

Chapter 2. Method of Separation of Variables

Section 2.3

2.3.1 (a) $u(r, t) = \phi(r)h(t)$ yields $\phi \frac{dh}{dt} = \frac{kh}{r} \frac{d}{dr} \left(r \frac{d\phi}{dr} \right)$. Dividing by $k\phi h$ yields $\frac{1}{kh} \frac{dh}{dt} = \frac{1}{r\phi} \frac{d}{dr} \left(r \frac{d\phi}{dr} \right) = -\lambda$ or $\frac{dh}{dt} = -\lambda kh$ and $\frac{1}{r} \frac{d}{dr} \left(r \frac{d\phi}{dr} \right) = -\lambda \phi$.

2.3.1 (c) $u(x, y) = \phi(x)h(y)$ yields $h \frac{d^2\phi}{dx^2} + \phi \frac{d^2h}{dy^2} = 0$. Dividing by ϕh yields $\frac{1}{\phi} \frac{d^2\phi}{dx^2} = -\frac{1}{h} \frac{d^2h}{dy^2} = -\lambda$ or $\frac{d^2\phi}{dx^2} = -\lambda\phi$ and $\frac{d^2h}{dy^2} = \lambda h$.

2.3.1 (e) $u(x, t) = \phi(x)h(t)$ yields $\phi(x) \frac{dh}{dt} = kh(t) \frac{d^4\phi}{dx^4}$. Dividing by $k\phi h$, yields $\frac{1}{kh} \frac{dh}{dt} = \frac{1}{\phi} \frac{d^4\phi}{dx^4} = \lambda$.

2.3.1 (f) $u(x, t) = \phi(x)h(t)$ yields $\phi(x) \frac{d^2h}{dt^2} = c^2 h(t) \frac{d^2\phi}{dx^2}$. Dividing by $c^2\phi h$, yields $\frac{1}{c^2 h} \frac{d^2h}{dt^2} = \frac{1}{\phi} \frac{d^2\phi}{dx^2} = -\lambda$.

2.3.2 (b) $\lambda = (n\pi/L)^2$ with $L = 1$ so that $\lambda = n^2\pi^2$, $n = 1, 2, \dots$

2.3.2 (d)

(i) If $\lambda > 0$, $\phi = c_1 \cos \sqrt{\lambda}x + c_2 \sin \sqrt{\lambda}x$. $\phi(0) = 0$ implies $c_1 = 0$, while $\frac{d\phi}{dx}(L) = 0$ implies $c_2 \sqrt{\lambda} \cos \sqrt{\lambda}L = 0$. Thus $\sqrt{\lambda}L = -\pi/2 + n\pi$ ($n = 1, 2, \dots$).

(ii) If $\lambda = 0$, $\phi = c_1 + c_2x$. $\phi(0) = 0$ implies $c_1 = 0$ and $d\phi/dx(L) = 0$ implies $c_2 = 0$. Therefore $\lambda = 0$ is not an eigenvalue.

(iii) If $\lambda < 0$, let $\lambda = -s$ and $\phi = c_1 \cosh \sqrt{s}x + c_2 \sinh \sqrt{s}x$. $\phi(0) = 0$ implies $c_1 = 0$ and $d\phi/dx(L) = 0$ implies $c_2 \sqrt{s} \cosh \sqrt{s}L = 0$. Thus $c_2 = 0$ and hence there are no eigenvalues with $\lambda < 0$.

2.3.2 (f) The simplest method is to let $x' = x - a$. Then $d^2\phi/dx'^2 + \lambda\phi = 0$ with $\phi(0) = 0$ and $\phi(b-a) = 0$. Thus (from p. 46) $L = b - a$ and $\lambda = [n\pi/(b-a)]^2$, $n = 1, 2, \dots$

2.3.3 From (2.3.30), $u(x, t) = \sum_{n=1}^{\infty} B_n \sin \frac{n\pi x}{L} e^{-k(n\pi/L)^2 t}$. The initial condition yields $2 \cos \frac{3\pi x}{L} = \sum_{n=1}^{\infty} B_n \sin \frac{n\pi x}{L}$. From (2.3.35), $B_n = \frac{2}{L} \int_0^L 2 \cos \frac{3\pi x}{L} \sin \frac{n\pi x}{L} dx$.

2.3.4 (a) Total heat energy = $\int_0^L c\rho u A dx = c\rho A \sum_{n=1}^{\infty} B_n e^{-k(\frac{n\pi}{L})^2 t} \frac{1 - \cos \frac{n\pi}{L}}$, using (2.3.30) where B_n satisfies (2.3.35).

2.3.4 (b)

heat flux to right = $-K_0 \partial u / \partial x$

total heat flow to right = $-K_0 A \partial u / \partial x$

heat flow out at $x = 0 = K_0 A \frac{\partial u}{\partial x} \Big|_{x=0}$

heat flow out ($x = L$) = $-K_0 A \frac{\partial u}{\partial x} \Big|_{x=L}$

2.3.4 (c) From conservation of thermal energy, $\frac{d}{dt} \int_0^L u dx = k \frac{\partial u}{\partial x} \Big|_0^L = k \frac{\partial u}{\partial x}(L) - k \frac{\partial u}{\partial x}(0)$. Integrating from $t = 0$ yields

$$\underbrace{\int_0^L u(x, t) dx}_{\text{heat energy at } t} - \underbrace{\int_0^L u(x, 0) dx}_{\text{initial heat energy}} = k \underbrace{\int_0^t \left[\frac{\partial u}{\partial x}(L) - \frac{\partial u}{\partial x}(0) \right] dx}_{\text{integral of flow in at } x=L} - \underbrace{\int_0^t \left[\frac{\partial u}{\partial x}(L) - \frac{\partial u}{\partial x}(0) \right] dx}_{\text{integral of flow out at } x=L}.$$

2.3.8 (a) The general solution of $k \frac{d^2 u}{dx^2} = \alpha u$ ($\alpha > 0$) is $u(x) = a \cosh \sqrt{\frac{\alpha}{k}}x + b \sinh \sqrt{\frac{\alpha}{k}}x$. The boundary condition $u(0) = 0$ yields $a = 0$, while $u(L) = 0$ yields $b = 0$. Thus $u = 0$.

2.3.8 (b) Separation of variables, $u = \phi(x)h(t)$ or $\phi \frac{dh}{dt} + \alpha\phi h = kh \frac{d^2\phi}{dx^2}$, yields two ordinary differential equations (divide by $k\phi h$): $\frac{1}{kh} \frac{dh}{dt} + \frac{\alpha}{k} = \frac{1}{\phi} \frac{d^2\phi}{dx^2} = -\lambda$. Applying the boundary conditions, yields the eigenvalues $\lambda = (n\pi/L)^2$ and corresponding eigenfunctions $\phi = \sin \frac{n\pi x}{L}$. The time-dependent part are exponentials, $h = e^{-\lambda kt} e^{-\alpha t}$. Thus by superposition, $u(x, t) = e^{-\alpha t} \sum_{n=1}^{\infty} b_n \sin \frac{n\pi x}{L} e^{-k(n\pi/L)^2 t}$, where the initial conditions $u(x, 0) = f(x) = \sum_{n=1}^{\infty} b_n \sin \frac{n\pi x}{L}$ yields $b_n = \frac{2}{L} \int_0^L f(x) \sin \frac{n\pi x}{L} dx$. As $t \rightarrow \infty$, $u \rightarrow 0$, the only equilibrium solution.

2.3.9 (a) If $\alpha < 0$, the general equilibrium solution is $u(x) = a \cos \sqrt{\frac{-\alpha}{k}} x + b \sin \sqrt{\frac{-\alpha}{k}} x$. The boundary condition $u(0) = 0$ yields $a = 0$, while $u(L) = 0$ yields $b \sin \sqrt{\frac{-\alpha}{k}} L = 0$. Thus if $\sqrt{\frac{-\alpha}{k}} L \neq n\pi$, $u = 0$ is the only equilibrium solution. However, if $\sqrt{\frac{-\alpha}{k}} L = n\pi$, then $u = A \sin \frac{n\pi x}{L}$ is an equilibrium solution.

2.3.9 (b) Solution obtained in 2.3.8 is correct. If $-\frac{\alpha}{k} = \left(\frac{\pi}{L}\right)^2$, $u(x, t) \rightarrow b_1 \sin \frac{\pi x}{L}$, the equilibrium solution. If $-\frac{\alpha}{k} < \left(\frac{\pi}{L}\right)^2$, then $u \rightarrow 0$ as $t \rightarrow \infty$. However, if $-\frac{\alpha}{k} > \left(\frac{\pi}{L}\right)^2$, $u \rightarrow \infty$ (if $b_1 \neq 0$). Note that $b_1 > 0$ if $f(x) \geq 0$. Other more unusual events can occur if $b_1 = 0$. [Essentially, the other possible equilibrium solutions are unstable.]

Section 2.4

2.4.1 The solution is given by (2.4.19), where the coefficients satisfy (2.4.21) and hence (2.4.23-24).

$$(a) A_0 = \frac{1}{L} \int_{L/2}^L 1 dx = \frac{1}{2}, A_n = \frac{2}{L} \int_{L/2}^L \cos \frac{n\pi x}{L} dx = \frac{2}{L} \cdot \frac{L}{n\pi} \sin \frac{n\pi x}{L} \Big|_{L/2}^L = -\frac{2}{n\pi} \sin \frac{n\pi}{2}$$

(b) by inspection $A_0 = 6, A_3 = 4$, others = 0.

$$(c) A_0 = \frac{-2}{L} \int_0^L \sin \frac{\pi x}{L} dx = \frac{2}{\pi} \cos \frac{\pi x}{L} \Big|_0^L = \frac{2}{\pi} (1 - \cos \pi) = 4/\pi, A_n = \frac{-4}{L} \int_0^L \sin \frac{\pi x}{L} \cos \frac{n\pi x}{L} dx$$

(d) by inspection $A_8 = -3$, others = 0.

2.4.3 Let $x' = x - \pi$. Then the boundary value problem becomes $d^2\phi/dx'^2 = -\lambda\phi$ subject to $\phi(-\pi) = \phi(\pi)$ and $d\phi/dx'(-\pi) = d\phi/dx'(\pi)$. Thus, the eigenvalues are $\lambda = (n\pi/L)^2 = n^2\pi^2$, since $L = \pi, n = 0, 1, 2, \dots$ with the corresponding eigenfunctions being both $\sin n\pi x'/L = \sin n(x-\pi) = (-1)^n \sin nx \Rightarrow \sin nx$ and $\cos n\pi x'/L = \cos n(x-\pi) = (-1)^n \cos nx \Rightarrow \cos nx$.

Section 2.5

2.5.1 (a) Separation of variables, $u(x, y) = h(x)\phi(y)$, implies that $\frac{1}{h} \frac{d^2h}{dx^2} = -\frac{1}{\phi} \frac{d^2\phi}{dy^2} = -\lambda$. Thus $d^2h/dx^2 = -\lambda h$ subject to $h'(0) = 0$ and $h'(L) = 0$. Thus as before, $\lambda = (n\pi/L)^2, n = 0, 1, 2, \dots$ with $h(x) = \cos n\pi x/L$. Furthermore, $\frac{d^2\phi}{dy^2} = \lambda\phi = \left(\frac{n\pi}{L}\right)^2 \phi$ so that

$$n = 0 : \phi = c_1 + c_2 y, \text{ where } \phi(0) = 0 \text{ yields } c_1 = 0$$

$$n \neq 0 : \phi = c_1 \cosh \frac{n\pi y}{L} + c_2 \sinh \frac{n\pi y}{L}, \text{ where } \phi(0) = 0 \text{ yields } c_1 = 0.$$

The result of superposition is

$$u(x, y) = A_0 y + \sum_{n=1}^{\infty} A_n \cos \frac{n\pi x}{L} \sinh \frac{n\pi y}{L}.$$

The nonhomogeneous boundary condition yields

$$f(x) = A_0 H + \sum_{n=1}^{\infty} A_n \sinh \frac{n\pi H}{L} \cos \frac{n\pi x}{L},$$

so that

$$A_0 H = \frac{1}{L} \int_0^L f(x) dx \text{ and } A_n \sinh \frac{n\pi H}{L} = \frac{2}{L} \int_0^L f(x) \cos \frac{n\pi x}{L} dx.$$

2.5.1 (c) Separation of variables, $u = h(x)\phi(y)$, yields $\frac{1}{h} \frac{d^2 h}{dx^2} = -\frac{1}{\phi} \frac{d^2 \phi}{dy^2} = \lambda$. The boundary conditions $\phi(0) = 0$ and $\phi(H) = 0$ yield an eigenvalue problem in y , whose solution is $\lambda = (n\pi/H)^2$ with $\phi = \sin n\pi y/H, n = 1, 2, 3, \dots$. The solution of the x -dependent equation is $h(x) = \cosh n\pi x/H$ using $dh/dx(0) = 0$. By superposition:

$$u(x, y) = \sum_{n=1}^{\infty} A_n \cosh \frac{n\pi x}{H} \sin \frac{n\pi y}{H}.$$

The nonhomogeneous boundary condition at $x = L$ yields $g(y) = \sum_{n=1}^{\infty} A_n \cosh \frac{n\pi L}{H} \sin \frac{n\pi y}{H}$, so that A_n is determined by $A_n \cosh \frac{n\pi L}{H} = \frac{2}{H} \int_0^H g(y) \sin \frac{n\pi y}{H} dy$.

2.5.1 (e) Separation of variables, $u = \phi(x)h(y)$, yields the eigenvalues $\lambda = (n\pi/L)^2$ and corresponding eigenfunctions $\phi = \sin n\pi x/L, n = 1, 2, 3, \dots$. The y -dependent differential equation, $\frac{d^2 h}{dy^2} = \left(\frac{n\pi}{L}\right)^2 h$, satisfies $h(0) - \frac{dh}{dy}(0) = 0$. The general solution $h = c_1 \cosh \frac{n\pi y}{L} + c_2 \sinh \frac{n\pi y}{L}$ obeys $h(0) = c_1$, while $\frac{dh}{dy} = \frac{n\pi}{L} (c_1 \sinh \frac{n\pi y}{L} + c_2 \cosh \frac{n\pi y}{L})$ obeys $\frac{dh}{dy}(0) = c_2 \frac{n\pi}{L}$. Thus, $c_1 = c_2 \frac{n\pi}{L}$ and hence $h_n(y) = \cosh \frac{n\pi y}{L} + \frac{L}{n\pi} \sinh \frac{n\pi y}{L}$. Superposition yields

$$u(x, y) = \sum_{n=1}^{\infty} A_n h_n(y) \sin n\pi x/L,$$

where A_n is determined from the boundary condition, $f(x) = \sum_{n=1}^{\infty} A_n h_n(H) \sin n\pi x/L$, and hence

$$A_n h_n(H) = \frac{2}{L} \int_0^L f(x) \sin n\pi x/L dx.$$

2.5.2 (a) From physical reasoning (or exercise 1.5.8), the total heat flow across the boundary must equal zero in equilibrium (without sources, i.e. Laplace's equation). Thus $\int_0^L f(x) dx = 0$ for a solution.

2.5.3 In order for u to be bounded as $r \rightarrow \infty, c_1 = 0$ in (2.5.43) and $\bar{c}_2 = 0$ in (2.5.44). Thus,

$$u(r, \theta) = \sum_{n=0}^{\infty} A_n r^{-n} \cos n\theta + \sum_{n=1}^{\infty} B_n r^{-n} \sin n\theta.$$

(a) The boundary condition yields $A_0 = \ln 2, A_3 a^{-3} = 4$, other $A_n = 0, B_n = 0$.

(b) The boundary conditions yield (2.5.46) with a^{-n} replacing a^n . Thus, the coefficients are determined by (2.5.47) with a^n replaced by a^{-n} .

2.5.4 By substituting (2.5.47) into (2.5.45) and interchanging the orders of summation and integration

$$u(r, \theta) = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\bar{\theta}) \left[\frac{1}{2} + \sum_{n=1}^{\infty} \left(\frac{r}{a}\right)^n (\cos n\theta \cos n\bar{\theta} + \sin n\theta \sin n\bar{\theta}) \right] d\bar{\theta}.$$

Noting the trigonometric addition formula and $\cos z = \text{Re}[e^{iz}]$, we obtain

$$u(r, \theta) = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\bar{\theta}) \left[-\frac{1}{2} + \text{Re} \sum_{n=0}^{\infty} \left(\frac{r}{a}\right)^n e^{in(\theta-\bar{\theta})} \right] d\bar{\theta}.$$

Summing the geometric series enables the bracketed term to be replaced by

$$-\frac{1}{2} + \text{Re} \frac{1}{1 - \frac{r}{a} e^{i(\theta-\bar{\theta})}} = -\frac{1}{2} + \frac{1 - \frac{r}{a} \cos(\theta-\bar{\theta})}{1 + \frac{r^2}{a^2} - \frac{2r}{a} \cos(\theta-\bar{\theta})} = \frac{\frac{1}{2} - \frac{1}{2} \frac{r^2}{a^2}}{1 + \frac{r^2}{a^2} - \frac{2r}{a} \cos(\theta-\bar{\theta})}.$$

2.5.5 (a) The eigenvalue problem is $d^2\phi/d\theta^2 = -\lambda\phi$ subject to $d\phi/d\theta(0) = 0$ and $\phi(\pi/2) = 0$. It can be shown that $\lambda > 0$ so that $\phi = \cos\sqrt{\lambda}\theta$ where $\phi(\pi/2) = 0$ implies that $\cos\sqrt{\lambda}\pi/2 = 0$ or $\sqrt{\lambda}\pi/2 = -\pi/2 + n\pi, n = 1, 2, 3, \dots$. The eigenvalues are $\lambda = (2n - 1)^2$. The radially dependent term satisfies (2.5.40), and hence the boundedness condition at $r = 0$ yields $G(r) = r^{2n-1}$. Superposition yields

$$u(r, \theta) = \sum_{n=1}^{\infty} A_n r^{2n-1} \cos(2n - 1)\theta.$$

The nonhomogeneous boundary condition becomes

$$f(\theta) = \sum_{n=1}^{\infty} A_n \cos(2n - 1)\theta \quad \text{or} \quad A_n = \frac{4}{\pi} \int_0^{\pi/2} f(\theta) \cos(2n - 1)\theta \, d\theta.$$

2.5.5 (c) The boundary conditions of (2.5.37) must be replaced by $\phi(0) = 0$ and $\phi(\pi/2) = 0$. Thus, $L = \pi/2$, so that $\lambda = (n\pi/L)^2 = (2n)^2$ and $\phi = \sin \frac{n\pi\theta}{L} = \sin 2n\theta$. The radial part that remains bounded at $r = 0$ is $G = r^{\sqrt{\lambda}} = r^{2n}$. By superposition,

$$u(r, \theta) = \sum_{n=1}^{\infty} A_n r^{2n} \sin 2n\theta.$$

To apply the nonhomogeneous boundary condition, we differentiate with respect to r :

$$\frac{\partial u}{\partial r} = \sum_{n=1}^{\infty} A_n (2n) r^{2n-1} \sin 2n\theta.$$

The bc at $r = 1$, $f(\theta) = \sum_{n=1}^{\infty} 2nA_n \sin 2n\theta$, determines $A_n, 2nA_n = \frac{4}{\pi} \int_0^{\pi/2} f(\theta) \sin 2n\theta \, d\theta$.

2.5.6 (a) The boundary conditions of (2.5.37) must be replaced by $\phi(0) = 0$ and $\phi(\pi) = 0$. Thus $L = \pi$, so that the eigenvalues are $\lambda = (n\pi/L)^2 = n^2$ and corresponding eigenfunctions $\phi = \sin n\pi\theta/L = \sin n\theta, n = 1, 2, 3, \dots$. The radial part which is bounded at $r = 0$ is $G = r^{\sqrt{\lambda}} = r^n$. Thus by superposition

$$u(r, \theta) = \sum_{n=1}^{\infty} A_n r^n \sin n\theta.$$

The bc at $r = a$, $g(\theta) = \sum_{n=1}^{\infty} A_n a^n \sin n\theta$, determines $A_n, A_n a^n = \frac{2}{\pi} \int_0^{\pi} g(\theta) \sin n\theta \, d\theta$.

2.5.7 (b) The boundary conditions of (2.5.37) must be replaced by $\phi'(0) = 0$ and $\phi'(\pi/3) = 0$. This will yield a cosine series with $L = \pi/3, \lambda = (n\pi/L)^2 = (3n)^2$ and $\phi = \cos n\pi\theta/L = \cos 3n\theta, n = 0, 1, 2, \dots$. The radial part which is bounded at $r = 0$ is $G = r^{\sqrt{\lambda}} = r^{3n}$. Thus by superposition

$$u(r, \theta) = \sum_{n=0}^{\infty} A_n r^{3n} \cos 3n\theta.$$

The boundary condition at $r = a$, $g(\theta) = \sum_{n=0}^{\infty} A_n a^{3n} \cos 3n\theta$, determines A_n : $A_0 = \frac{3}{\pi} \int_0^{\pi/3} g(\theta) \, d\theta$ and $(n \neq 0) A_n a^{3n} = \frac{6}{\pi} \int_0^{\pi/3} g(\theta) \cos 3n\theta \, d\theta$.

2.5.8 (a) There is a full Fourier series in θ . It is easier (but equivalent) to choose radial solutions that satisfy the corresponding homogeneous boundary condition. Instead of r^n and r^{-n} (1 and $\ln r$ for $n = 0$), we choose $\phi_1(r)$ such that $\phi_1(a) = 0$ and $\phi_2(r)$ such that $\phi_2(b) = 0$:

$$\phi_1(r) = \begin{cases} \ln(r/a) & n = 0 \\ \left(\frac{r}{a}\right)^n - \left(\frac{a}{r}\right)^n & n \neq 0 \end{cases} \quad \phi_2(r) = \begin{cases} \ln(r/b) & n = 0 \\ \left(\frac{r}{b}\right)^n - \left(\frac{b}{r}\right)^n & n \neq 0 \end{cases}.$$

Then by superposition

$$u(r, \theta) = \sum_{n=0}^{\infty} \cos n\theta [A_n \phi_1(r) + B_n \phi_2(r)] + \sum_{n=1}^{\infty} \sin n\theta [C_n \phi_1(r) + D_n \phi_2(r)].$$

The boundary conditions at $r = a$ and $r = b$,

$$f(\theta) = \sum_{n=0}^{\infty} \cos n\theta [A_n \phi_1(a) + B_n \phi_2(a)] + \sum_{n=1}^{\infty} \sin n\theta [C_n \phi_1(a) + D_n \phi_2(a)]$$

$$g(\theta) = \sum_{n=0}^{\infty} \cos n\theta [A_n \phi_1(b) + B_n \phi_2(b)] + \sum_{n=1}^{\infty} \sin n\theta [C_n \phi_1(b) + D_n \phi_2(b)]$$

easily determine A_n, B_n, C_n, D_n since $\phi_1(a) = 0$ and $\phi_2(b) = 0 : D_n \phi_2(a) = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\theta) \sin n\theta d\theta$, etc.

2.5.9 (a) The boundary conditions of (2.5.37) must be replaced by $\phi(0) = 0$ and $\phi(\pi/2) = 0$. This is a sine series with $L = \pi/2$ so that $\lambda = (n\pi/L)^2 = (2n)^2$ and the eigenfunctions are $\phi = \sin n\pi\theta/L = \sin 2n\theta, n = 1, 2, 3, \dots$. The radial part which is zero at $r = a$ is $G = (r/a)^{2n} - (a/r)^{2n}$. Thus by superposition,

$$u(r, \theta) = \sum_{n=1}^{\infty} A_n \left[\left(\frac{r}{a} \right)^{2n} - \left(\frac{a}{r} \right)^{2n} \right] \sin 2n\theta.$$

The nonhomogeneous boundary condition, $f(\theta) = \sum_{n=1}^{\infty} A_n \left[\left(\frac{b}{a} \right)^{2n} - \left(\frac{a}{b} \right)^{2n} \right] \sin 2n\theta$, determines $A_n : A_n \left[\left(\frac{b}{a} \right)^{2n} - \left(\frac{a}{b} \right)^{2n} \right] = \frac{4}{\pi} \int_0^{\pi/2} f(\theta) \sin 2n\theta d\theta$.

2.5.9 (b) The two homogeneous boundary conditions are in r , and hence $\phi(r)$ must be an eigenvalue problem. By separation of variables, $u = \phi(r)G(\theta), d^2G/d\theta^2 = \lambda G$ and $r^2 \frac{d^2\phi}{dr^2} + r \frac{d\phi}{dr} + \lambda\phi = 0$. The radial equation is equidimensional (see p.78) and solutions are in the form $\phi = r^p$. Thus $p^2 = -\lambda$ (with $\lambda > 0$) so that $p = \pm i\sqrt{\lambda}$. $r^{\pm i\sqrt{\lambda}} = e^{\pm i\sqrt{\lambda} \ln r}$. Thus real solutions are $\cos(\sqrt{\lambda} \ln r)$ and $\sin(\sqrt{\lambda} \ln r)$. It is more convenient to use independent solutions which simplify at $r = a, \cos[\sqrt{\lambda} \ln(r/a)]$ and $\sin[\sqrt{\lambda} \ln(r/a)]$. Thus the general solution is

$$\phi = c_1 \cos[\sqrt{\lambda} \ln(r/a)] + c_2 \sin[\sqrt{\lambda} \ln(r/a)].$$

The homogeneous condition $\phi(a) = 0$ yields $0 = c_1$, while $\phi(b) = 0$ implies $\sin[\sqrt{\lambda} \ln(r/a)] = 0$. Thus $\sqrt{\lambda} \ln(b/a) = n\pi, n = 1, 2, 3, \dots$ and the corresponding eigenfunctions are $\phi = \sin \left[n\pi \frac{\ln(r/a)}{\ln(b/a)} \right]$. The solution of the θ -equation satisfying $G(0) = 0$ is $G = \sinh \sqrt{\lambda}\theta = \sinh \frac{n\pi\theta}{\ln(b/a)}$. Thus by superposition

$$u = \sum_{n=1}^{\infty} A_n \sinh \frac{n\pi\theta}{\ln(b/a)} \sin \left[n\pi \frac{\ln(r/a)}{\ln(b/a)} \right].$$

The nonhomogeneous boundary condition,

$$f(r) = \sum_{n=1}^{\infty} A_n \sinh \frac{n\pi^2}{2 \ln(b/a)} \sin \left[n\pi \frac{\ln(r/a)}{\ln(b/a)} \right],$$

will determine A_n . One method (for another, see exercise 5.3.9) is to let $z = \ln(r/a)/\ln(b/a)$. Then $a < r < b$, lets $0 < z < 1$. This is a sine series in z (with $L = 1$) and hence

$$A_n \sinh \frac{n\pi^2}{2 \ln(b/a)} = 2 \int_0^1 f(r) \sin \left[n\pi \frac{\ln(r/a)}{\ln(b/a)} \right] dz.$$

But $dz = dr/r \ln(b/a)$. Thus

$$A_n \sinh \frac{n\pi^2}{2 \ln(b/a)} = \frac{2}{\ln(b/a)} \int_0^1 f(r) \sin \left[n\pi \frac{\ln(r/a)}{\ln(b/a)} \right] dr/r.$$