Questions for P435 Lecture Notes 1

1.) Is Coulomb's force law valid for *all* separation distances r_{ab}? Is it valid for $r_{ab} \equiv 0$?

2.) What is the physics origin of the $1/r^2$ dependence of Coulomb's force law?

3.) What is the physics origin of the $1/\varepsilon_o$ dependence of Coulomb's force law?

4.) What is the physics origin of the $1/4\pi$ factor in Coulomb's force law?

5.) What really *is* electric charge?
What really *is* "charge" associated with any/all of the 4 fundamental forces of nature?

6.) Why is electric charge quantized (in units of *e*)?
What operative physics governs/dictates this?
Ditto for the charges associated with *each* of the 4 fundamental forces of nature…

7.) What really is *negative* vs. *positive* electric charge (i.e. –*e* vs. +*e*)?

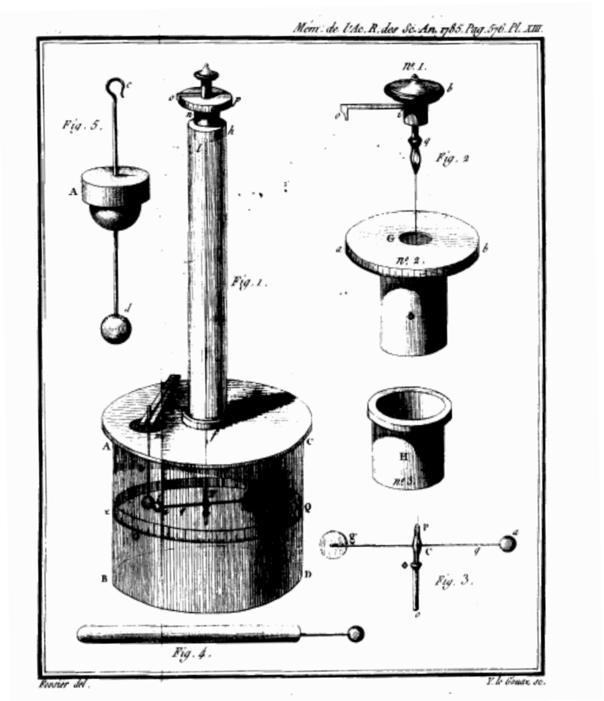
8.) Why does the Coulomb force vary as the *product* of two electric charges q_1q_2?

9.) What *is* a {macrosopic} vector field, such as $\vec{E}(\vec{r},t)$
What really is the *E*-field associated with e.g. a point electric charge, *e*?

10.) Are electric field lines (*aka* "lines of $\vec{E}(\vec{r},t)$") real? Do they *really* exist in space and time?

Answers to Questions for P435 Lecture Notes 1

1.) Is Coulomb's force law valid for *all* separation distances r_{ab} ? Is it valid for $r_{ab} \equiv 0$?



Charles Augustine de Coulomb's original 1785 torsion balance experiment investigated the nature of Coulomb's law over separation distance scales r_{ab} of a fraction of a cm to ~ few cm. He deduced the $1/r_{\mathrm{ab}}^2$ dependence from his own experiment's data. Today, the validity of Coulomb's force law has been experimentally tested over larger and smaller distance scales, down to $\sim 10^{-17}\,m$ in relativistic collisions of electrically-charged particles at high energies, e.g. in high-energy e^+e^- collisions, and which is quite far into the wave-like quantum mechanical realm, which for electrons, have a characteristic distance scale of the so-called {reduced} Compton wavelength $\lambdabar_e \equiv \lambda_e/2\pi = \hbar c/m_e c^2 = 3.86\times10^{-13}\,m$. The so-called "classical" radius of the electron r_e (the distance scale where the classical potential energy is set equal to the rest mass energy of the electron: $eV\left(r = r_e\right) = e^2/4\pi\varepsilon_o r_e^2 = m_e c^2 = 0.511\,MeV$) is $r_e = e^2/4\pi\varepsilon_o m_e c^2 = \alpha_{EM}\lambdabar_e = 2.82\times10^{-15}\,m$, where $\alpha_{EM} = e^2/4\pi\varepsilon_o\hbar c = 1/137.036$ = so-called "fine-structure constant" = the dimensionless strength of the *EM* interaction (at very low energies).

The attractive electrostatic interaction between an electron and a positron, as described classically/macroscopically by Coulomb's law manifestly breaks down at ~ atomic distance scales – where quantum mechanics becomes operative – because in this regime, the electron and positron form bound states of *positronium* (analogous to the Hydrogen atom, with the proton replaced by the postitron). The bound states of positronium are well-described by the Schroedinger wave equation, with a ground state radius of $a_o^{ps} = \tfrac{1}{2}a_o^{Bohr} = \tfrac{1}{2}r_e/\alpha_{EM}^2 = \tfrac{1}{2}0.53\text{Å} = 0.265\times10^{-10}\,m$.

We have no reason to believe that Coulomb's law is valid for $r_{ab} \equiv 0$, since a.) we do not currently have the technological wherewithal to directly test this zero distance regime, and b.) we also know that at a distance scale equal to the Planck scale, $L_P \equiv \sqrt{\hbar G_N/c^3} = 1.62\times10^{-35}\,m$, with corresponding Planck time $t_P \equiv L_P/c = \sqrt{\hbar G_N/c^5} = 5.39\times10^{-44}\,s$, space-time itself can no longer be considered as continuous – it is thought to be "foam-like" in nature – thus we anticipate new physics (beyond that of quantum mechanics) to take over at (and below) this distance scale – and thus, we have no reason to believe that Coulomb's law should be obeyed all the way down to $r_{ab} \equiv 0$. Furthermore, c.) at an even shorter distance scale than the Planck scale, that of the so-called Schwartzschild radius of the electron $r_e^{BH} = 2G_N m_e/c^2 = 1.35\times10^{-57}\,m$, the electron behaves as a black hole – i.e. space and time interchange roles at this distance scale due to the mass of the electron warping space-time around it! However, reconciling this extremely short distance scale with the (much larger) distance scale of Planck scale {where space-time itself is thought to become foam-like} is conceptually difficult/mind-boggling in itself…

2.) What is the physics origin of the $1/r^2$ dependence of Coulomb's force law?

Again, since Coulomb's force law directly ties experimental results to a mathematical description of the nature of the electrostatic interaction, Coulomb's law mathematically describes the macroscopic, time-averaged force $F_C(r)$ acting on a test electric charge Q_T due to a (source) electric charge q_s separated by a distance r from each other. Today we know that at the microscopic level, the two electric charges are swapping large numbers of virtual photons between them on very short time scales, each of which has momentum and kinetic energy associated with it, the total sum of which results in the macroscopic, time-averaged Coulomb force!

3.) What is the physics origin of the $1/\varepsilon_o$ dependence of Coulomb's force law?

At the microscopic level, virtual photons exchanged between two electrically charged particles propagate through the vacuum – seemingly empty space. However, at the microscopic level, the vacuum is not empty – it is a very busy/frenetic environment – seething with virtual particle-antiparticle pairs that flit in and out of existence – many of these virtual particle-antiparticle pairs are electrically charged, such as virtual e^+e^-, and $\mu^+\mu^-$, $\tau^+\tau^-$ pairs{heavier cousins of the electron}, 6 types of quark-antiquark pairs $q\bar{q}$ and also W^+W^- pairs (the electrically-charged W bosons are one of two mediators of the weak interaction), as allowed by the Heisenberg uncertainty principle $\Delta E\Delta t \geq \hbar$. The macroscopic, time-averaged electric permittivity of free space $\varepsilon_o = 8.85\times10^{-12}\ F/m$ is a direct consequence of the existence of these virtual particle-antiparticle pairs at the microscopic level.

4.) What is the physics origin of the $1/4\pi$ factor in Coulomb's force law?

At the microscopic level, electrically charged particles emit virtual photons into 4π steradians.

5.) What really *is* electric charge?

The electron was discovered by J.J. Thompson in 1897. Today, 110 years later, despite all our collective efforts we have gained little in a true, detailed/quantitative understanding of what an electron actually is, and hence what electric charge actually is.

What really *is* "charge" associated with any/all of the 4 fundamental forces of nature?

The same comments above apply for strong charge, weak charge, etc.

6.) Why is electric charge quantized (in units of *e*)?
What operative physics governs/dictates this?

Again, we have no detailed/quantitative answers for this.

Ditto for the charges associated with ***each*** of the 4 fundamental forces of nature…

Same comments above apply for the strong and weak interactions, etc. Why are there 4 fundamental forces of nature – why not just one? {we don't know the answer(s)} Are there more? We don't know – collectively we're always looking for evidence of new kinds of forces…

7.) What really is *negative* vs. *positive* electric charge (i.e. $-e$ vs. $+e$)?

Since we don't understand what electric charge e truly is, we also currently have no quantitative explanation for $-e$ vs. $+e$.

8.) Why does the Coulomb force vary as the *product* of two electric charges q_1q_2?

Experimentally, we observe that two oppositely electrically-charged particles have

9.) What *is* a {macroscopic} vector field, such as $\vec{E}(\vec{r},t)$
What really is the E-field associated with e.g. a point electric charge, e?

Since Coulomb's force law describes the macroscopic, time-averaged force acting on a test electric charge Q_T due to a (source) electric charge q_s separated by a distance r from each other, then the relation $\vec{F}_C(\vec{r},t) = Q_T\vec{E}(\vec{r},t)$ implies that $\vec{E}(\vec{r},t)$ is also a macroscopic, time-averaged quantity. Any time dependence associated with the macroscopic, time-averaged $\vec{F}_C(\vec{r},t)$ on the RHS is implicitly associated with human-type time scales, i.e. much larger than the characteristic time scales $\Delta t \geq \hbar/\Delta E$ associated with the exchange of virtual photons between the two electrically charged particles. Thus, the notion of a vector field, such as the macroscopic, time-averaged electric field $\vec{E}(\vec{r},t)$ is a human construct, used to mathematically describe the physics in a so-called mean-field manner.

10.) Are electric field lines (*aka* "lines of $\vec{E}(\vec{r},t)$") real? Do they *really* exist in space and time?

Since $\vec{E}(\vec{r},t)$ is a human construct, the concept of electric field lines to describe/map out the spatial/temporal behavior of the so-called electric field is also a human construct – thus electric field lines associated with the macroscopic, time-averaged electric field do not truly exist in space-time.