PHYS 501: Mathematical Physics I

Fall 2018

Solutions to Homework #6

1. (a) Fourier transforming the equation gives

$$-k^2\tilde{\phi}(k) = 4\pi G\tilde{\rho}(k),$$

so

$$\tilde{\phi} = -\frac{4\pi G\tilde{\rho}}{k^2}$$

and the solution is

$$\phi(\mathbf{x}) = -4\pi G(2\pi)^{-3/2}\int d^3k e^{i\mathbf{k}\cdot\mathbf{x}}\frac{\tilde{\rho}(k)}{k^2}.$$

(b) If $\rho(\mathbf{x}) = m\delta(\mathbf{x})$, $\tilde{\rho} = (2\pi)^{-3/2}m$, so

$$\begin{aligned}\phi &= -\frac{4\pi Gm}{(2\pi)^3}\int d^3k\frac{e^{i\mathbf{k}\cdot\mathbf{x}}}{k^2}\\ &= -\frac{4\pi Gm}{(2\pi)^3}\int k^2dk\sin\theta_k d\theta_k d\phi_k\frac{e^{ikr\cos\theta_k}}{k^2},\end{aligned}$$

where we have taken the "z axis" in k space to run parallel to $\mathbf{x}$, as usual. Doing the ϕ_k integral, setting $\mu = \cos\theta_k$, and simplifying, we find

$$\begin{aligned}\phi &= -\frac{Gm}{\pi}\int_0^\infty dk\int_{-1}^1 e^{ikr\mu}d\mu\\ &= -\frac{2Gm}{\pi}\int_0^\infty dk\,\frac{\sin kr}{kr}\\ &= -\frac{Gm}{\pi}\int_{-\infty}^\infty dk\,\frac{\sin kr}{kr}\\ &= -\frac{Gm}{\pi r}\int_{-\infty}^\infty dz\,\frac{\sin z}{z}\\ &= -\frac{Gm}{r},\end{aligned}$$

since the final integral has been shown in class to be π.

2. The Green's function $G(x,x')$ for the inhomogeneous ODE $y'' - k^2y = f(x)$ is determined by solving the differential equation with $f(x) = \delta(x-x')$ in $0 \le (x,x') \le L$, and matching solutions at $x = x'$ so that G is continuous and $[G']_-^+ = 1$. The boundary conditions are $y(0) = y(L) = 0$. In $0 \le x < x'$, the solution satisfying the boundary condition at $x = 0$ is

$$y(x) = C\sinh kx\,.$$

The corresponding solution in $x' < x \le L$ is

$$y(x) = C'\sinh k(x-L)\,.$$

The continuity and jump conditions at $x = x'$ are

$$\begin{aligned} C \sinh kx' &= C' \sinh k(x' - L) \\ Ck \cosh kx' &= C'k \cosh k(x' - L) - 1 \,, \end{aligned}$$

so

$$\begin{aligned} C &= \frac{\sinh k(x' - L)}{k \sinh kL} \\ C' &= \frac{\sinh kx'}{k \sinh kL} \,, \end{aligned}$$

where we have used the identity

$$\sinh a \ \cosh b - \cosh a \ \sinh b \ = \ \sinh(a - b) \,.$$

Thus the Green's function is

$$\begin{aligned} G(x, x') &= \frac{\sinh kx \ \sinh k(x' - L)}{k \sinh kL}, \ x < x' \\ &= \frac{\sinh k(x - L) \ \sinh kx'}{k \sinh kL}, \ x > x' \,. \end{aligned}$$

3. Assume that the solution is a function of $\mathbf{x} - \mathbf{x}'$ and take $\mathbf{x}' = 0$ for convenience. Then the Green's function satisfies

$$\nabla^2 G + k^2 G = \delta(\mathbf{x}).$$

For $\mathbf{x} \neq 0$, we have $\nabla^2 G + k^2 G = 0$ and G is a sum of terms of the form

$$[a_l j_l(kr) + b_l n_l(kr)] \, Y_l^m(\theta, \phi).$$

Since $j_0(x) = \sin x/x$ and $n_0(x) = -\cos x/x$, we obtain the solution representing an outgoing spherical wave at infinity ($G \sim e^{ikr}/r$) by adopting spherical symmetry ($l = m = 0$) and choosing $b_0 = ia_0$ (so $G = -ib_0 h_0^{(1)}(kr)$, where $h_0^{(1)} = j_0 + in_0$ is a Hankel function). Near $r = 0$,

$$G \ \sim \ b_0 \, n_0(kr) \ \sim \ -\frac{b_0}{kr}.$$

Integrating the differential equation over an infinitesimal sphere centered on the origin, assuming G is continuous, and applying the divergence theorem to the $\nabla^2 G$ term as discussed in class, we find, near $r = 0$,

$$\begin{aligned} \frac{\partial G}{\partial r} &\sim \frac{1}{4\pi r^2} \\ \Rightarrow \qquad G &\sim -\frac{1}{4\pi r}. \end{aligned}$$

The two expressions for $G(r \to 0)$ are consistent if

$$b_0 = \frac{k}{4\pi}.$$

so

$$G \ = \ -\frac{e^{ikr}}{4\pi r} \ = \ -\frac{ikh_0^{(1)}(kr)}{4\pi}.$$

4. The Green's function is

$$G(\mathbf{x},\mathbf{x}') = -\frac{1}{4\pi|\mathbf{x}'-\mathbf{x}|} + \frac{\beta}{4\pi|\mathbf{x}'-\mathbf{x}_1|},$$

where $\mathbf{x}_1 = \alpha\mathbf{x}$ is the image point.

(a) We apply the boundary condition $G(\mathbf{x},\mathbf{x}') = 0$ when $r' \equiv |\mathbf{x}'| = a$ at the two points $\mathbf{x}_A = a\mathbf{x}/r$ and $\mathbf{x}_B = -a\mathbf{x}/r$ where the diameter through $\mathbf{x}$ intersects the surface of the sphere. When $\mathbf{x}' = \mathbf{x}_A$, we have $|\mathbf{x}'-\mathbf{x}| = a - r$, $|\mathbf{x}'-\mathbf{x}_1| = \alpha r - a$, so setting $G = 0$ implies

$$\frac{-1}{a-r} + \frac{\beta}{\alpha r - a} = 0,$$

or

$$\beta(a-r) = \alpha r - a.$$

Similarly, when $\mathbf{x}' = \mathbf{x}_B$, we have

$$\beta(a+r) = \alpha r + a.$$

The solutions to these two equations are easily seen to be

$$\beta = \frac{a}{r}, \qquad \alpha = \frac{a^2}{r^2} = \beta^2 .$$

We assume without proof that G is in fact zero whenever $r' = a$.

(b) The solution to $\nabla^2 u = 0$ with $u(a,\theta,\phi) = f(\theta,\phi)$ is then

$$u(r,\theta,\phi) = \int a^2 d\Omega' \, f(\theta',\phi') \left.\frac{\partial G(\mathbf{x},\mathbf{x}')}{\partial r'}\right|_{r'=a} .$$

Writing $\rho = |\mathbf{x}'-\mathbf{x}|$, $\rho_1 = |\mathbf{x}'-\mathbf{x}_1|$, and noting that

$$\begin{aligned} \rho^2 &= (r')^2 + r^2 - 2r'r\cos\gamma, \\ \text{where} \quad \cos\gamma &= \frac{\mathbf{x}'\cdot\mathbf{x}}{r'r} \\ &= \cos\theta'\cos\theta + \sin\theta'\sin\theta\cos(\phi'-\phi), \end{aligned}$$

it follows that

$$\frac{\partial\rho}{\partial r'} = \frac{r' - r\cos\gamma}{\rho}$$

and similarly for $\partial\rho_1/\partial r'$. Hence

$$\begin{aligned} \frac{\partial}{\partial r'}\left(\frac{1}{\rho}\right)_{r'=a} &= -\frac{a - r\cos\gamma}{\rho^3}, \\ \frac{\partial}{\partial r'}\left(\frac{1}{\rho_1}\right)_{r'=a} &= -\frac{a - \alpha r\cos\gamma}{\beta^3\rho^3}, \end{aligned}$$

where we have used the fact that $\rho_1 = \beta\rho$ when $r' = a$. Substituting in, we have

$$\begin{aligned} \left.\frac{\partial G}{\partial r'}\right|_{r'=a} &= -\frac{1}{4\pi}\frac{\partial}{\partial r'}\left(\frac{1}{\rho}\right) + \frac{\beta}{4\pi}\frac{\partial}{\partial r'}\left(\frac{1}{\rho_1}\right) \\ &= \frac{1}{4\pi}\left(\frac{a - r\cos\gamma}{\rho^3}\right) - \frac{\beta}{4\pi}\left(\frac{a - \alpha r\cos\gamma}{\beta^3\rho^3}\right) \\ &= \frac{1}{4\pi\rho^3}\left(a - r\cos\gamma - \frac{r^2}{a^2} + r\cos\gamma\right) \\ &= \frac{a}{4\pi\rho^3}\left(1 - \frac{r^2}{a^2}\right), \end{aligned}$$

where have used the relation $\alpha = \beta^2 = r^2/a^2$. Hence

$$u(r,\theta,\phi) = \frac{1}{4\pi}\left(1 - \frac{r^2}{a^2}\right)\int d\Omega'\, f(\theta',\phi')\left(\frac{a}{\rho}\right)^3.$$

(c) The series solution to the problem is

$$u(r,\theta,\phi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} a_{lm} r^l Y_l^m(\theta,\phi),$$

where

$$a_{lm}a^l = \int d\Omega'\, f(\theta',\phi')\, Y_l^{m*}(\theta',\phi'),$$

so

$$u(r,\theta,\phi) = \sum_{l,m}\left(\frac{r}{a}\right)^l \int d\Omega'\, f(\theta',\phi')\, Y_l^{m*}(\theta',\phi')\, Y_l^m(\theta,\phi).$$

We can connect this to the Green's function solution as follows. Using the addition theorem for $r < a$, $r_1 > a$, $r' \approx a$, expand

$$\frac{1}{\rho} = \sum_{l,m}\frac{4\pi}{2l+1} Y_l^{m*}(\theta',\phi')\, Y_l^m(\theta,\phi)\frac{r^l}{(r')^{l+1}},$$

with a similar expression for $1/\rho_1$ (with the same θ and ϕ). The Green's function thus is

$$G = -\sum_{l,m}\frac{1}{2l+1} Y_l^{m*}(\theta',\phi')\, Y_l^m(\theta,\phi)\left[\frac{r^l}{(r')^{l+1}} - \beta\frac{(r')^l}{r_1^{l+1}}\right].$$

Hence

$$\begin{aligned}\left.\frac{\partial G}{\partial r'}\right|_{r'=a} &= -\sum_{l,m}\frac{1}{2l+1} Y_l^{m*}(\theta',\phi')\, Y_l^m(\theta,\phi)\left[-(l+1)\frac{r^l}{a^{l+2}} - l\frac{r^l}{a^{l+2}}\right] \\ &= \frac{1}{a^2}\sum_{l,m}\left(\frac{r}{a}\right)^l Y_l^{m*}(\theta',\phi')\, Y_l^m(\theta,\phi),\end{aligned}$$

in agreement with the series solution.

5. The Green's function for this problem is

$$G(\mathbf{x}-\mathbf{x}', t-t') = \begin{cases} 0 & (t < t') \\ -\frac{1}{4\pi|\mathbf{x}-\mathbf{x}'|}\,\delta(t - t' - \frac{1}{c}|\mathbf{x}-\mathbf{x}'|) & (t > t'),\end{cases}$$

so

$$\phi(\mathbf{x},t) = -\frac{1}{4\pi}\int d^3\mathbf{x}' \int dt'\, \frac{\delta[\mathbf{x}' - \boldsymbol{\xi}(t')]\,\delta(t - t' - \frac{1}{c}|\mathbf{x}-\mathbf{x}'|)}{|\mathbf{x}-\mathbf{x}'|}.$$

Clearly the only contribution to the integral occurs when $\mathbf{x}' = \boldsymbol{\xi}(t')$, $t - t' = |\mathbf{x}-\mathbf{x}'|/c$. To determine the contribution from that point, we note that the integral

$$I = \int\int\int\int dx\, dy\, dz\, dt\, \delta[f_1(x,y,z,t)]\,\delta[f_2(x,y,z,t)]\,\delta[f_3(x,y,z,t)]\,\delta[f_4(x,y,z,t)]$$

(temporarily dropping the primes for convenience) can be evaluated by transforming to f_1, f_2, f_3, f_4 as independent variables in the vicinity of $f_i = 0$, to obtain

$$\begin{aligned} I &= \int\int\int\int df_1\, df_2\, df_3\, df_4 \left|\frac{\partial(x,y,z,t)}{\partial(f_1,f_2,f_3,f_4)}\right| \delta(f_1)\delta(f_2)\delta(f_3)\delta(f_4) \\ &= \left|\frac{\partial(x,y,z,t)}{\partial(f_1,f_2,f_3,f_4)}\right|_{f_i=0} \\ &= \left|\frac{\partial(f_1,f_2,f_3,f_4)}{\partial(x,y,z,t)}\right|^{-1}_{f_i=0}, \end{aligned}$$

where $J = \partial(x_1, x_2, x_3, x_4)/\partial(f_1, f_2, f_3, f_4)$ is the Jacobian matrix

$$J_{ij} = \frac{\partial x_i}{\partial f_j}\,.$$

Here (reinstating the primes),

$$\begin{aligned} f_1 &= x' - \xi_x(t') \\ f_2 &= y' - \xi_y(t') \\ f_3 &= z' - \xi_z(t') \\ f_4 &= t - t' - \frac{1}{c}|\mathbf{x}-\mathbf{x}'|\,, \end{aligned}$$

so

$$\frac{\partial(f_1,f_2,f_3,f_4)}{\partial(x',y',z',t')} = \begin{pmatrix} 1 & 0 & 0 & -\dot{\xi}_x(t') \\ 0 & 1 & 0 & -\dot{\xi}_y(t') \\ 0 & 0 & 1 & -\dot{\xi}_z(t') \\ -\frac{x-x'}{c|\mathbf{x}-\mathbf{x}'|} & -\frac{y-y'}{c|\mathbf{x}-\mathbf{x}'|} & -\frac{z-z'}{c|\mathbf{x}-\mathbf{x}'|} & -1 \end{pmatrix},$$

(where we have used the fact that if $r = |\mathbf{x}|$, then $\nabla r = \mathbf{x}/r$), and hence

$$\left|\frac{\partial(f_1,f_2,f_3,f_4)}{\partial(x',y',z',t')}\right| = -1 + \frac{1}{c}\,\frac{\dot{\boldsymbol{\xi}}(t')\cdot(\mathbf{x}-\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}\,.$$

Doing the integrals, the delta functions now imply $\mathbf{x}' = \boldsymbol{\xi}(t')$, and

$$\phi(\mathbf{x},t) = -\frac{1}{4\pi}\,\frac{1}{|\mathbf{x}-\boldsymbol{\xi}(t')| - \frac{1}{c}\dot{\boldsymbol{\xi}}(t')\cdot[\mathbf{x}-\boldsymbol{\xi}(t')]}\,,$$

where t' is the solution of the implicit equation

$$c(t-t') = |\mathbf{x}-\boldsymbol{\xi}(t')|.$$

The above expression for ϕ is the so-called *Lienard-Wiechert* potential.