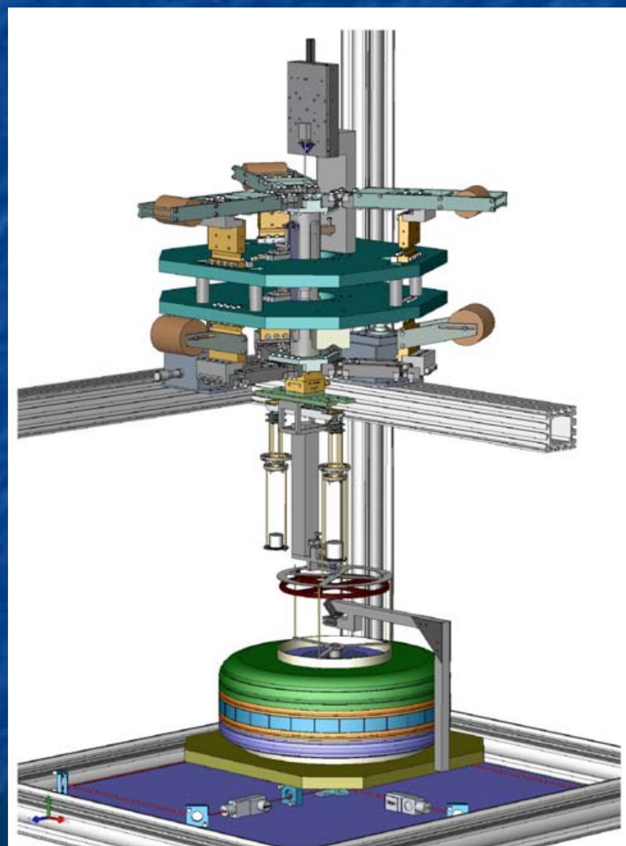
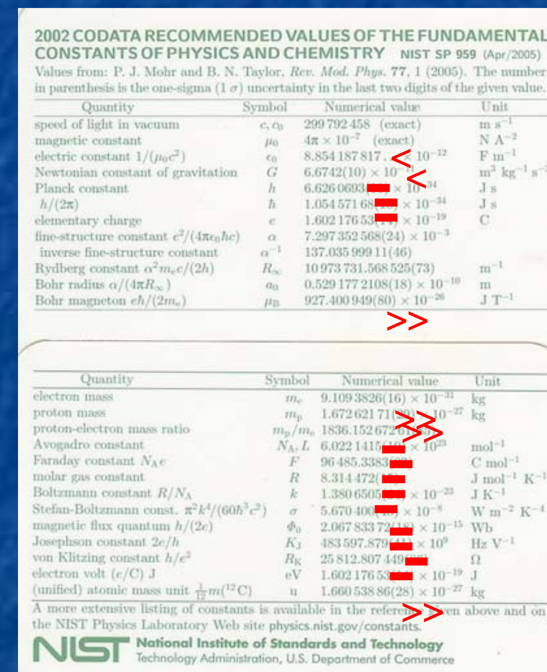
Proposed changes to the SI , their impact on fundamental constants and other SI units .



Planck constant, *h*,*e*
LNE



2002 CODATA RECOMMENDED VALUES OF THE FUNDAMENTAL CONSTANTS OF PHYSICS AND CHEMISTRY NIST SP 959 (Apr/2005)

Values from: P. J. Mohr and B. N. Taylor, *Rev. Mod. Phys.* 77, 1 (2005). The number in parenthesis is the one-sigma (1σ) uncertainty in the last two digits of the given value.

Quantity	Symbol	Numerical value	Unit
speed of light in vacuum	c, c_0	299 792 458 (exact)	$m\ s^{-1}$
magnetic constant	μ_0	$4\pi \times 10^{-7}$ (exact)	$N\ A^{-2}$
electric constant $1/(\mu_0 c^2)$	ϵ_0	8.854 187 817... $\times 10^{-12}$	$F\ m^{-1}$
Newtonian constant of gravitation	G	6.6742(10) $\times 10^{-11}$	$m^3\ kg^{-1}\ s^{-2}$
Planck constant	h	6.626 0693([illegible]) $\times 10^{-34}$	J s
$h/(2\pi)$	$\hbar$	1.054 571 68([illegible]) $\times 10^{-34}$	J s
elementary charge	e	1.602 176 53([illegible]) $\times 10^{-19}$	C
fine-structure constant $e^2/(4\pi\epsilon_0\hbar c)$	α	7.297 352 568(24) $\times 10^{-3}$	
inverse fine-structure constant	α^{-1}	137.035 999 11(46)	
Rydberg constant $\alpha^2 m_e c/(2h)$	R_∞	10 973 731.568 525(73)	m^{-1}
Bohr radius $\alpha/(4\pi R_\infty)$	a_0	0.529 177 2108(18) $\times 10^{-10}$	m
Bohr magneton $e\hbar/(2m_e)$	μ_B	927.400 949(80) $\times 10^{-26}$	$J\ T^{-1}$

Quantity	Symbol	Numerical value	Unit
electron mass	m_e	9.109 3826(16) $\times 10^{-31}$	kg
proton mass	m_p	1.672 621 71([illegible]) $\times 10^{-27}$	kg
proton-electron mass ratio	m_p/m_e	1836.152 672 [illegible]	
Avogadro constant	N_A, L	6.022 1415([illegible]) $\times 10^{23}$	mol^{-1}
Faraday constant $N_A e$	F	96 485.3383([illegible])	$C\ mol^{-1}$
molar gas constant	R	8.314 472([illegible])	$J\ mol^{-1}\ K^{-1}$
Boltzmann constant R/N_A	k	1.380 6505([illegible]) $\times 10^{-23}$	$J\ K^{-1}$
Stefan-Boltzmann const. $\pi^2 k^4/(60\hbar^3 c^2)$	σ	5.670 400([illegible]) $\times 10^{-8}$	$W\ m^{-2}\ K^{-4}$
magnetic flux quantum $h/(2e)$	Φ_0	2.067 833 72([illegible]) $\times 10^{-15}$	Wb
Josephson constant $2e/h$	K_J	483 597.879([illegible]) $\times 10^{9}$	$Hz\ V^{-1}$
von Klitzing constant h/e^2	R_K	25 812.807 449([illegible])	Ω
electron volt (e/C) J	eV	1.602 176 53([illegible]) $\times 10^{-19}$	J
(unified) atomic mass unit $\frac{1}{12}m(^{12}C)$	u	1.660 538 86(28) $\times 10^{-27}$	kg

A more extensive listing of constants is available in the references given above and on the NIST Physics Laboratory Web site physics.nist.gov/constants.

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Fundamental Constants

Edwin Williams
LNE, Guest Scientist
& NIST

CCM is asking:

- What system is best for the CCM and your metrology Community?
  The new SI in which we scale our system by fixing the values of *e*, *h*, N_A and *k* provides:
  - A system that is favorable to the mass community.
    - Agreement with other measurements of *h* and N_A.
  - A system more stable over time and more suitable for the expression of the values of the fundamental constants. (P. Mohr)
- What is needed to implement the new system?
  - Educate your community.
  - Implement the changes required to be consistent with new values of *h* and N_A .
- When? 2011 If 1ppm discrepancy resolved.
- Atomic mass and quantum electric standards are more stable, long term, than macroscopic mass standards

What is the purpose of SI

- Provide a basis for a practical measurement system so that both science and industry can prosper
- We are being asked to simply choose the scales against which all measurements are made
  - We still have the same metric system but it won’t drift and the scales will be clearer (have less uncertainty)

Scientists can only disprove theories never prove them.

- The SI assumes that our present knowledge is valid but it is understood that the sciences upon which it is based must be tested.
- The SI simply provides a system where we can compare results from around the world.
- The adjustment of the fundamental constants is the most stringent test we make of the system.
- Defining e, h, N_A and k make it easier for everyone to see the points of disagreement.
- The SI must adjust as new theories become "present knowledge".
  - JJ and QHE are driving the proposed redefinition.

Example:

- Alpha, the fine-stucture constant

$$\alpha^{-1} = \frac{2h}{\mu_o c e^2} = \left[\frac{2i}{\mu_o c} \left(\mathrm{R_H} \right) \right]$$

100 times less

Avogadro constant from *h* & *h*/*m*(X)

F. Biraben, et al.
Laboratoire Kastler Brossel
Laoratoire National de Metrologie et d'Essais
Institut National de Metrologie,CNAM

$$N_A = \left\{ \frac{K_J^2 R_K g^{(w)}}{4} \right\} \left\{ \frac{h}{m(^{87}\mathrm{Rb}) g^{(a)}} \right\} \left\{ \frac{g^{(a)}}{g^{(w)}} \right\} A_r(^{87}\mathrm{Rb}) M_u$$

Present

$$N_A = \left\{ \frac{1}{h} \right\} \left\{ \frac{c\alpha^2}{2R_\infty} \right\} A_r(m_e) M_u$$

Quantum based systems

1998 codata

From 2001

Relative std. uncert. x 10^{-9}

Constant	Define Kg IPK	Define Kg N_A or m_u	Define Kg h	Define V 2e/h
IPK	exact	79 (IPK_{01})	78 (IPK_{01})	78 (IPK_{01})
N_A	79	exact	8	5
h	78	8	exact	4
e	39	4	2	4
m_e	79	2	8	5
2e/h	39 (K_{J-90})	3	2	exact
m_p	79	0.35	8	5
m_u	79 (amu)	exact	8 (amu)	5 (amu)

( ) Indicate an additional system or “representation”

Metrologia **42** (2005). _ Ian Mills, Peter Mohr, Terry Quinn, Barry Taylor, and Ed Williams
"Redefinition of the kilogram: A decision whose time has come"

If we define a quantum kilogram today using CODATA 2002

Quantum based system
Relative std. uncert. x 10^{-9}

Constant	Define *m(K)*	Define u, e, N_A, k	Define h, e, N_A, k
m(K)	exact	170 (IPK_{2011}) (>20)	170 (IPK_{2011}) (>20)
h	170	1.4	exact
N_A	170	exact	exact
e	85	exact	exact
m_e	170	0.44	1.4
$2e/h$	85 (K_{J-90})	1.4 (K_{J-90})	exact
m_p	170	0.13	1.4
u, m_u	170 (amu)	exact (amu)	1.4 (amu)
h/e^2	.7(R_{K90})	1.4 (R_{K90})	exact
F	86	exact	exact
J in eV	85	exact	exact

( ) Indicate an additional system or "representation"

Redefining the kilogram is <u>win-win</u> for centuries into the future.

SI defined by fixing the values of a set of constants

The International System of Units, the SI, is the system of units scaled so that the

(1) ground state hyperfine splitting transition frequency of the cesium 133 atom □$\Delta\nu(^{133}Cs)_{hfs}$ is 9 192 631 770 hertz,

(2) speed of light in vacuum c_0 is 299 792 458 meters per second,

(3) Planck constant h is 6.626 069 3 x 10^{-34} joule second,

$m(K) = 1$ kg $(1 \pm 2 \times 10^{-8})$

(4) elementary charge e is 1.602 176 53 x 10^{-19} coulomb,

$\mu_0 = 4\pi \times 10^{-7}$ N/A$^{-2}(1 \pm 7 \times 10^{-10})$

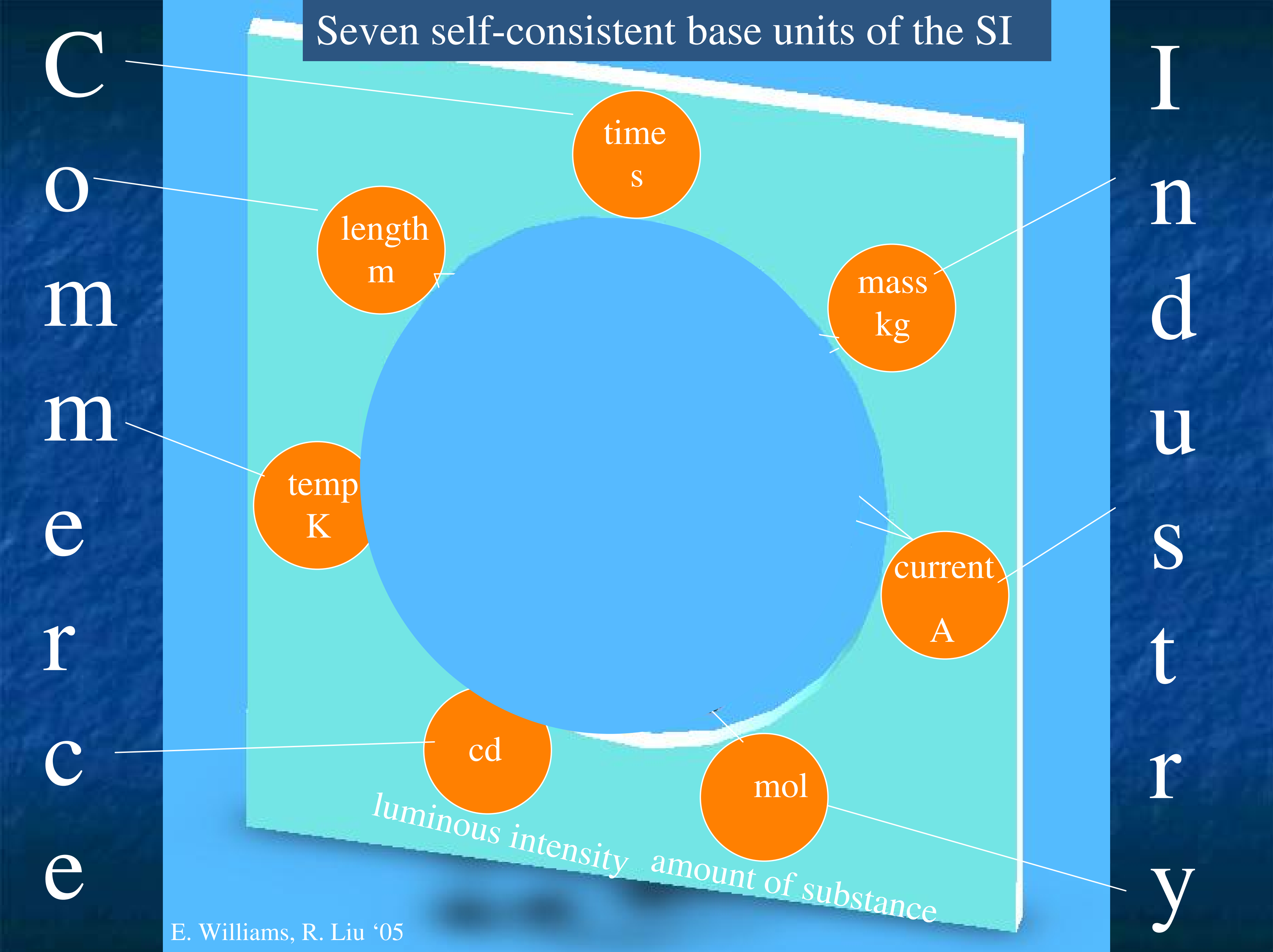
(5) Boltzmann constant k is 1.380 650 5 x 10^{-23} joules per kelvin,

Triple point H_2O =273.16 K $(1 \pm 2 \times 10^{-6})$

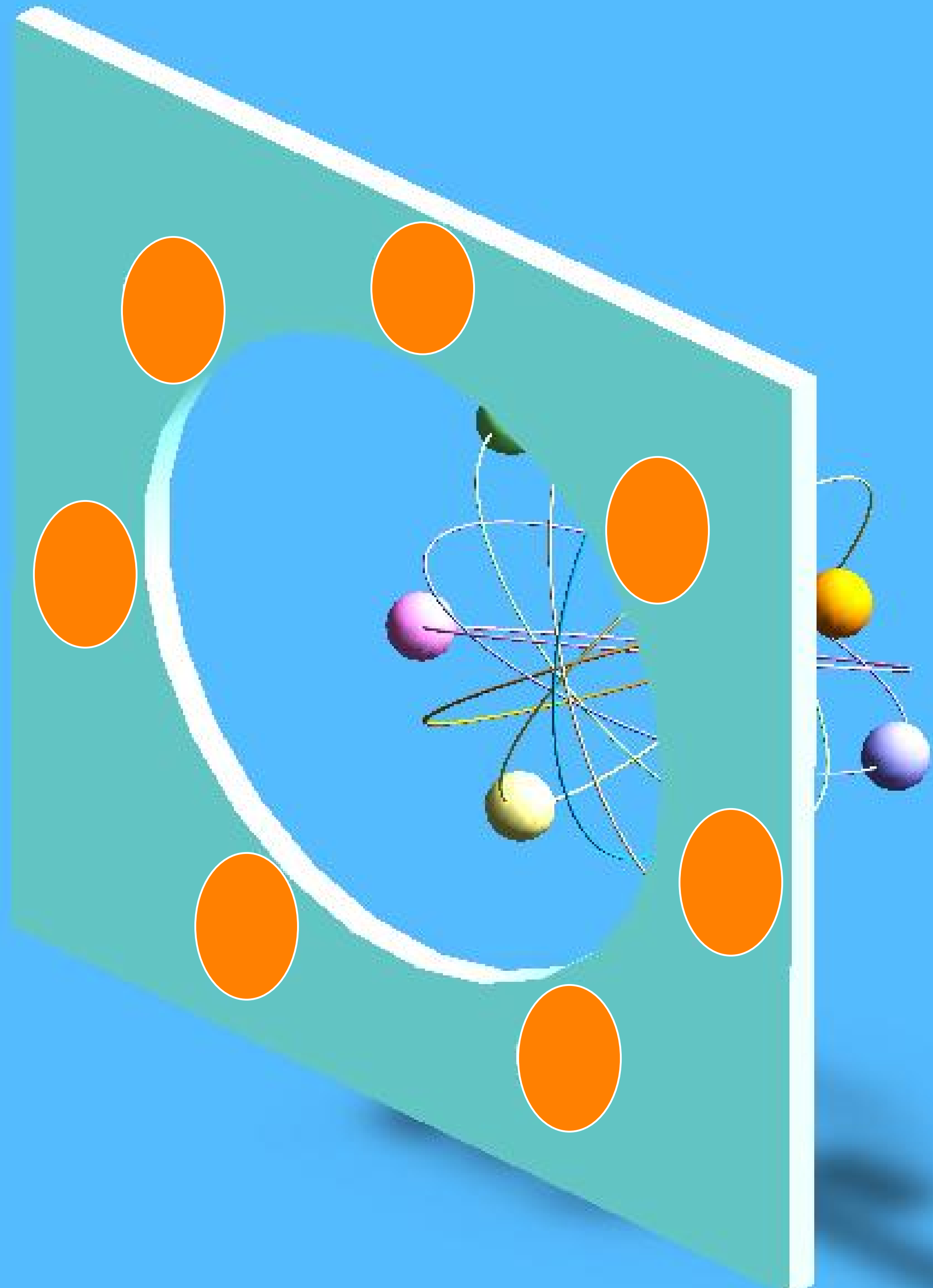
(6) Avogadro constant N_A is 6.022 141 5 x 10^{23} per mole and

Mole of C_{12} = 12 g $(1 \pm 1.4 \times 10^{-9})$

(7) spectral luminous efficacy of monochromatic radiation of frequency 540 x 10^{12} hertz $K(\lambda_{555})$ is 683 lumens per watt.

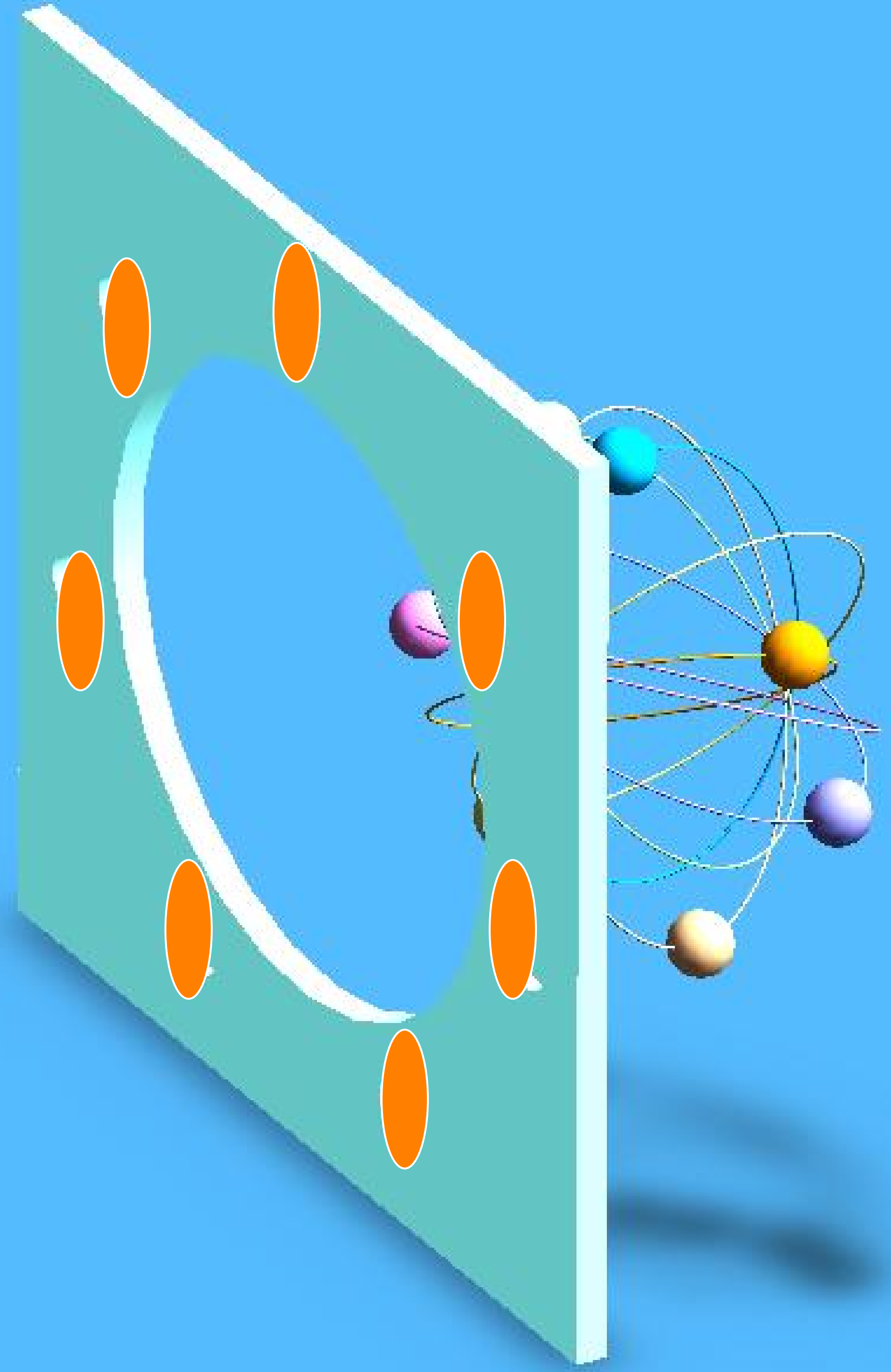

Seven self-consistent base units of the SI
Commerce
Industry
time
s
length
m
mass
kg
temp
K
current
A
cd
mol
luminous intensity
amount of substance
E. Williams, R. Liu '05

Commerce



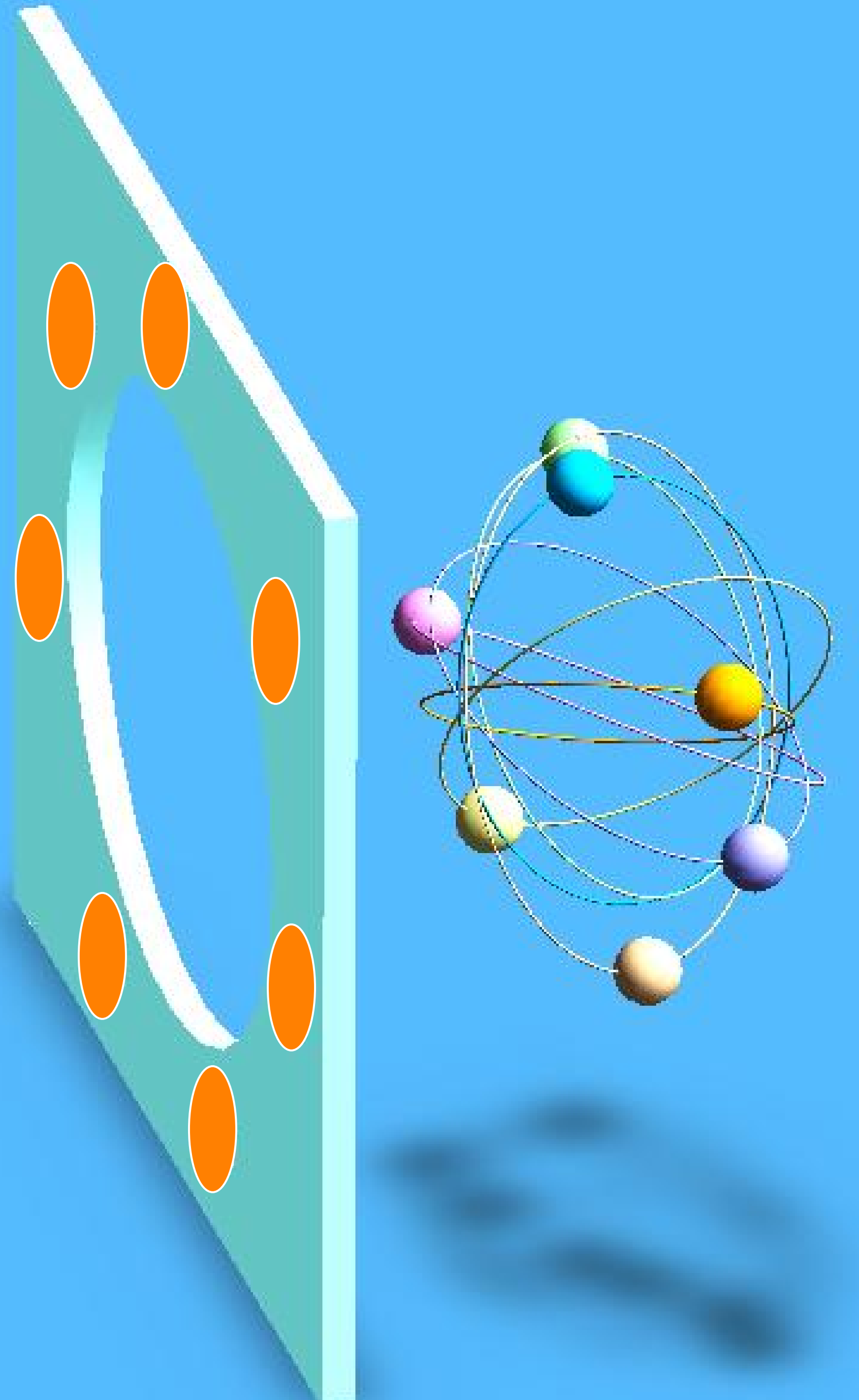
Industry

Commerce



Industbr

Commerce



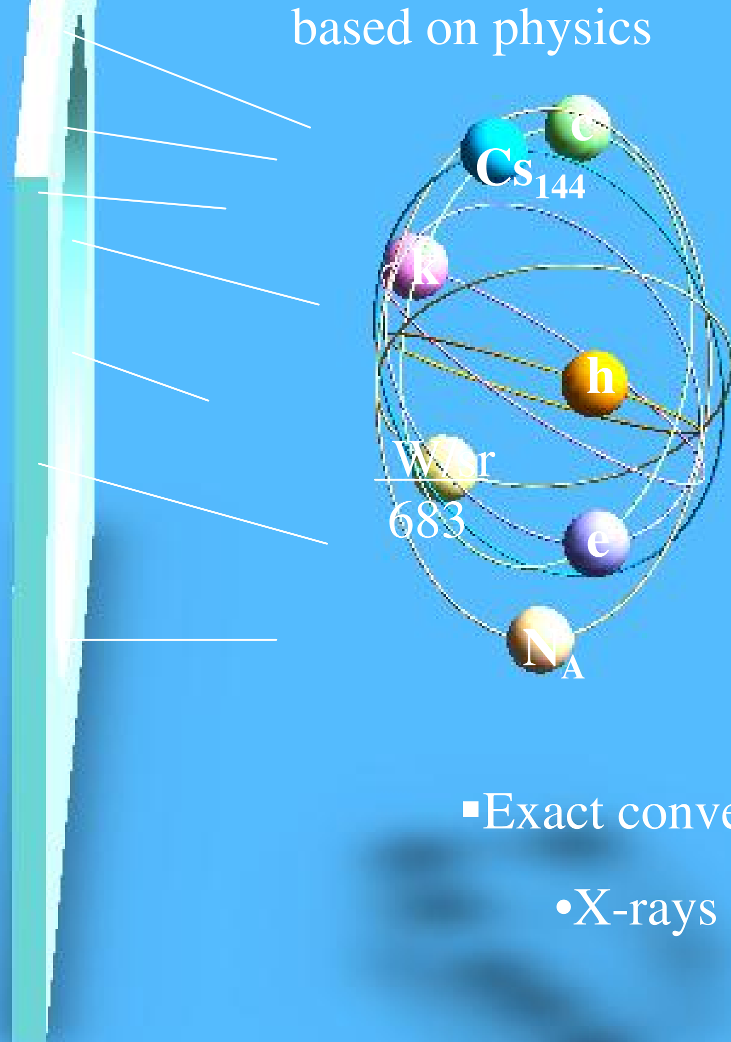
Industry

E. Williams, R. Liu ‘05

C o m m e r c e

- Much better fundamental constants
  - Mass of atoms connected to h

Seven self-consistent constants based on physics



- Direct SI tie to constants
  - Atomic clocks
  - Josephson volt
  - QH Resistance
  - Temperature via *k*

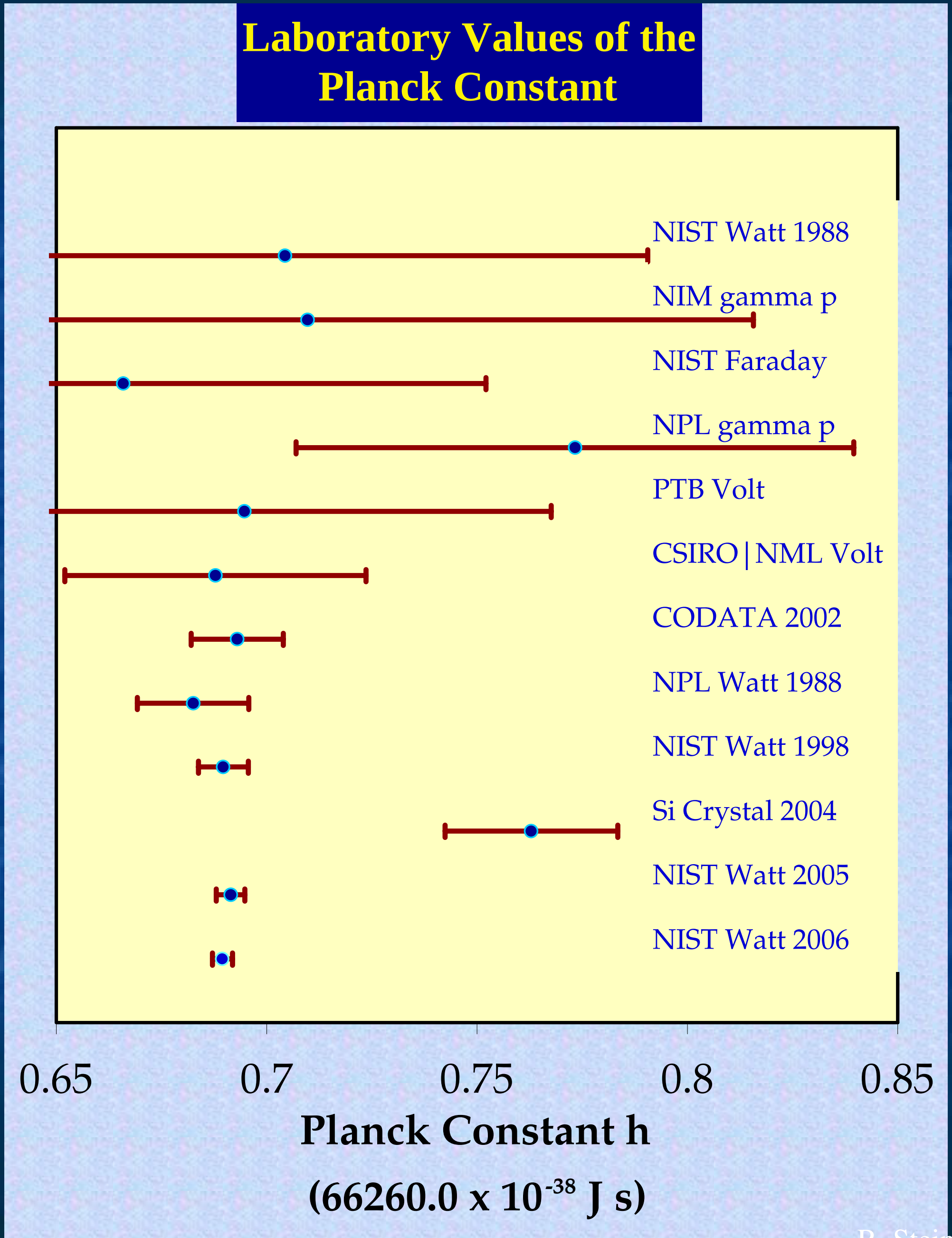
- Exact conversion factors
  - X-rays in eV

I n d u s t r y

E. Williams, R. Liu ‘05

Improving techniques

The Planck constant



R. Steiner

The new SI; An opportunity

- Provide the scientific community with an atomic based system.
  - Use to steer new macroscopic mass.
  - Science is the best source of new research.
- Opportunity to improve macroscopic mass dissemination.
  - Vacuum and inert gas environment.
  - Use a group of artifacts.
- Provide a opportunity for more fundamental research in mass metrology.
  - Need to compare Watt Balance and SI results.
  - Both vacuum masses and small masses tied to SI.

k, N_A, e, h

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NIST SP 959 (Apr/2005)

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magnetic constant	μ_0	$4\pi \times 10^{-7}$ (exact)	$\mathrm{N\ A^{-2}}$	No longer exact
electric constant $1/(\mu_0 c^2)$	ϵ_0	$8.854\,187\,817\ldots \times 10^{-12}$	$\mathrm{F\ m^{-1}}$	No longer exact
Newtonian constant of gravitation	G	$6.6742(10) \times 10^{-11}$	$\mathrm{m^3\ kg^{-1}\ s^{-2}}$	
Planck constant	h	6.626 0693~~(11)~~ $\times 10^{-34}$	J s	Exact
$h/(2\pi)$	$\hbar$	1.054 571 68~~(18)~~ $\times 10^{-34}$	J s	Exact
elementary charge	e	1.602 176 53~~(14)~~ $\times 10^{-19}$	C	Exact
fine-structure constant $e^2/(4\pi\epsilon_0\hbar c)$	α	$7.297\,352\,568(24) \times 10^{-3}$		
inverse fine-structure constant	α^{-1}	137.035 999 11(46)		
Rydberg constant $\alpha^2 m_e c/(2h)$	R_∞	10 973 731.568 525(73)	$\mathrm{m^{-1}}$	
Bohr radius $\alpha/(4\pi R_\infty)$	a_0	$0.529\,177\,2108(18) \times 10^{-10}$	m	
Bohr magneton $e\hbar/(2m_e)$	μ_B	927.400 949(80) $\times 10^{-26}$	$\mathrm{J\ T^{-1}}$	Improved

Quantity	Symbol	Numerical value	Unit	
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proton mass	m_p	1.672 621 71(29) $\times 10^{-27}$	kg	Improved
proton-electron mass ratio	m_p/m_e	1836.152 672 61(85)		
Avogadro constant	N_A, L	6.022 1415~~(10)~~ $\times 10^{23}$	$\mathrm{mol^{-1}}$	Exact
Faraday constant $N_A e$	F	96 485.3383~~(83)~~	$\mathrm{C\ mol^{-1}}$	Exact
molar gas constant	R	8.314 472~~(15)~~	$\mathrm{J\ mol^{-1}\ K^{-1}}$	Exact
Boltzmann constant R/N_A	k	1.380 6505~~(24)~~ $\times 10^{-23}$	$\mathrm{J\ K^{-1}}$	Exact
Stefan-Boltzmann const. $\pi^2 k^4/(60\hbar^3 c^2)$	σ	5.670 400~~(40)~~ $\times 10^{-8}$	$\mathrm{W\ m^{-2}\ K^{-4}}$	Exact
magnetic flux quantum $h/(2e)$	Φ_0	2.067 833 72~~(18)~~ $\times 10^{-15}$	Wb	Exact
Josephson constant $2e/h$	K_J	483 597.879~~(41)~~ $\times 10^{9}$	$\mathrm{Hz\ V^{-1}}$	Exact
von Klitzing constant h/e^2	R_K	25 812.807 449~~(86)~~	Ω	Exact
electron volt (e/C) J	eV	1.602 176 53~~(14)~~ $\times 10^{-19}$	J	Exact
(unified) atomic mass unit $\frac{1}{12}m(^{12}\mathrm{C})$	u	1.660 538 86(28) $\times 10^{-27}$	kg	Improved

A more extensive listing of constants is available in the reference given above and on the NIST Physics Laboratory Web site physics.nist.gov/constants.

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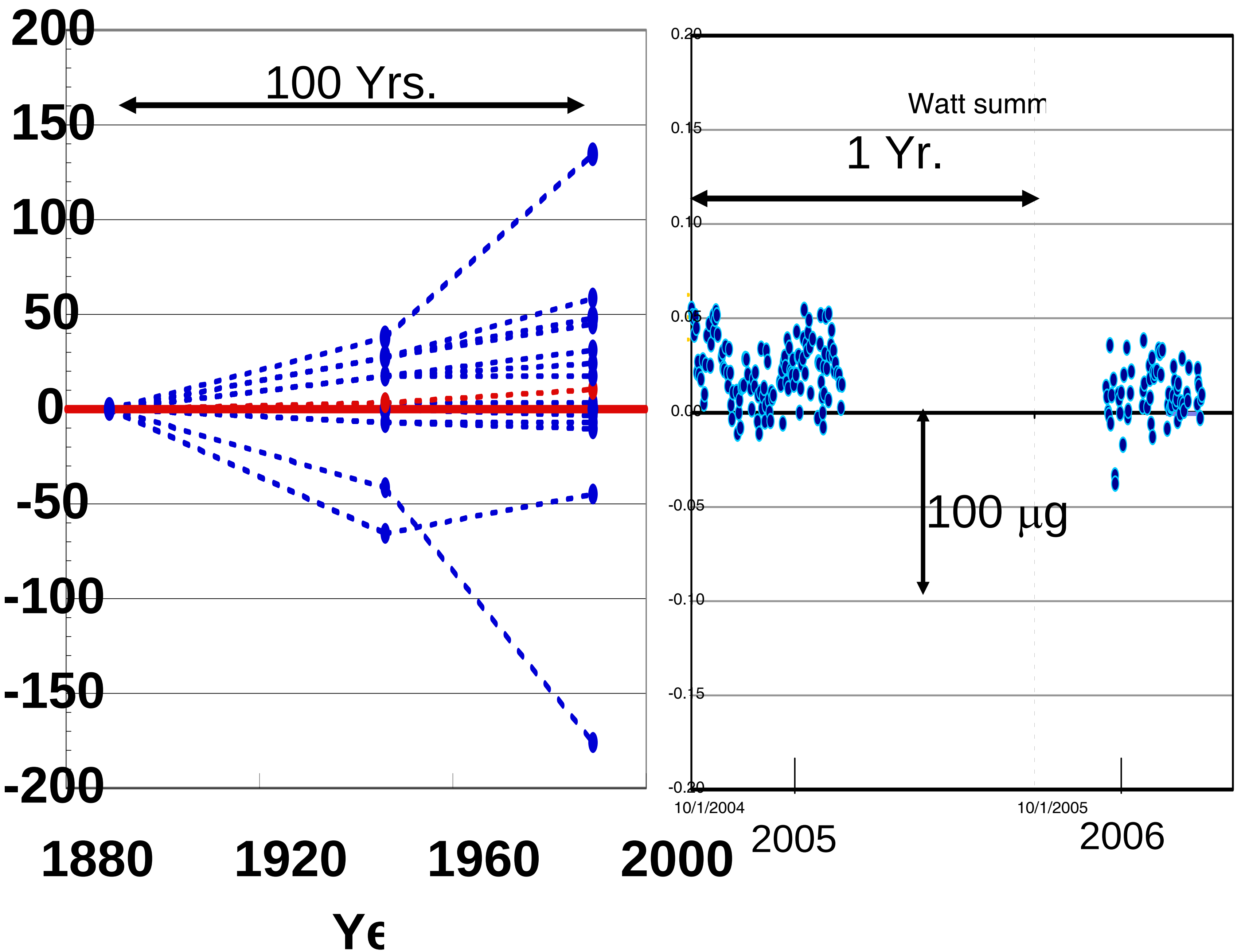
Explaining the kilogram

The kilogram is the mass of 6.022 141 5 $\times 10^{26}$ idealized atoms, each of these atoms having a mass such that the Planck constant, the most important constant in quantum mechanics, has the specified value of 6.626 069 3 $\times 10^{-34}$ joule second.

Such atoms have a mass very close (within an uncertainty of 1.4 ng/g) to 1/12th the mass of ^{12}C. This means that a mole of ^{12}C weighs $12 \times (1 \pm 1.4 \times 10^{-9})$ g.



200
150
100
50
0
-50
-100
-150
-200
100 Yrs.
1880
1920
1960
2000
Ye
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
Watt summ
1 Yr.
100 μg
10/1/2004
10/1/2005
2005
2006

Why Now?
Nobel prizes in physics

F. Bloch & E. Purcell	NMR	1952
A. Kastler	Spectroscopy	1966
Brian Josephson	Josephson effect	1973
Klaus von Klitzing	QHE	1985
Hans Dehmelt	Electron Traps	1989
Norman Ramsey	Separate osc. Fields	1989
Chu, Cohen-Tannoudji, Phillips	Atom cooling & trap	1997
Cornell, Ketterle, Wieman	BEC	2001
T. Hansch & J. Hall	Spectroscopy	2005

Equations used to define or realize mass via from seven constants

$E = h\nu = mc^2$ *Einstein*

$$mgv = \frac{U^2}{R} = S\frac{V_J^{\,2}}{R_H}\; mgv = S\left(\frac{nf}{2}\right)^2 ih \quad S\left(\frac{nf}{2}\right)^2 ih \quad \left(\frac{h}{\overline{ie^2}}\right)^2$$

Watt balance

Measure atomic mass unit ***u*** from XRCD

$$u = m(^{12}\mathrm{C}/12) = m_e/A_{\mathrm{r}}(e) = 2hR_\infty/\alpha^2 c\, A_{\mathrm{r}}(e)$$

$A_{\mathrm{r}}(e)$ = **atomic mass of electron**

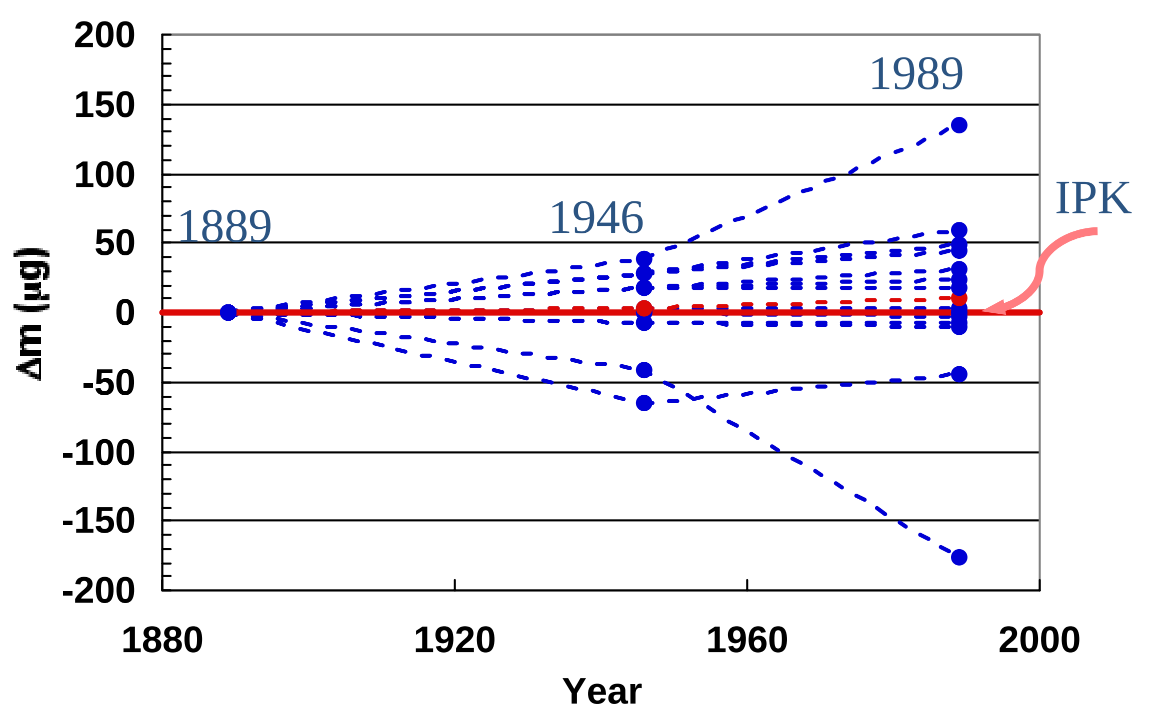
R_∞ = **Rydberg constant**

The kilogram is the unit of mass; it is equal to the mass of the international prototype of the kilogram

CON:

- Can be damaged
- Gains mass from adsorption
- "Mass Correction" required after cleaning
- Long-term stability is inferred from other artifacts

PRO:: Worked well!



The ampere

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

Physics tells us $F/l = (\mu_0 /2\pi)(I^2/r)$

Magnetic permeability

$\mu_0 = 4\pi \times 10^{-7}$ N/A^2 $(1+\varepsilon)$ where $\varepsilon = 0$ in 2011 $\sigma_r = 7 \times 10^{-10}$

Maxwell Eqs.?

CODATA 1998--2002 Deadline: Dec 31, 2006

B. Taylor & P. Mohr www.nist.gov/physic/constants

Kilogram alternatives are related

$u \leftrightarrow h$

$$u = C_{12} / 12 = X \{m\}_{SI} \{gv\}_{SI} / \{UI\}_{90}$$

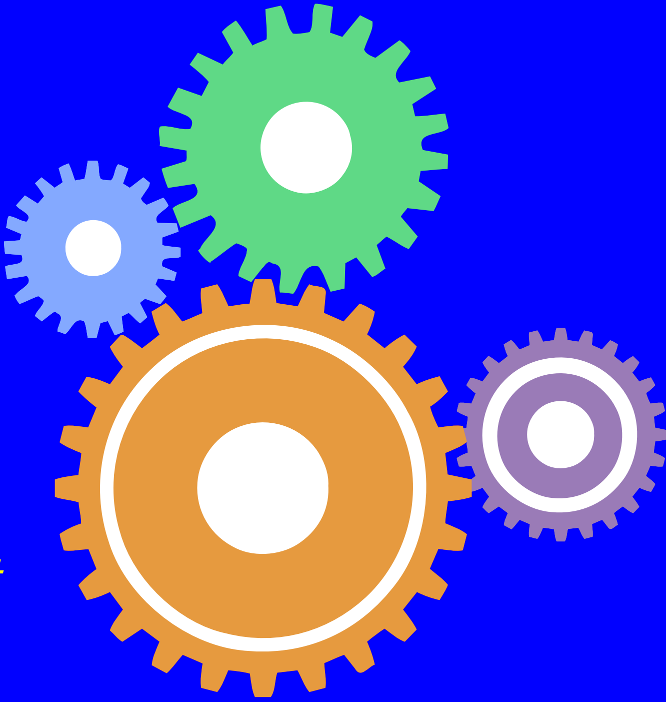
Where

$$X = 8R_{\infty} / [c\ \alpha^2 (K_{J-90})^2 R_{k-90} A_r(e)].$$

and

$A_r(e)$ = **atomic mass of electron**

$R_{\infty} = \alpha^2 m_e c / (2h)$ = ***Rydberg constant***



Uncertainty of X = 8 ppb

JE & QHE

Josephson Effect relation for the voltage U_J is:

$$U_J = nf/K_J$$ where n is a small integer, *f* an applied microwave frequency and

$$K_J = 2e/h$$

K_J = 483597.9?(.012) GHz/V (20 x 10^{-9})

CPEM 6/2006 Steiner, Willia

Quantum Hall effect

Von Klitzing constant

$$R_K = h/e^2 = \mu_0 c/2\alpha$$

R_K = 25812.807? Ω (0.7 x 10^{-9})