The electromagnetic Spectrum
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If only the speed of light were 10^9 m/s!

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When senior or first year graduate students are asked questions about the electromagnetic spectrum [1] like: What is the wavelength range covered by what we refer to as the visible spectrum?, List the name of the various portions of the electromagnetic spectrum going from short to very long wavelength?, At what frequency does a microwave oven or cellular phone or a FM radio station operate?, they typically get the correct answer. However, if they are asked slightly more specific questions like: What is the energy range (in eV) covered by the infrared (IR) or ultraviolet (UV) range of the electromagnetic spectrum?, students typically feel the urge to pull our their calculator and start plugging in numbers in the two formulas that most of them remember well, i.e, the relation between the wavelength λ and frequency f of a photon propagating in free space,

$$\lambda f = c, \tag{1}$$

where c is the speed of light in vacuum, and the energy-frequency relationship for a photon is given by

$$E = hf, \tag{2}$$

where h is Planck's constant (see Table I).

For something as fundamental as the electromagnetic spectrum, it seems as if scientists and engineers should be able to answer questions such as the ones listed above within seconds. To prove my point, let us start this article by asking you to take a little test in the form of ten questions about the electromagnetic spectrum which I believe you should be able to answer in just a few minutes. Give yourself a maximum of five minutes to complete the test by whatever means you choose. Anyone can answer these questions given enough time and a minimum amount of computational effort. Find out for yourself if your performance in answering the simple questions is acceptable to you.

The test:

- (1) Assuming you correlate a temperature T (in Kelvin) to a frequency f using the relation

$$E = k_B T = hf, \tag{3}$$

  where k_B is Boltzmann's constant (See Table I), to what temperature does an energy of 1 GeV (one giga electron-Volt) correspond [2]?

- (2) What is the frequency range covered by what is referred to as the IR portion of the electromagnetic spectrum?

- (3) Repeat question 2 for the UV portion of the electromagnetic spectrum.

- (4) What is the energy (in μeV) corresponding to the frequency of a FM radio station broadcasting at 100 MHz?

- (5) What temperature corresponds to the clock frequency of the microchip in your laptop if it is listed by the manufacturer as being 3 GHz? (Again, use eq.(3) as the relation between temperature and frequency).

- (6) What is the energy (in eV) of a photon whose wavelength is equal to the diameter of the smallest of all atoms (hydrogen), which is roughly one angstrom?

- (7) You have discovered a new type of electromagnetic radiation with energy of 1 μ eV. What part of the electromagnetic spectrum are you working in?

- (8) If you design a laser emitting at a wavelength λ of 5,000 $\mathring{A}$, what temperature T does this radiation correspond to?

- (9) Using again the relation $k_B T = hf$ correlate temperature and frequency, to what portion of the electromagnetic spectrum does the temperature of liquid nitrogen (with a boiling point of 77 K at atmospheric pressure) correspond?

- (10) An electron in a quantum well drops from an excited state to a lower energy state by emitting a photon of 100 meV. To what part of the electromagnetic spectrum does this correspond?

Having struggled myself with the type of questions listed above, I came up with a useful visual way to memorize the electromagnetic spectrum which I am going to share with you. With this visual aid I can actually answer questions like the ones listed above in seconds. Now, this should impress the person interviewing you for a job should they decide to ask you similar questions. By the way, the answers to the test are given at the end of the article, but you are not allowed to look at them now since you will have to retake the test after I teach you my trick.

I believe the main difficulty in navigating across the electromagnetic spectrum in split seconds may partly be due to the fact that textbooks typically display the electromagnetic spectrum using a linear scale, as shown in Figure 1. The basic idea for a better display of this scale came to me after realizing that the various regions of the spectrum as we know them today cover about 24 orders in magnitude in wavelength, and so also in frequency according to equation (1). Why 24? For the sake of this discussion, let us associate the magnitude of the wavelength with some familiar distances. Well, a nuclear physicist or engineer will from 500-1,500 kHz), used your microwave in your office for a mid-afternoon tea break or hot snack (zapping stuff at a few Gigahertz), used your cell phone a few times and your computer which both work at frequencies around of a few GHz. I hate to break it to you but, if you keep your eyes on the proposed electromagnetic clock, you have been zapped for the last 6 hours (from noon to 6.00p.m) by a mere 12 orders of magnitude in electromagnetic signals. This includes the radio range (below 300 MHz with AM, FM radio and television channels) and the microwave range from 300 MHz to 300 GHz. The portion of the latter ranging from 30 GHz to 300 GHz is better know as the millimeter-wave band and corresponds to wavelength in vacuum ranging from 1cm (30 GHz) down to 1mm (300 GHz).

By now, I hope you appreciate the time dial approach to remember the wavelength range of the various regions of the electromagnetic spectrum by relating them to typical daily activities. The sharp demarcation between the different ranges of frequencies could be a matter of debate but by keeping it as a power of 10, it makes it much easier to remember the various regions of the electromagnetic spectrum.

To figure out which frequency range actually corresponds to a specific region of the electromagnetic spectrum, we can then use the approximate relation given by equation (4) which, by taking the logarithm (in base 10) on both sides leads to

$$log_{10}f^* = 9 - log_{10}\lambda \tag{5}$$

or

$$f^* = 10^{(9-log_{10}\lambda)} \tag{6}$$

Using this simple estimate, the UV range of radiation from 1 to 100 nm or 10^{-9} to 10^{-7} m, corresponds roughly to frequencies between 10^{16} to 10^{18} Hz. However, the time dial approach gives a very simple way to derive the frequency f^* associated to a wavelength λ. Referring to Fig.2, it is simply given by

$$f = 10^{2Hour}, \tag{7}$$

The moment of truth: If the time dial representation of the electromagnetic spectrum presented above is of any use, you should be able to retake the test at the beginning of the paper, and get a much higher score in a much shorter time! Now, after you are done reading this paragraph, please close your eyes and just take a few minutes to visualize the time dial shown in Fig.2 and its different sections. Just make a mental picture of the wavelength range corresponding to the different portions of the electromagnetic spectrum and then the estimate of the corresponding frequency range is easily obtained from the approximation given by equation (7). Recall that this is indeed a quick way to estimate the frequency which came from assuming that the speed of light was 10^9 m/s. Once you get that estimate, remember to divide the number by 3 to get the correct frequency. When you feel that you can indeed visualize the time dial within seconds, you are now ready to take the test at the beginning of the article for the second time and see how much faster and more accurately you can go through it. It is time to take the test again and record your answer as well as the time it takes to answer all questions.

Check your answers at the bottom of this article. I hope the time dial trick has now helped you become a true guru of the electromagnetic spectrum. I would really like to hear your comments (send me an email at marc.cahay@uc.edu). I typically give the time dial trick to students in my classes and they indeed do much better answering questions similar to the ones listed in this paper the second time around. They typically can answer the test in half the time it took them in their first trial.

Answers to the questions: (1) Roughly 10^{13} K! (2) 0.33X[10^{12} - 10^{15}] Hz, (3) 0.33X[10^{16} - 10^{18}] Hz, (4) $\sim$ 0.4 μ eV, (5) $\sim$ 0.15 K, (6) $\sim$ 13 eV, the ionization energy of the hydrogen atom, (7) radio spectrum, (8) $\sim$ 8,000 K, (9) IR, (10) IR.

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About the author: Marc Cahay is a Professor in the Department of Electrical and Computer Engineering at the University of Cincinnati. His research interests include modeling of charge and spin transport in nanoscale devices and experimental investigation of rare-earth compounds for cold cathodes, organic light-emitting diodes, and solar cell applications.

Table I: Values of some of the physical constants mentioned in this paper.

Boltzmann's constant, k_B	$1.38X10^{-23}$ J/K
Speed of light in vacuum, c	$3X10^{8}$ m/s
light-year	$9.46X10^{12}$ km $\sim 10^{13}$ km
Planck's constant, h	$6.63X10^{-34}$ Js

References

[1] See, for instance, Fawwaz T. Ulaby, Fundamentals of Applied Electromagnetics, Prentice Hall, New Jersey (1997).

[2] This is a choice to define a temperature associated to a frequency that solid state engineers working with nanoscale devices like to use because sharp features in electrical or optical measurements in quantum confined geometries can only be seen if the temperature is low enough. This is because many physical quantities of interest are a convolution of some function of energy and the Fermi-Dirac factor which changes abruptly around the Fermi energy over an energy range roughly equal to $k_B T$. Another way to define a temperature associated to a given frequency would be to use Wien's law,

$$hf_{max}/k_B T \sim 2.82, \tag{11}$$

which gives the location of the maximum of the energy spectral density of the blackbody radiation [4, 5].

[3] Another useful rule to quickly find the relationship between energy and inverse length scale is

$$1meV = 8cm^{-1}, \tag{12}$$

which is well-known to spectroscopists.

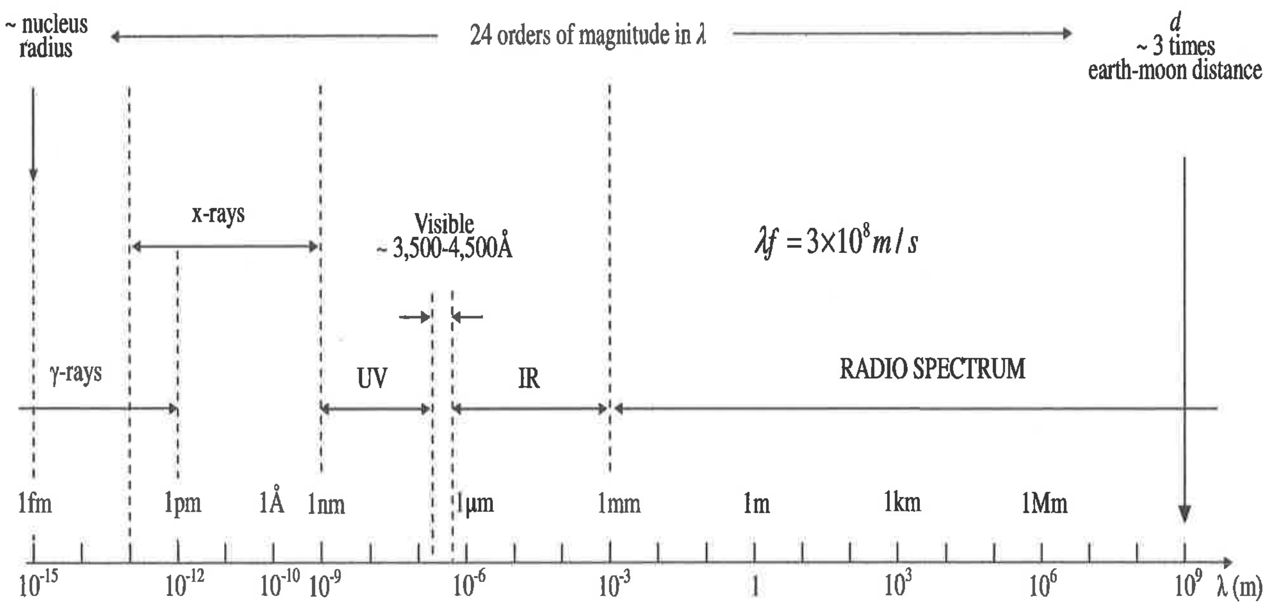
[4] Ronald Gautreau and William Savin, Modern Physics, Schaum's Outlines (2nd edition), McGraw Hill, New York, p.289 (1999).

[5] C. Kittel and H. Kroemer, Thermal Physics, 2nd edition, W.H. Freeman and Company, New York (1980).

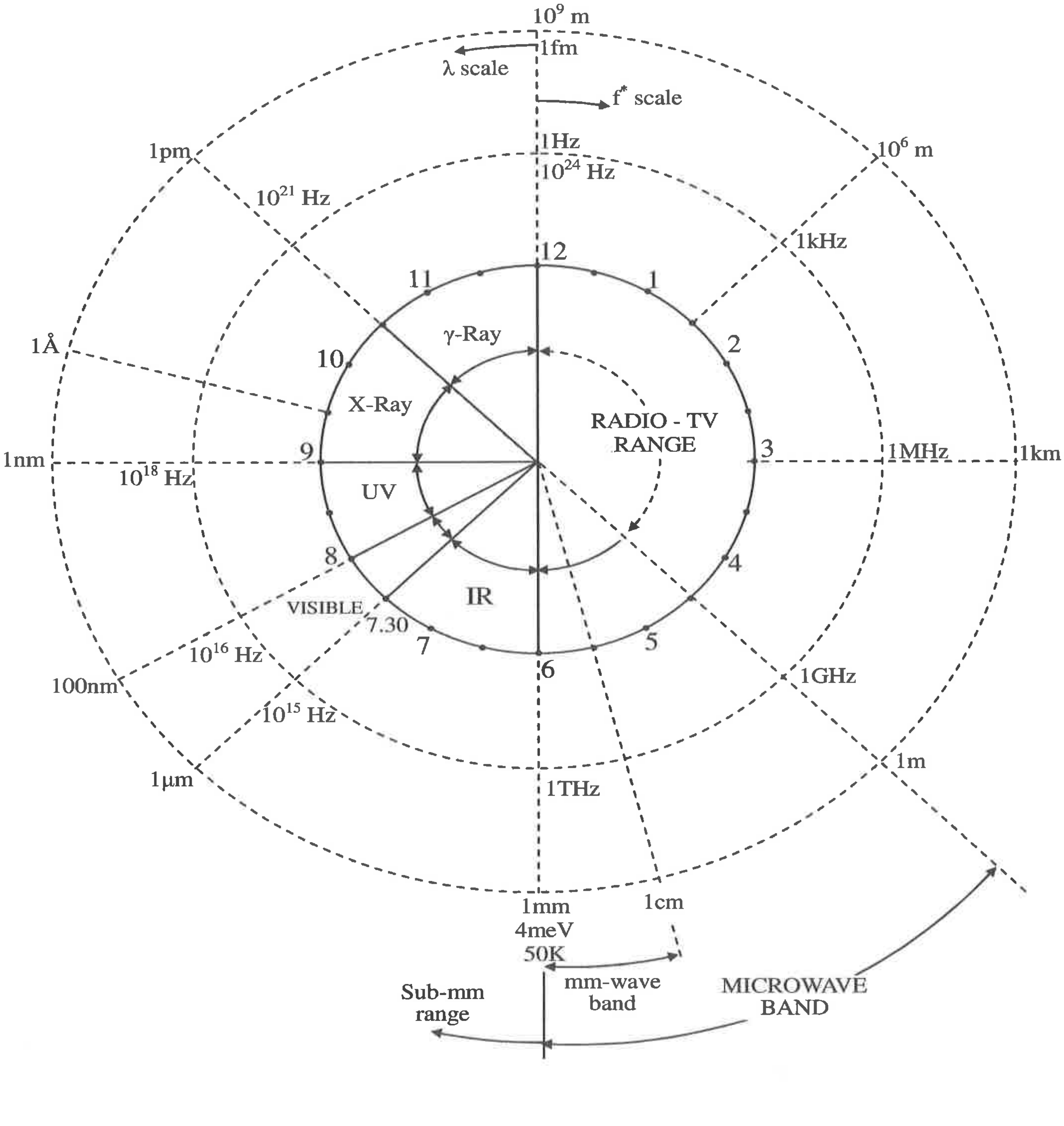
Figure Captions:

Figure 1: Typical linear display based on a logarithmic scale (in base 10) to illustrate the various wavelength and frequency regions of the electromagnetic spectrum [1].

Figure 2: Time dial representation of the electromagnetic spectrum to facilitate its memorization and the navigation through its various portions.



~ nucleus radius
24 orders of magnitude in λ
d
~ 3 times
earth-moon distance
x-rays
Visible
~ 3,500-4,500Å
$\lambda f = 3\times10^8 m/s$
γ-rays
UV
IR
RADIO SPECTRUM
1fm
1pm
1Å
1nm
1μm
1mm
1m
1km
1Mm
10^{-15}
10^{-12}
10^{-10}
10^{-9}
10^{-6}
10^{-3}
1
10^{3}
10^{6}
10^{9}
λ (m)



10^9 m
1fm
λ scale
f* scale
1Hz
10^24 Hz
10^6 m
1pm
10^21 Hz
1kHz
12
11
1
γ-Ray
2
1Å
10
X-Ray
RADIO - TV
RANGE
1nm
9
3
1MHz
1km
10^18 Hz
UV
8
4
VISIBLE
IR
7.30
7
5
6
10^16 Hz
1GHz
100nm
10^15 Hz
1μm
1m
1THz
1mm
4meV
50K
1cm
Sub-mm
range
mm-wave
band
MICROWAVE
BAND