Electrostatic

$-\nabla^2\phi = 4\pi\rho$ with $\vec{E} = -\vec{\nabla}\phi$ (statics only)

physical meaning of the potential ϕ

work done to move a test charge δq from $\vec{r}_1$ to $\vec{r}_2$ in presence of an electric field $\vec{E}$ is

$$W_{12} = \int_{\vec{r}_1}^{\vec{r}_2} d\vec{l}\cdot\vec{F}$$

where $\vec{F}$ is the force required to move the charge. Since $\vec{E}$ exerts a force $\delta q\vec{E}$ on the charge, $\vec{F}$ must counter-balance this electric force so we can move the charge quasi statically $\Rightarrow \vec{F} = -\delta q\vec{E}$

$$W_{12} = -\delta q\int_{\vec{r}_1}^{\vec{r}_2} d\vec{l}\cdot\vec{E} = \delta q\int_{\vec{r}_1}^{\vec{r}_2} d\vec{l}\cdot\vec{\nabla}\phi = \delta q\left[\phi(\vec{r}_2)-\phi(\vec{r}_1)\right]$$

$$\phi(\vec{r}_2)-\phi(\vec{r}_1) = \frac{W_{12}}{\delta q}$$

difference in potential between two points is the work per unit charge to move a test charge between the two points

only true in statics ~~the~~ because $\vec{E} = -\vec{\nabla}\phi$ only in statics

Green's Functions – part I

$$-\nabla^2\phi = 4\pi\rho$$

We already know that for a point charge q at position $\vec{r}'$, ie $\rho(\vec{r}) = q\,\delta(\vec{r}-\vec{r}')$, the solution to the above is

$$\phi(\vec{r}) = \frac{q}{|\vec{r}-\vec{r}'|} \qquad \text{ie} \quad -\nabla^2\left(\frac{1}{|\vec{r}-\vec{r}'|}\right) = 4\pi\delta(\vec{r}-\vec{r}')$$

We call the special solution for a point source the Green function for the differential operator

$$-\nabla^2 G(\vec{r},\vec{r}') = 4\pi\,\delta(\vec{r}-\vec{r}')$$

$G(\vec{r},\vec{r}')$ gives the potential at position $\vec{r}$ due to a unit source at position $\vec{r}'$

Generally, one also has to specify a desired boundary condition for the Green function on the boundary of the system.

For the Coulomb solution for a point charge the implicit boundary condition is that the potential vanish infinitely far from the charge

$$G(\vec{r},\vec{r}') \to 0 \quad \text{as} \quad |\vec{r}-\vec{r}'| \to \infty$$

boundary of the system is taken to infinity

If one knows the Green's function, then one can find the solution for any distribution of sources $\rho(\vec{r})$

$$\phi(\vec{r}) = \int d^3r' \, G(\vec{r}, \vec{r}') \, \rho(\vec{r}')$$

<u>proof:</u> $$-\nabla^2\phi = \int d^3r' \left[-\nabla^2 G(\vec{r}, \vec{r}')\right] \rho(\vec{r}')$$

$$= \int d^3r' \left[4\pi \delta(\vec{r}-\vec{r}')\right] \rho(\vec{r}')$$

$$= 4\pi \rho(\vec{r})$$

We will return to concept of Greens function when we discuss solution of Poisson's eqn in a finite volume

We will also see Greens functions again when we discuss solution of the inhomogeneous wave equation.

The Coulomb problem as a boundary value problem

Consider a conducting sphere of radius R with net charge q (as $R \to 0$ we get a point charge).
What is $\phi(\vec{r})$? What is $E(\vec{r})$?

Review: Properties of conductors in electrostatics

1) $\vec{E}=0$ inside conductor - if $\vec{E} \neq 0$ then a current $\vec{j} = \sigma \vec{E}$ flows and it is not statics (σ is conductivity)
2) $\rho = 0$ inside conductor - if $\vec{E}=0$ inside, then $\vec{\nabla} \cdot \vec{E} = 4\pi\rho = 0$
3) Any net charge on the conductor must lie on the surface - follows from (2)
4) $\phi =$ constant throughout conductor - if $\vec{E}=0$ then $\vec{E} = -\vec{\nabla}\phi \Rightarrow \phi$ is constant
5) Just outside the conductor, $\vec{E}$ is $\perp$ to surface.
   - If $\vec{E}$ has a component $\parallel$ to surface then it exerts a force on electrons at the surface leading to a surface current - so would not be static

For conducting sphere, $\rho = 0$ for $r > R$ and $r < R$
all charge is on the surface $\Rightarrow \nabla^2 \phi = 0$ for $\begin{cases} r > R \\ r < R \end{cases}$

spherical symmetry $\Rightarrow$ expect spherically symmetric solution

$\Rightarrow \phi(\vec{r})$ depends only on $r = |\vec{r}|$

⇒ Solve Laplace's eqn by writing ∇^2 in spherical coords. Only the radial terms do not vanish.

$$\nabla^2\phi = \frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\phi}{dr}\right) = 0$$

$$r^2\frac{d\phi}{dr} = -C_0 \quad \text{a constant}$$

$$\frac{d\phi}{dr} = -\frac{C_0}{r^2}$$

$$\phi(r) = \frac{C_0}{r} + C_1 \quad , \quad C_1 \text{ a constant}$$

"outside" $r > R$ $\quad \phi^{out}(r) = \frac{C_0^{out}}{r} + C_1^{out}$

"inside" $r < R$ $\quad \phi^{in}(r) = \frac{C_0^{in}}{r} + C_1^{in}$

solution "outside" does not necessarily go smoothly into the solution "inside" because of the charge layer at $r = R$ that separates the two regions. We need to determine the constants, C_0^{in}, C_0^{out}, C_1^{in}, C_1^{out} by applying boundary conditions corresponding to the physical situation.

① For $r > R$, assume $\phi \to 0$ as $r \to \infty$ – boundary condition at infinity

$$\Rightarrow C_1^{out} = 0$$

$\phi^{out}(r) = \frac{C_0^{out}}{r}$ recover the expected Coulomb form.

2) For $r < R$.

i) we could use the fact that the region $r < R$ is a conductor with ϕ = constant to conclude $C_0^{in} = 0$

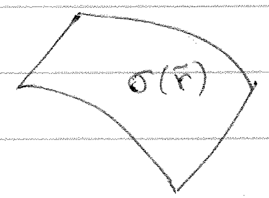
ii) or, if we were dealing with a charged shell instead of a conductor, we could argue as follows:

no charge at origin $r = 0 \Rightarrow$ expect ϕ should be finite at origin $\Rightarrow C_0^{in} = 0$

So $\phi^{in}(r) = C^{in}$ a constant

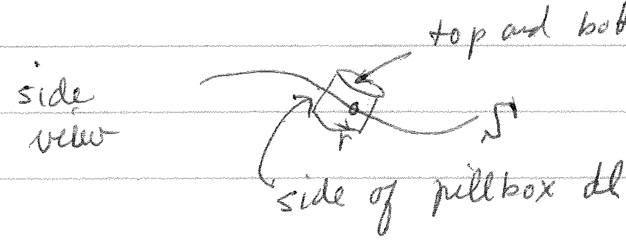
3) Now we need boundary condition at $r = R$ where "inside" and "outside" meet.

Review: <u>Electric field and potential at a surface charge layer</u>



← a general surface S with surface charge density $\sigma(\vec{r})$ for $\vec{r}$ on S, $\sigma(\vec{r})da$ is total charge in area da on surface

i) Take "Gaussian pillbox" surface about point $\vec{r}$ on the surface S



Gauss' Law in integral form $\oint_S da\, \hat{n} \cdot \vec{E} = 4\pi Q_{enclosed}$

expect $\vec{E}$ is finite $\Rightarrow$ contribution from sides of pillbox vanish as $dl \to 0$.

$$\oint_S da\, \hat{n}\cdot\vec{E} = \int_{top} da\, \hat{n}\cdot\vec{E} + \int_{bottom} da\, \hat{n}\cdot\vec{E}$$

$$= \left(\hat{n}^{top}\cdot\vec{E}^{top} + \hat{n}^{bottom}\cdot\vec{E}^{bottom}\right) da$$ since da is small

$\vec{E}^{top}$ is electric field at $\vec{r}$ just above the surface S

$\vec{E}^{bottom}$ is electric field at $\vec{r}$ just below the surface S

$\hat{n}^{top} \equiv \hat{n}$ is outward normal on top

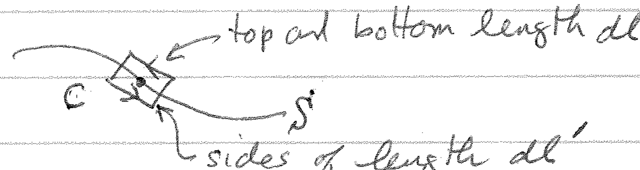
$\hat{n}^{bottom} = -\hat{n}$ is outward normal on bottom

$$\Rightarrow \left(\vec{E}^{top} - \vec{E}^{bottom}\right)\cdot\hat{n}\, da = 4\pi Q_{enclosed} = 4\pi\sigma(\vec{r})\, da$$

$$\boxed{\left(\vec{E}^{top} - \vec{E}^{bottom}\right)\cdot\hat{n} = 4\pi\sigma(\vec{r})}$$ discontinuity in normal component of $\vec{E}$

ii) Take "Amperian loop" C at surface about point $\vec{r}$.

side view



$\vec{\nabla}\times\vec{E} = 0 \Rightarrow \oint_C d\vec{l}\cdot\vec{E} = 0$ since $\vec{E}$ is finite at surface, if take sides $dl' \to 0$ their contribution to integral vanishes

$$\Rightarrow \oint_C d\vec{l}\cdot\vec{E} = \boxed{\left(\vec{E}^{top} - \vec{E}^{bottom}\right)\cdot d\vec{l} = 0}$$

where $d\vec{l}$ is any infinitesimal tangent to the surface at $\vec{r}$.

$\Rightarrow$ tangential component of $\vec{E}$ is continuous

combine above to write $\boxed{\vec{E}^{\,top} - \vec{E}^{\,bottom} = 4\pi\sigma(\vec{r})\,\hat{m}}$

iii) $\vec{E} = -\vec{\nabla}\phi \Rightarrow \phi(r_2) - \phi(r_1) = -\int_{\vec{r}_1}^{\vec{r}_2} d\vec{l}\cdot\vec{E}$

Take $\left.\begin{array}{l}\vec{r}_2 \text{ just above } \vec{r} \text{ on surface}\\ \vec{r}_1 \text{ just below } \vec{r} \text{ on surface}\end{array}\right\}\ d\vec{l} \to 0$

Since $\vec{E}$ is finite $\Rightarrow \int d\vec{l}\cdot\vec{E} \to 0$

$\Rightarrow \boxed{\phi^{top} = \phi^{bottom}}$

potential ϕ is continuous at surface charge layer

can rewrite (i) as

$$\left(-\vec{\nabla}\phi^{top} + \vec{\nabla}\phi^{bottom}\right)\cdot\hat{m} = 4\pi\sigma$$

$$\boxed{-\frac{\partial\phi^{top}}{\partial m} + \frac{\partial\phi^{bottom}}{\partial m} = 4\pi\sigma}$$

directional derivative of ϕ in direction $\hat{m}$

discontinuity in normal derivative of ϕ at surface

Apply to conducting sphere

ϕ continuous $\Rightarrow \phi^{in}(R) = \phi^{out}(R)$

$$C_1^{in} = \frac{C_0^{out}}{R}$$

only one unknown left

normal derivative of ϕ is discontinuous

$$-\frac{\partial \phi^{top}}{\partial n} + \frac{\partial \phi^{bottom}}{\partial n} = 4\pi\sigma$$

here $\hat{n} = \hat{r}$ the radial direction

$$\left[-\frac{d\phi^{out}}{dr} + \frac{d\phi^{in}}{dr} \right]_{r=R} = 4\pi\sigma$$

but $\frac{d\phi^{in}}{dr} = 0$ as ϕ^{in} = constant

$$-\frac{d\phi^{out}}{dr}\bigg|_{r=R} = 4\pi\sigma$$

charge q is uniformly distributed on surface at R

$$-\frac{d}{dr}\left(\frac{C_0^{out}}{r}\right)_{r=R} = \frac{C_0^{out}}{R^2} = 4\pi\sigma = 4\pi\left(\frac{q}{4\pi R^2}\right) = \frac{q}{R^2}$$

$$\Rightarrow C_0^{out} = q \quad , \quad C_1^{in} = \frac{C_0^{out}}{R} = \frac{q}{R}$$

$$\phi(r) = \begin{cases} \frac{q}{R} & r < R \quad \text{inside} \\ \frac{q}{r} & r > R \quad \text{outside} \end{cases}$$

$$\Rightarrow \vec{E} = -\vec{\nabla}\phi = -\frac{d\phi}{dr}\hat{r} = \begin{cases} 0 & r<R \quad \text{inside} \\ \frac{q}{r^2}\hat{r} & r>R \quad \text{outside} \end{cases}$$

we get familiar Coulomb solution!

Summary: We can view the preceding solution for ϕ^{out} as solving Laplace's eqn $\nabla^2\phi = 0$ subject to a specified boundary condition on the normal derivative of ϕ at the boundary $r = R$ of the "outside" region of the system.

Alternate problem:

Another physical situation would be to connect conducting sphere to a battery that charges the sphere to a fixed voltage ϕ_0 (stat volts!) with respect to ground $\phi = 0$ at $r \to \infty$.

As before, outside the sphere $\phi = \frac{c_0}{r}$
Now the boundary condition is to specify the value of ϕ on the boundary of the outside region, ie

$$\phi(R) = \phi_0$$

$$\Rightarrow \frac{c_0}{R} = \phi_0 \ , \quad c_0 = \phi_0 R$$

$$\phi(r) = \phi_0 \frac{R}{r}$$

(from preceding solution, we know that charging the sphere to voltage ϕ_0 (statvolts) induces a net charge $q = \phi_0 R$ on it)

These two versions of the conducting sphere problem are examples of a more general <u>boundary value problem</u>

Solve $\nabla^2 \phi = 0$ in a given region of space subject to one of the following two types of boundary conditions on the bounding surfaces of the region

i) Neumann boundary condition

$\frac{\partial \phi}{\partial n}$ - normal derivative of ϕ is specified on the bounding surface

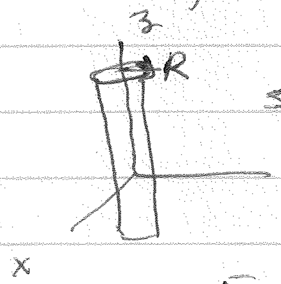
ii) Dirichlet boundary condition

ϕ - value of ϕ is specified on the bounding surfaces

If the bounding surfaces consist of <u>disjoint</u> pieces, it is possible to specify either (i) or (ii) on each piece separately to get a mixed boundary value problem.

Some more problems

infinite conducting wire of radius R with line charge density λ = charge per unit length



surface charge $\sigma = \frac{\lambda}{2\pi R}$

Expect cylindrical symmetry $\Rightarrow \phi$ depends only on cylindrical coord r.

$\nabla^2 \phi = 0$ for $r > R$, $r < R$

use ∇^2 in cylindrical coords – only radial term non vanishing

"r" is cylindrical radial coordinate

$$\nabla^2 \phi = \frac{1}{r}\frac{d}{dr}\left(r \frac{d\phi}{dr}\right) = 0$$

$$r\frac{d\phi}{dr} = C_0 \quad \text{constant}$$

$$\frac{d\phi}{dr} = \frac{C_0}{r}$$

$$\phi(r) = C_0 \ln r + C_1 \quad \text{const}$$

note: one cannot now choose $\phi \to 0$ as $r \to \infty$!

one needs to fix zero of ϕ at some other radius. a convenient choice is $r = R$, but any other choice could also be made.

$$\phi^{out} = C_0^{out} \ln r + C_1^{out}$$
$$\phi^{in} = C_0^{in} \ln r + C_1^{in}$$

ϕ^{in} = const in conductor $\Rightarrow C_0^{in} = 0$
or ϕ^{in} should not diverge as $r \to 0 \Rightarrow C_0^{in} = 0$

So $\phi^{in} = C_1^{in}$ constant

boundary condition at $r = R$

$$\left[-\frac{d\phi^{out}}{dr} + \frac{d\phi^{in}}{dr} \right]_{r=R} = 4\pi\sigma$$

$$\Rightarrow \quad -\frac{C_0^{out}}{R} = 4\pi\sigma = 4\pi\left(\frac{\lambda}{2\pi R}\right) = \frac{2\lambda}{R}$$

$$C_0^{out} = -2\lambda$$

$$\phi^{out}(r) = -2\lambda \ln r + C_1^{out}$$

continuity of ϕ

$$\phi^{in}(R) = \phi^{out}(R) \quad \Rightarrow \quad C_1^{in} = -2\lambda \ln R + C_1^{out}$$

Remaining const C_1^{out} is not too important as it is just a common additive constant to both ϕ^{in} and ϕ^{out} $\Rightarrow$ does not change $\vec{E} = -\vec{\nabla}\phi$.

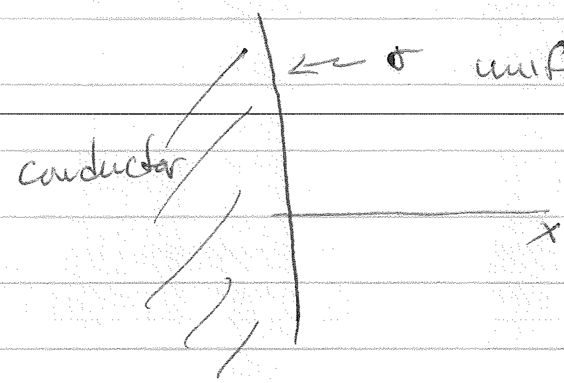
If use the condition $\phi(R) = 0$ then we can solve for C_1^{out}.

$$0 = -2\lambda \ln R + c_1^{out} \Rightarrow c_1^{out} = 2\lambda \ln R$$

$$\Rightarrow \phi(r) = \begin{cases} -2\lambda \ln(r/R) & r > R \\ 0 & r < R \end{cases}$$

$$\Rightarrow \vec{E}(\vec{r}) = \begin{cases} \frac{2\lambda}{r}\hat{r} & r > R \\ 0 & r < R \end{cases}$$

infinite conducting half space



← σ uniform surface charge density

expect ϕ depends only on x

$$\nabla^2\phi = \frac{d^2\phi}{dx^2} = 0$$

$$\Rightarrow \begin{cases} \phi^+(x) = c_0^+ x + c_1^+ & x > 0 \\ \phi^-(x) = c_0^- x + c_1^- & x < 0 \end{cases}$$

for $x < 0$, $\phi = \text{const}$ in conductor $\Rightarrow c_0^- = 0$

at $x = 0$, ϕ continuous $\Rightarrow \phi^-(0) = \phi^+(0)$

$$c_1^- = c_1^+$$

$\frac{d\phi}{dx}$ discontinuous $\Rightarrow$

$$-\left.\frac{d\phi^+}{dx}\right|_{x=0} = 4\pi\sigma$$

$$c_0^+ = -4\pi\sigma$$

$$\Rightarrow \phi(x) = \begin{cases} -4\pi\sigma x + c_1^+ & x > 0 \\ c_1^+ & x < 0 \end{cases}$$

const c_1^+ does not change value of $\vec{E}$

as for the wire, we cannot choose $\phi \to 0$ as $x \to \infty$.
~~we can set $\phi = 0$ at~~. If we choose $\phi = 0$ at $x = 0$, then $c_1^+ = 0$.

$$-\vec{\nabla}\phi = \vec{E} = \begin{cases} 4\pi\sigma\,\hat{x} & x > 0 \\ 0 & x < 0 \end{cases}$$

<u>infinite charged plane</u>

similar to previous problem, but now no conductor at $x < 0$, just free space on both sides of the charged plane at $x = 0$.

~~expect ϕ depends only on $|x|$ by symmetry~~

$$\nabla^2\phi = \frac{d^2\phi}{dx^2} = 0 \quad \Rightarrow \quad \begin{array}{ll} \phi^+ = c_0^+ x + c_1^+ & x > 0 \\ \phi^- = c_0^- x + c_1^- & x < 0 \end{array}$$

continuity of ϕ at $x = 0$

$$\rightarrow \quad \phi^+(0) = \phi^-(0) \quad \Rightarrow \quad c_1^+ = c_1^-$$

discontinuity of $d\phi/dx$ at $x = 0$

$$-\frac{d\phi^+}{dx} + \frac{d\phi^-}{dx} = 4\pi\sigma$$

$$-c_0^+ + c_0^- = 4\pi\sigma$$

Define $\bar{c}_0 = \dfrac{c_0^+ + c_0^-}{2}$

Then we can write

$$C_0^- = \bar{C}_0 + 2\pi\sigma$$
$$C_0^+ = \bar{C}_0 - 2\pi\sigma$$

$$\phi = \begin{cases} -2\pi\sigma x + \bar{C}_0 x + C_1^+ & x > 0 \\ 2\pi\sigma x + \bar{C}_0 x + C_1^+ & x < 0 \end{cases}$$

$$\Rightarrow -\frac{d\phi}{dx} = \vec{E} = \begin{cases} (2\pi\sigma - \bar{C}_0)\,\hat{x} & x > 0 \\ (-2\pi\sigma - \bar{C}_0)\,\hat{x} & x < 0 \end{cases}$$

Const C_1^+ does not effect $\vec{E}$ – additive const to ϕ

$\bar{C}_0$ represents const uniform electric field $-\bar{C}_0\hat{x}$, that exists independently of the charged surface ie remains even as $\sigma \to 0$.

If we assumed that all $\vec{E}$ fields are just those arising from the plane, then we can set $\bar{C}_0 = 0$. Equivalently, if the plane is the only source of $\vec{E}$, then we expect ϕ depends only on $|x|$ by symmetry.
$\Rightarrow$ $C_0^- = -C_0^+$ and again $\bar{C}_0 = 0$. In this case

$$\phi(x) = \begin{cases} -2\pi\sigma x & x > 0 \\ 2\pi\sigma x & x < 0 \end{cases}$$

(we also set $C_1^+ = 0$ here corresponding to $\phi(0) = 0$

$$\vec{E}(x) = \begin{cases} 2\pi\sigma\,\hat{x} & x > 0 \\ -2\pi\sigma\,\hat{x} & x < 0 \end{cases}$$

$\vec{E}$ is constant but oppositely directed on either side of the charged plane