Problem 1. A spherical shell of radius R has a total charge Q uniformly spread over the shell. The shell is now put into uniform rotation about the z axis with angular velocity ω. Find the vector potential $\mathbf{A}(\mathbf{x})$ and magnetic field $\mathbf{B}(\mathbf{x})$ everywhere, i.e., both inside and outside of the shell.

Solution. Let $\rho(\mathbf{x})$ be the charge density everywhere in space, so

$$\rho(\mathbf{x}) = \frac{1}{4\pi}\frac{Q}{R^2}\delta(r-R).$$

The linear velocity of the moving charge everywhere is

$$\mathbf{v}(\mathbf{x}) = \omega r\,\delta(r-R)\,\hat{\boldsymbol{\varphi}}.$$

Then the current density $\mathbf{J}$ is simply the product of charge density and the linear velocity of the charge:

$$\mathbf{J}(\mathbf{x}) = \rho(\mathbf{x})\,\mathbf{v}(\mathbf{x}) = \frac{Q\omega}{4\pi}\frac{r}{R^2}\delta(r-R)\,\hat{\boldsymbol{\varphi}}.$$

From Eq. (4.21) in the lecture notes, $\mathbf{A}(\mathbf{x})$ everywhere is given by

$$\mathbf{A}(\mathbf{x}) = \frac{1}{c}\int \frac{\mathbf{J}(\mathbf{x})'}{|\mathbf{x}-\mathbf{x}'|}\,d^3\mathbf{x}'\,.$$

The integral we need to evaluate is then

$$\mathbf{A}(\mathbf{x}) = \frac{1}{4\pi c}\frac{Q\omega}{R^2}\int \frac{r'\,\delta(r'-R)}{|\mathbf{x}-\mathbf{x}'|}\,d^3\mathbf{x}'\,.$$

The problem is azimuthally symmetric, so we will rotate our coordinate system such that $\mathbf{x}$ points along the z axis. In the new coordinate system,

$$\frac{1}{|\mathbf{x}-\mathbf{x}'|} = \frac{1}{\sqrt{\mathbf{x}^2 - 2\mathbf{x}\cdot\mathbf{x}' + \mathbf{x}'^2}} = \frac{1}{\sqrt{r^2 - 2rr'\cos\theta' + r'^2}}.$$

Let $\boldsymbol{\omega}$ be the angular velocity vector (that lay along the z axis of the original coordinate system), which we choose to lie in the xz plane. Let α be the angle between $\boldsymbol{\omega}$ and the z axis. Then the linear velocity of the moving charge is

$$\begin{aligned}\mathbf{v}(\mathbf{x}') = \boldsymbol{\omega}\times\mathbf{x}' &= \begin{vmatrix} \hat{\mathbf{x}} & \hat{\mathbf{y}} & \hat{\mathbf{z}} \\ \omega\sin\alpha & 0 & \omega\cos\alpha \\ r'\sin\theta'\cos\varphi' & r'\sin\theta'\sin\varphi' & r'\cos\theta' \end{vmatrix} \\ &= -\omega r'(\cos\alpha\sin\theta'\sin\varphi')\,\hat{\mathbf{x}} + \omega r'(\cos\alpha\sin\theta'\cos\varphi' - \sin\alpha\cos\theta')\,\hat{\mathbf{y}} + \omega r'(\sin\alpha\sin\theta'\sin\varphi')\,\hat{\mathbf{z}},\end{aligned}$$

so in the new coordinate system,

$$\mathbf{J}(\mathbf{x}') = \frac{Q}{4\pi}\frac{\boldsymbol{\omega}\times\mathbf{x}'}{R^2}\,\delta(r'-R) = \frac{Q\omega}{4\pi}\frac{r'}{R^2}(\hat{\boldsymbol{\omega}}\times\hat{\mathbf{x}}')\,\delta(r'-R),$$

where

$$\hat{\boldsymbol{\omega}}\times\hat{\mathbf{x}}' = -(\cos\alpha\sin\theta'\sin\varphi')\,\hat{\mathbf{x}} + (\cos\alpha\sin\theta'\cos\varphi' - \sin\alpha\cos\theta')\,\hat{\mathbf{y}} + (\sin\alpha\sin\theta'\sin\varphi')\,\hat{\mathbf{z}}.$$

The integral we need to evaluate becomes

$$\mathbf{A}(\mathbf{x}) = \frac{1}{4\pi c}\frac{Q\omega}{R^2}\int_0^{2\pi}\int_{-1}^{1}\int_0^{\infty}\frac{r'^3(\hat{\boldsymbol{\omega}}\times\hat{\mathbf{x}}')\,\delta(r'-R)}{\sqrt{r^2-2rr'\cos\theta'+r'^2}}\,dr'\,d(\cos\theta')\,d\varphi\,.$$

Evaluating the radial integral, we have

$$\mathbf{A}(\mathbf{x}) = \frac{Q\omega R}{4\pi c}\int_0^{2\pi}\int_{-1}^{1}\frac{\hat{\boldsymbol{\omega}}\times\hat{\mathbf{x}}'}{\sqrt{r^2-2Rr\cos\theta'+R^2}}\,d(\cos\theta')\,d\varphi\,.$$

For the angular integrals, the $\hat{\mathbf{x}}$ term is

$$-\cos\alpha\,\hat{\mathbf{x}}\int_{-1}^{1}\frac{\sin\theta'}{\sqrt{r^2-2Rr\cos\theta'+R^2}}\,d(\cos\theta')\int_0^{2\pi}\sin\varphi'\,d\varphi \propto \Big[-\cos\varphi'\Big]_0^{2\pi} = 0.$$

Similarly, the $\hat{\mathbf{z}}$ term is

$$\sin\alpha\,\hat{\mathbf{z}}\int_{-1}^{1}\frac{\sin\theta'}{\sqrt{r^2-2Rr\cos\theta'+R^2}}\,d(\cos\theta')\int_0^{2\pi}\sin\varphi'\,d\varphi \propto \Big[-\cos\varphi'\Big]_0^{2\pi} = 0.$$

There are two $\hat{\mathbf{y}}$ terms. For the first,

$$\cos\alpha\,\hat{\mathbf{y}}\int_{-1}^{1}\frac{\sin\theta'}{\sqrt{r^2-2Rr\cos\theta'+R^2}}\,d(\cos\theta')\int_0^{2\pi}\cos\varphi'\,d\varphi \propto \Big[\sin\varphi'\Big]_0^{2\pi} = 0.$$

For the second,

$$\begin{aligned}
-\sin\alpha\,\hat{\mathbf{y}}\int_{-1}^{1}\frac{\cos\theta'}{\sqrt{r^2-2Rr\cos\theta'+R^2}}\,d(\cos\theta')\int_0^{2\pi}d\varphi &= -2\pi\sin\alpha\,\hat{\mathbf{y}}\int_{-1}^{1}\frac{\cos\theta'}{\sqrt{r^2-2Rr\cos\theta'+R^2}}\,d(\cos\theta') \\
&= -2\pi\sin\alpha\,\hat{\mathbf{y}}\left(\left[-\frac{\cos\theta'\sqrt{r^2-2Rr\cos\theta'+R^2}}{Rr}\right]_{-1}^{1}+\frac{1}{Rr}\int_{-1}^{1}\sqrt{r^2-2Rr\cos\theta'+R^2}\,d(\cos\theta')\right) \\
&= -2\pi\sin\alpha\,\hat{\mathbf{y}}\left(\left[-\frac{\cos\theta'\sqrt{r^2-2Rr\cos\theta'+R^2}}{Rr}\right]_{-1}^{1}+\frac{1}{Rr}\left[-\frac{(r^2-2Rr\cos\theta'+R^2)^{3/2}}{3Rr}\right]_{-1}^{1}\right) \\
&= -2\pi\sin\alpha\,\hat{\mathbf{y}}\left(-\frac{\sqrt{r^2+2Rr+R^2}}{Rr}+\frac{\sqrt{r^2-2Rr+R^2}}{Rr}-\frac{(r^2-2Rr+R^2)^{3/2}}{3R^2r^2}+\frac{(r^2+2Rr+R^2)^{3/2}}{3R^2r^2}\right) \\
&= 2\pi\sin\alpha\frac{3Rr\sqrt{(r+R)^2}-3Rr\sqrt{(r-R)^2}+[(r-R)^2]^{3/2}-[(r+R)^2]^{3/2}}{3R^2r^2}\hat{\mathbf{y}} \\
&= 2\pi\sin\alpha\frac{3Rr|r+R|-3Rr|r-R|+(r-R)^2|r-R|-(r+R)^2|r+R|}{3R^2r^2}\hat{\mathbf{y}} \\
&= 2\pi\sin\alpha\frac{(r^2+Rr+R^2)|r-R|-(r^2-Rr+R^2)(r+R)}{3R^2r^2}\hat{\mathbf{y}} \\
&= \frac{2\pi\sin\alpha\,\hat{\mathbf{y}}}{3R^2r^2}\begin{cases}(r^2+Rr+R^2)(R-r)-(r^2-Rr+R^2)(r+R) & r<R, \\ (r^2+Rr+R^2)(r-R)-(r^2-Rr+R^2)(r+R) & r>R\end{cases} \\
&= -\frac{4}{3}\pi\sin\alpha\,\hat{\mathbf{y}}\begin{cases}\dfrac{r}{R^2} & r<R, \\ \dfrac{R}{r^2} & r>R.\end{cases}
\end{aligned}$$

Finally, in the new coordinate system we have

$$\mathbf{A}(\mathbf{x}) = -\frac{Q\omega}{3c}\sin\alpha\,\hat{\mathbf{y}}\begin{cases}\dfrac{r}{R} & r<R, \\ \dfrac{R^2}{r^2} & r>R.\end{cases}$$

Transforming back to the old coordinate system, $\sin\alpha \to -\sin\theta$. Since the original system is azimuthally symmetric, $\varphi = 0$ so $\hat{\mathbf{y}} = \sin\theta\sin\varphi\,\hat{\mathbf{r}} + \cos\theta\sin\varphi\,\hat{\boldsymbol{\theta}} + \cos\varphi\,\hat{\boldsymbol{\varphi}} = \hat{\boldsymbol{\varphi}}$. Thus we have

$$\mathbf{A}(\mathbf{x}) = \frac{Q\omega}{3c}\sin\theta\,\hat{\boldsymbol{\varphi}}\begin{cases}\dfrac{r}{R} & r < R,\\[2ex] \dfrac{R^2}{r^2} & r > R.\end{cases}$$

The magnetic field is given by Eq. (1.7),

$$\mathbf{B} = \boldsymbol{\nabla}\times\mathbf{A}. \tag{1}$$

In spherical coordinates,

$$\boldsymbol{\nabla}\times\mathbf{A} = \frac{1}{r\sin\theta}\left(\frac{\partial}{\partial\theta} - \frac{\partial A_\theta}{\partial\varphi}\right)\hat{\mathbf{r}} + \frac{1}{r}\left(\frac{1}{\sin\theta}\frac{\partial A_r}{\partial\varphi} - \frac{\partial}{\partial r}\right)\hat{\boldsymbol{\theta}} + \frac{1}{r}\left(\frac{\partial}{\partial r} - \frac{\partial A_r}{\partial\theta}\right)\hat{\boldsymbol{\varphi}},$$

so

$$\mathbf{B} = \frac{1}{r\sin\theta}\frac{\partial}{\partial\theta}\hat{\mathbf{r}} - \frac{1}{r}\frac{\partial}{\partial r}\hat{\boldsymbol{\theta}}.$$

For $r < R$,

$$\begin{aligned}\mathbf{B}(\mathbf{x}) &= \frac{Q\omega}{3c}\frac{1}{r}\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\frac{r}{R}\sin^2\theta\right)\hat{\mathbf{r}} - \frac{\partial}{\partial r}\left(\frac{r^2}{R}\sin\theta\right)\hat{\boldsymbol{\theta}}\right] = \frac{Q\omega}{3c}\frac{1}{r}\left(\frac{r}{R}\frac{2\cos\theta\sin\theta}{\sin\theta}\,\hat{\mathbf{r}} - \frac{2r}{R}\sin\theta\,\hat{\boldsymbol{\theta}}\right)\\ &= \frac{2}{3}\frac{Q\omega}{cR}(\cos\theta\,\hat{\mathbf{r}} - \sin\theta\,\hat{\boldsymbol{\theta}}) = \frac{2}{3}\frac{Q\omega}{cR}\,\hat{\mathbf{z}}.\end{aligned}$$

For $r > R$,

$$\begin{aligned}\mathbf{B}(\mathbf{x}) &= \frac{Q\omega}{3c}\frac{1}{r}\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\frac{R^2}{r^2}\sin^2\theta\right)\hat{\mathbf{r}} - \frac{\partial}{\partial r}\left(\frac{R^2}{r}\sin\theta\right)\hat{\boldsymbol{\theta}}\right] = \frac{Q\omega}{3c}\frac{1}{r}\left(\frac{R^2}{r^2}\frac{2\cos\theta\sin\theta}{\sin\theta}\,\hat{\mathbf{r}} + 2\frac{R^2}{r^2}\sin\theta\,\hat{\boldsymbol{\theta}}\right)\\ &= \frac{2}{3}\frac{Q\omega}{c}\frac{R^2}{r^3}(\cos\theta\,\hat{\mathbf{r}} + \sin\theta\,\hat{\boldsymbol{\theta}}).\end{aligned}$$

In summary,

$$\mathbf{B}(\mathbf{x}) = \frac{2}{3}\frac{Q\omega}{c}\begin{cases}\dfrac{\hat{\mathbf{z}}}{R} & r < R,\\[2ex] \dfrac{R^2}{r^3}(\cos\theta\,\hat{\mathbf{r}} + \sin\theta\,\hat{\boldsymbol{\theta}}) & r > R.\end{cases}$$

Problem 2. If an electric and magnetic field are both present, the momentum density carried by the electromagnetic field is given by Poynting's formula

$$\mathcal{P} = \frac{1}{4\pi c}(\mathbf{E}\times\mathbf{B}).$$

Consider a bounded distribution of time-independent charges and currents, i.e., $\rho(\mathbf{x})$ and $\mathbf{J}(\mathbf{x})$ are time independent and vanish when $|\mathbf{x}| > R$ for some R.

2.a Show that the total momentum can be written as

$$\mathbf{P} \equiv \int \mathcal{P}(\mathbf{x})\,d^3x = \int \phi(\mathbf{x})\,\mathbf{J}(\mathbf{x})\,d^3x\,.$$

Solution. Applying (1),

$$\mathbf{E} \times \mathbf{B} = \mathbf{E} \times (\boldsymbol{\nabla} \times \mathbf{A}).$$

Vector identity (4) in Griffiths is

$$\boldsymbol{\nabla}(\mathbf{a} \cdot \mathbf{b}) = \mathbf{a} \times (\boldsymbol{\nabla} \times \mathbf{b}) + \mathbf{b} \times (\boldsymbol{\nabla} \times \mathbf{a}) + (\mathbf{a} \cdot \boldsymbol{\nabla})\mathbf{b} + (\mathbf{b} \cdot \boldsymbol{\nabla})\mathbf{a},$$

which allows us to write

$$\mathbf{E} \times \mathbf{B} = \boldsymbol{\nabla}(\mathbf{A} \cdot \mathbf{E}) - \mathbf{A} \times (\boldsymbol{\nabla} \times \mathbf{E}) - (\mathbf{A} \cdot \boldsymbol{\nabla})\mathbf{E} - (\mathbf{E} \cdot \boldsymbol{\nabla})\mathbf{A} = \boldsymbol{\nabla}(\mathbf{A} \cdot \mathbf{E}) - (\mathbf{A} \cdot \boldsymbol{\nabla})\mathbf{E} - (\mathbf{E} \cdot \boldsymbol{\nabla})\mathbf{A},$$

since $\boldsymbol{\nabla} \times E = 0$ in electrostatics by Eq. (1.4) in the lecture notes. From the Wikipedia article on vector calculus identities (because I couldn't find a better source), the product rule for the outer product $\mathbf{ba} = \mathbf{b} \otimes \mathbf{a}^{\mathrm{T}}$ is

$$\boldsymbol{\nabla} \cdot (\mathbf{ba}) = \mathbf{a}(\boldsymbol{\nabla} \cdot \mathbf{b}) + (\mathbf{b} \cdot \boldsymbol{\nabla})\mathbf{a}.$$

Adding and subtracting $\mathbf{A}(\boldsymbol{\nabla} \cdot \mathbf{E})$, we apply the product rule to obtain

$$\mathbf{E} \times \mathbf{B} = \boldsymbol{\nabla}(\mathbf{A} \cdot \mathbf{E}) + \mathbf{A}(\boldsymbol{\nabla} \cdot \mathbf{E}) - \mathbf{A}(\boldsymbol{\nabla} \cdot \mathbf{E}) - (\mathbf{A} \cdot \boldsymbol{\nabla})\mathbf{E} - (\mathbf{E} \cdot \boldsymbol{\nabla})\mathbf{A} = \boldsymbol{\nabla}(\mathbf{A} \cdot \mathbf{E}) + \mathbf{A}(\boldsymbol{\nabla} \cdot \mathbf{E}) - \boldsymbol{\nabla} \cdot (\mathbf{EA}) - (\mathbf{E} \cdot \boldsymbol{\nabla})\mathbf{A}.$$

2.b Give an example of a stationary, bounded charge and current distribution for which $\mathbf{P} \neq 0$.

Problem 3. The angular momentum density of the electromagnetic field is given by

$$\mathbf{l} = \mathbf{x} \times \mathcal{P} = \frac{1}{4\pi c}\mathbf{x} \times (\mathbf{E} \times \mathbf{B}).$$

Consider a source free ($\rho = 0$, $\mathbf{J} = 0$) solution to Maxwell's equations in electrodynamics with $\mathbf{E}$ and $\mathbf{B}$ vanishing rapidly as $|\mathbf{x}| \to \infty$, so the total angular momentum

$$\mathbf{L} = \int \mathbf{l}\, d^3x$$

is well defined. Show that $\mathbf{L}$ is conserved, i.e., independent of time.

In addition to the course lecture notes, I consulted Griffiths's *Introduction to Electrodynamics*, Jackson's *Classical Electrodynamics*, and Wolfram Mathworld while writing up these solutions.