Temperature	K	K	K	K	K
Tension	N	dyn	dyn	dyn	dyn
Time	s	s	s	s	s
Torque	N m	dyn cm	dyn cm	dyn cm	dyn cm
Velocity	m s^{-1}	cm s^{-1}	cm s^{-1}	cm s^{-1}	cm s^{-1}
Viscosity (dynamic)	Pa s	P	P	P	P
Viscosity (kinematic)	m^2 s^{-1}	St	St	St	St
Volume	m^3	cm^3	cm^3	cm^3	cm^3
Wave number	m^{-1}	kayser	kayser	kayser	kayser
Weight	N	dyn	dyn	dyn	dyn
Work	J	erg	erg	erg	erg
Young's modulus	N m^{-2}	dyn cm^{-2}	dyn cm^{-2}	dyn cm^{-2}	dyn cm^{-2}

Chapter 8

Formula Conversion Table

This table may be used to convert any electromagnetic formula between Gaussian, SI, electrostatic, electromagnetic, and Heaviside-Lorentz units; simply make the substitutions indicated. To simplify the results with SI units, you may use $\varepsilon_0 \mu_0 = 1/c^2$.

Note that in SI units there are two conventions for magnetic pole strength and dipole moment: one based on the B field (pole strength in A m), and one based on the H field (pole strength in Wb). Both conventions are given here.

As an example, given Coulomb's law in Gaussian units ($F = q_1 q_2 / r^2$), we use the table to create the corresponding equation in SI units: $F = (q_1/\sqrt{4\pi\varepsilon_0})(q_2/\sqrt{4\pi\varepsilon_0})/r^2 = (1/4\pi\varepsilon_0)\, q_1 q_2 / r^2$.

Quantity	Gaussian	SI	Electrostatic	Electromagnetic	Heaviside-Lorentz
Electric field	$\mathbf{E}$	$\sqrt{4\pi\varepsilon_0}\,\mathbf{E}$	$\mathbf{E}$	$\mathbf{E}/c$	$\sqrt{4\pi}\mathbf{E}$
Electric potential	V	$\sqrt{4\pi\varepsilon_0}\,V$	V	V/c	$\sqrt{4\pi}V$
Electric displacement	$\mathbf{D}$	$\sqrt{4\pi/\varepsilon_0}\,\mathbf{D}$	$\mathbf{D}$	$c\mathbf{D}$	$\sqrt{4\pi}\mathbf{D}$
Electric charge	q	$q/\sqrt{4\pi\varepsilon_0}$	q	cq	$q/\sqrt{4\pi}$
Electric charge density	ρ	$\rho/\sqrt{4\pi\varepsilon_0}$	ρ	$c\rho$	$\rho/\sqrt{4\pi}$
Electric current	I	$I/\sqrt{4\pi\varepsilon_0}$	I	cI	$I/\sqrt{4\pi}$
Electric current density	$\mathbf{J}$	$\mathbf{J}/\sqrt{4\pi\varepsilon_0}$	J	cJ	$J/\sqrt{4\pi}$
Electric polarization	$\mathbf{P}$	$\mathbf{P}/\sqrt{4\pi\varepsilon_0}$	$\mathbf{P}$	$c\mathbf{P}$	$\mathbf{P}/\sqrt{4\pi}$
Electric dipole moment	$\mathbf{p}$	$\mathbf{p}/\sqrt{4\pi\varepsilon_0}$	$\mathbf{p}$	$c\mathbf{p}$	$\mathbf{p}/\sqrt{4\pi}$
Magnetic induction	$\mathbf{B}$	$\sqrt{4\pi/\mu_0}\,\mathbf{B}$	$c\mathbf{B}$	$\mathbf{B}$	$\sqrt{4\pi}\mathbf{B}$
Magnetic flux	Φ_B	$\sqrt{4\pi/\mu_0}\,\Phi_B$	$c\Phi_B$	Φ_B	$\sqrt{4\pi}\,\Phi_B$
Magnetic vector potential	$\mathbf{A}$	$\sqrt{4\pi/\mu_0}\,\mathbf{A}$	$c\mathbf{A}$	$\mathbf{A}$	$\sqrt{4\pi}\mathbf{A}$
Magnetic scalar potential	φ^*	$\sqrt{4\pi\mu_0}\,\varphi^*$	φ^*/c	φ^*	$\sqrt{4\pi}\varphi^*$
Magnetic intensity	$\mathbf{H}$	$\sqrt{4\pi\mu_0}\,\mathbf{H}$	$\mathbf{H}/c$	$\mathbf{H}$	$\sqrt{4\pi}\mathbf{H}$
Magnetomotive force	mmf	$\sqrt{4\pi\mu_0}$ mmf	mmf$/c$	mmf	$\sqrt{4\pi}$mmf

Table 8-1 (cont'd). SI / Gaussian Formula Conversion Table.

Quantity	Gaussian	SI	Electrostatic	Electromagnetic	Heaviside-Lorentz
Magnetic pole strength (B conv.)	q^*	$\sqrt{\mu_0/4\pi}\, q^*$	q^*/c	q^*	$q^*/\sqrt{4\pi}$
Magnetic moment (B conv.)	$\mathbf{m}$	$\sqrt{\mu_0/4\pi}\, \mathbf{m}$	$\mathbf{m}/c$	$\mathbf{m}$	$\mathbf{m}\sqrt{4\pi}$
Magnetization	$\mathbf{M}$	$\sqrt{\mu_0/4\pi}\, \mathbf{M}$	$\mathbf{M}/c$	$\mathbf{M}$	$\mathbf{M}\sqrt{4\pi}$
Magnetic pole strength (H conv.)	Q^*	$Q^*/\sqrt{4\pi\mu_0}$	$c\,Q*$	Q^*	$Q^*/\sqrt{4\pi}$
Magnetic moment (H conv.)	$\mathbf{d}$	$\mathbf{d}/\sqrt{4\pi\mu_0}$	$c\mathbf{d}$	$\mathbf{d}$	$\mathbf{d}/\sqrt{4\pi}$
Electric permittivity	ε	$\varepsilon/\varepsilon_0$	ε	$c^2\varepsilon$	ε
Magnetic permeability	μ	μ/μ_0	$c^2\mu$	μ	μ
Electric susceptibility	χ_e	$\chi_e/4\pi$	χ_e	χ_e	$\chi_e/4\pi$
Magnetic susceptibility	χ_m	$\chi_m/4\pi$	χ_m	χ_m	$\chi_m/4\pi$
Conductivity	σ	$\sigma/4\pi\varepsilon_0$	$c\sigma$	$c^2\sigma$	$\sigma/4\pi$
Conductance	S	$S/4\pi\varepsilon_0$	cS	c^2S	$S/4\pi$
Capacitance	C	$C/4\pi\varepsilon_0$	C	c^2C	$C/4\pi$
Resistivity	ρ	$4\pi\varepsilon_0\,\rho$	ρ/c	ρ/c^2	$4\pi\rho$
Resistance	R	$4\pi\varepsilon_0\,R$	R/c	R/c^2	$4\pi R$
Inductance	L	$4\pi\varepsilon_0\,L$	L/c	L/c^2	$4\pi L$
Memristance	M	$4\pi\varepsilon_0\,M$	M/c	M/c^2	$4\pi M$
Magnetic reluctance	$\mathcal{R}$	$\mu_0\,\mathcal{R}$	$\mathcal{R}/c^2$	$\mathcal{R}$	$\mathcal{R}$

Chapter 9

Unit Conversion Tables

Time

1 day = 24 hours = 1440 minutes = 86400 seconds
1 hour = 60 minutes = 3600 seconds
1 year = 31 557 600 seconds $\approx \pi \times 10^7$ seconds

Length

1 mile = 8 furlongs = 80 chains = 320 rods = 1760 yards = 5280 feet = 1.609344 km
1 yard = 3 feet = 36 inches = 0.9144 meter
1 foot = 12 inches = 0.3048 meter
1 inch = 2.54 cm
1 nautical mile = 1852 meters = 1.15077944802354 miles
1 fathom = 6 feet
1 parsec = 3.26156376188 light-years = 206264.806245 AU = $3.08567756703 \times 10^{16}$ meters
1 ångström = 0.1 nm = 10^5 fermi = 10^{-10} meter

Mass

1 kilogram = 2.20462262184878 lb
1 pound = 16 oz = 0.45359237 kg
1 slug = 32.1740485564304 lb = 14.5939029372064 kg
1 short ton = 2000 lb
1 long ton = 2240 lb
1 metric ton = 1000 kg

Velocity

15 mph = 22 fps
1 mph = 0.44704 m/s
1 knot = 1.15077944802354 mph = 0.514444444444444 m/s

Area

1 acre = 43560 ft^2 = 4840 yd^2 = 4046.8564224 m^2
1 $mile^2$ = 640 acres = 2.589988110336 km^2
1 are = 100 m^2
1 hectare = 10^4 m^2 = 2.47105381467165 acres

Volume

1 liter = 1 dm^3 = 10^{-3} m^3 $\approx$ 1 quart
1 m^3 = 1000 liters
1 cm^3 = 1 mL
1 ft^3 = 1728 in^3 = 7.48051948051948 gal = 28.316846592 liters
1 gallon = 231 in^3 = 4 quarts = 8 pints = 16 cups = 3.785411784 liters
1 cup = 8 floz = 16 tablespoons = 48 teaspoons
1 tablespoon = 3 teaspoons = 4 fluidrams
1 dry gallon = 268.8025 in^3 = 4.40488377086 liters
1 imperial gallon = 4.54609 liters
1 bushel = 4 pecks = 8 dry gallons

Density

1 g/cm^3 = 1000 kg/m^3 = 8.34540445201933 lb/gal = 1.043175556502416 lb/pint

Force

1 lbf = 4.44822161526050 newtons = 32.1740485564304 poundals
1 newton = 10^5 dynes

Energy

1 calorie = 4.1868 joules
1 BTU = 1055.05585262 joules
1 ft-lb = 1.35581794833140 joules
1 kW-hr = 3.6 MJ
1 eV = $1.602176565 \times 10^{-19}$ joules
1 joule = 10^7 ergs

Power

1 horsepower = 745.69987158227022 watts
1 statwatt = 1 abwatt = 1 erg/s = 10^{-7} watt

Angle

$$\text{rad} = \text{deg} \times \frac{\pi}{180} \qquad \text{deg} = \text{rad} \times \frac{180}{\pi}$$

1° = 60 arcminutes = 3600 arcseconds
= 216,000 arcthirds = 12,960,000 arcfourths

Temperature

$°C = (°F-32) \times \frac{5}{9}$ $°F = \left(°C \times \frac{9}{5}\right) + 32$
$K = °C + 273.15$
$°R = °F + 459.67$

Pressure

1 atm = 101325 Pa = 1.01325 bar = 1013.25 millibar = 760 torr
= 760 mmHg = 29.9212598425197 inHg = 14.6959487755134 psi
= 2116.21662367394 lb/ft^2 = 1.05810831183697 ton/ft^2
= 1013250 dyne/cm^2 = 1013250 barye

Electric Charge

1 statcoulomb = 1 franklin = $3.335640951981520 \times 10^{-10}$ coulomb
1 abcoulomb = 10 coulombs
1 hlu coulomb = $9.409669397816477 \times 10^{-11}$ coulomb

Electric Current

1 statampere = $3.335640951981520 \times 10^{-10}$ ampere
1 abampere = 1 biot = 10 amperes
1 hlu ampere = $9.409669397816477 \times 10^{-11}$ ampere

Electric Potential

1 statvolt = 299.792458 volts
1 abvolt = 10^{-8} volt
1 hlu volt = 1062.736593309060 volts

Electrical Resistance

1 statohm = $8.9875517873681764 \times 10^{11}$ ohms
1 abohm = 10^{-9} ohm
1 hlu ohm = $1.129409066758147 \times 10^{13}$ ohms

Magnetism

1 statweber = 299.792458 webers
1 maxwell = 1 abweber = 10^{-8} weber
1 gauss = 10^{-4} tesla
1 oersted = $250/\pi$ (= 79.57747154594767) A/m
pole strength: 1 unit pole = 4π Mx = $4\pi \times 10^{-8}$ Wb, equiv. to 0.1 A m
magnetic dipole moment: 1 pole cm = 4π Mx cm = $4\pi \times 10^{-10}$ Wb m, equiv. to 10^{-3} A m^2

Chapter 10

Physical Constants

Table 10-1. Fundamental physical constants (CODATA 2010).

Description	Symbol	Value
Speed of light (vacuum)	c	2.99792458×10^{8} m/s
		$= 2.99792458 \times 10^{10}$ cm/s
Gravitational constant	G	6.67384×10^{-11} m^3 kg^{-1} s^{-2}
		$= 6.67384 \times 10^{-8}$ cm^3 g^{-1} s^{-2}
Elementary charge	e	$1.602176565 \times 10^{-19}$ C
		$= 4.803204401 \times 10^{-10}$ statC
		$= 1.602176565 \times 10^{-20}$ abC
		$= 1.702691627 \times 10^{-9}$ hluC
Electron mass	m_e	$9.10938291 \times 10^{-31}$ kg
		$= 9.10938291 \times 10^{-28}$ g
Proton mass	m_p	$1.672621777 \times 10^{-27}$ kg
		$= 1.672621777 \times 10^{-24}$ g
Neutron mass	m_n	$1.674927351 \times 10^{-27}$ kg
		$= 1.674927351 \times 10^{-24}$ g
Atomic mass unit (amu)	u	$1.660538921 \times 10^{-27}$ kg
		$= 1.660538921 \times 10^{-24}$ g
Planck constant	h	$6.62606957 \times 10^{-34}$ J s
		$= 6.62606957 \times 10^{-27}$ erg s
Planck constant $\div 2\pi$	$\hbar$	$1.054571726 \times 10^{-34}$ J s
		$= 1.054571726 \times 10^{-27}$ erg s
Boltzmann constant	k_B	$1.3806488 \times 10^{-23}$ J/K
		$= 1.3806488 \times 10^{-16}$ erg/K