

Objectives

In this lesson we will learn:

- ▶ to classify second order, two-point boundary value problems,
- ▶ to place boundary value problems in self-adjoint form,
- ▶ properties of the eigenvalues and eigenfunctions of boundary value problems.

This enables us to generalize the method of separation of variables.

Boundary Value Problems

MATH 467 *Partial Differential Equations*

J Robert Buchanan

Department of Mathematics

Fall 2022

Background

When solving the heat equation for $0 \leq x \leq L$ with homogeneous boundary conditions we had to solve the induced **boundary value problem**:

$$\begin{aligned} X''(x) + \lambda X(x) &= 0 \\ X(0) &= 0 \\ X(L) &= 0. \end{aligned}$$

We saw that nontrivial solutions existed only if

$$\begin{aligned} \lambda &= \lambda_n = \frac{n^2 \pi^2}{L^2} \\ X(x) &= X_n(x) = \sin \frac{n\pi x}{L} \text{ for } n \in \mathbb{N}. \end{aligned}$$

The set $\{\lambda_n\}_{n=1}^{\infty}$ is called the set of **eigenvalues** and $\{X_n(x)\}_{n=1}^{\infty}$ is the corresponding set of **eigenfunctions**.

Generalization

Consider the following second-order, linear homogeneous ODE of the form

$$P(x)y''(x) + Q(x)y'(x) + R(x)y(x) = 0 \text{ for } a < x < b.$$

Suppose that $P(x)$, $Q(x)$, and $R(x)$ are continuous on interval $[a, b]$ and that $P(x) \neq 0$ for all x in $[a, b]$.

- ▶ If $Q(x) = P'(x)$ then the ODE can be written as

$$[P(x)y'(x)]' + R(x)y(x) = 0.$$

- ▶ If $Q(x) \neq P'(x)$ multiply both sides of the ODE by

$$r(x) = \frac{1}{P(x)} e^{\int_a^x Q(s)/P(s) ds} = \frac{p(x)}{P(x)}.$$

Self-Adjoint Form

$$\begin{aligned} P(x)y''(x) + Q(x)y'(x) + R(x)y(x) &= 0 \\ r(x)P(x)y''(x) + r(x)Q(x)y'(x) + r(x)R(x)y(x) &= 0 \\ p(x)y''(x) + p'(x)y'(x) + q(x)y(x) &= 0 \\ [p(x)y'(x)]' + q(x)y(x) &= 0 \end{aligned}$$

where $q(x) = r(x)R(x)$.

An ODE written in this last form is called **self-adjoint**.

Example

Suppose $0 < a \leq x \leq b$ and express the following ODE in self-adjoint form.

$$x y''(x) + (1 - x)y'(x) + y(x) = 0$$

Note that

$$r(x) = \frac{1}{x} e^{\int_a^x (1-s)/s ds} = \frac{1}{a} e^{-x+a}.$$

Multiplying both sides of the ODE by $r(x)$ produces,

$$\begin{aligned} x y''(x) + (1 - x)y'(x) + y(x) &= 0 \\ \frac{x}{a} e^{-x+a} y''(x) + \frac{1}{a} e^{-x+a} (1 - x)y'(x) + \frac{1}{a} e^{-x+a} y(x) &= 0 \\ [x e^{-x+a} y'(x)]' + e^{-x+a} y(x) &= 0. \end{aligned}$$

Introduction of Operator Notation

Given that the ODE:

$$P(x)y''(x) + Q(x)y'(x) + R(x)y(x) = 0$$

can be written in the self-adjoint form:

$$[p(x)y'(x)]' + q(x)y(x) = 0$$

define the **linear operator**,

$$L[y] = [p(x)y']' + q(x)y.$$

Sturm-Liouville BVP (1 of 2)

Consider a second-order linear ODE and boundary conditions:

$$\begin{aligned} [p(x)y']' + (q(x) + \lambda r(x))y &= 0 \text{ for } a < x < b \\ \alpha_1 y(a) + \beta_1 y'(a) &= 0 \\ \alpha_2 y(b) + \beta_2 y'(b) &= 0, \end{aligned}$$

where $\alpha_1^2 + \beta_1^2 \neq 0$ and $\alpha_2^2 + \beta_2^2 \neq 0$.

Remarks:

- ▶ This is known as a **Sturm-Liouville BVP** with **separated boundary conditions**.
- ▶ The unknown constant λ is the **eigenvalue parameter**.
- ▶ The function $r(x)$ is called the **weight function**.
- ▶ The solution $y(x)$ is the **eigenfunction** corresponding to λ .

Sturm-Liouville BVP (2 of 2)

The boundary value problem can be concisely written as,

$$L[y] + \lambda r(x)y = 0 \text{ for } a < x < b$$

$$\alpha_1 y(a) + \beta_1 y'(a) = 0$$

$$\alpha_2 y(b) + \beta_2 y'(b) = 0.$$

Remarks: if

- ▶ $p(a) = 0$ or $p(b) = 0$, or
- ▶ $p(a) = \pm\infty$, $p(b) = \pm\infty$, $q(a) = \pm\infty$, $q(b) = \pm\infty$, $r(a) = \pm\infty$, or $r(b) = \pm\infty$, or
- ▶ $a = \pm\infty$ or $b = \pm\infty$, then

the BVP is **singular**. Otherwise the BVP is **regular**.

Example

Find the eigenvalues and eigenfunctions of the regular Sturm-Liouville BVP:

$$y''(x) + \frac{1}{x}y'(x) + \frac{\lambda}{x^2}y(x) = 0 \text{ for } 1 < x < 2$$

$$y(1) = 0$$

$$y(2) = 0.$$

Hint: make the change of variable $z = \ln x$.

Solution (1 of 5)

$$\begin{aligned} \frac{dy}{dx} &= \frac{dy}{dz} \frac{dz}{dx} = \frac{1}{x} \frac{dy}{dz} = e^{-z} \frac{dy}{dz} \\ \frac{d^2y}{dx^2} &= \frac{d}{dx} \left[e^{-z} \frac{dy}{dz} \right] = e^{-2z} \frac{dy}{dz} + e^{-2z} \frac{d^2y}{dz^2} \end{aligned}$$

Substituting into the BVP yields:

$$\begin{aligned} e^{-2z} \frac{d^2y}{dz^2} + e^{-2z} e^{-z} \frac{dy}{dz} + \lambda (e^{-z})^2 y &= 0 \text{ for } 0 < z < \ln 2 \\ y''(z) + 2y'(z) + \lambda y(z) &= 0 \text{ for } 0 < z < \ln 2. \end{aligned}$$

Solution (2 of 5)

If $\lambda = 1$ the general solution can be expressed as

$$y(z) = (C_1 + C_2 z) e^{-z} \implies y(x) = (C_1 + C_2 \ln x) \frac{1}{x}.$$

Using the boundary conditions:

$$y(1) = 0 = (C_1 + C_2 \ln 1) \frac{1}{1} \implies C_1 = 0$$

$$y(2) = 0 = \frac{C_2}{2} \ln 2 \implies C_2 = 0.$$

Solution (3 of 5)

If $\lambda < 1$ the general solution can be expressed as

$$\begin{aligned} y(z) &= C_1 e^{(-1-(1-\lambda)^{1/2})z} + C_2 e^{(-1+(1-\lambda)^{1/2})z} \\ y(x) &= C_1 x^{(-1-(1-\lambda)^{1/2})} + C_2 x^{(-1+(1-\lambda)^{1/2})}. \end{aligned}$$

Using the boundary conditions:

$$\begin{aligned} y(1) = 0 &= C_1 + C_2 \implies C_1 = -C_2 \\ y(2) = 0 &= C_1 2^{(-1-(1-\lambda)^{1/2})} - C_1 2^{(-1+(1-\lambda)^{1/2})} \implies C_1 = C_2 = 0. \end{aligned}$$

Solution (4 of 5)

If $\lambda > 1$ the general solution can be expressed as

$$\begin{aligned} y(z) &= C_1 e^{(-1-i(\lambda-1)^{1/2})z} + C_2 e^{(-1+i(\lambda-1)^{1/2})z} \\ y(x) &= \frac{1}{x} \left(C_1 \cos((\lambda-1)^{1/2} \ln x) + C_2 \sin((\lambda-1)^{1/2} \ln x) \right). \end{aligned}$$

Using the boundary conditions:

$$\begin{aligned} y(1) = 0 &= C_1 \\ y(2) = 0 &= \frac{C_2}{2} \sin((\lambda-1)^{1/2} \ln 2). \end{aligned}$$

- ▶ If $C_2 = 0$ then there are no nontrivial solutions.
- ▶ If $C_2 \neq 0$ then $(\lambda-1)^{1/2} \ln 2 = n\pi$ for $n \in \mathbb{N}$.

Solution (5 of 5)

Finally, the eigenvalues are

$$\lambda = \lambda_n = 1 + \frac{n^2 \pi^2}{(\ln 2)^2}$$

with corresponding eigenfunctions

$$y(x) = y_n(x) = \frac{1}{x} \sin\left(\frac{n\pi}{\ln 2} \ln x\right)$$

for $n \in \mathbb{N}$.

Nontrivial Solutions (1 of 3)

Let $y_1(x)$ and $y_2(x)$ be any two linearly independent solutions to the BVP:

$$\begin{aligned} L[y] &= [p(x)y']' + q(x)y = 0 \text{ for } a < x < b \\ \alpha_1 y(a) + \beta_1 y'(a) &= 0 \\ \alpha_2 y(b) + \beta_2 y'(b) &= 0, \end{aligned}$$

where $\alpha_1^2 + \beta_1^2 \neq 0$ and $\alpha_2^2 + \beta_2^2 \neq 0$.

If $y(x)$ is any nontrivial solution to the BVP then there exist constants C_1 and C_2 such that

$$y(x) = C_1 y_1(x) + C_2 y_2(x).$$

Nontrivial Solutions (2 of 3)

Since $y(x)$ satisfies the boundary conditions at $x = a$ and $x = b$, then

$$\begin{bmatrix} \alpha_1 y_1(a) + \beta_1 y_1'(a) & \alpha_1 y_2(a) + \beta_1 y_2'(a) \\ \alpha_2 y_1(b) + \beta_2 y_1'(b) & \alpha_2 y_2(b) + \beta_2 y_2'(b) \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

The matrix equation has nontrivial solutions if and only if

$$\begin{vmatrix} \alpha_1 y_1(a) + \beta_1 y_1'(a) & \alpha_1 y_2(a) + \beta_1 y_2'(a) \\ \alpha_2 y_1(b) + \beta_2 y_1'(b) & \alpha_2 y_2(b) + \beta_2 y_2'(b) \end{vmatrix} = 0.$$

Nontrivial Solutions (3 of 3)

We can summarize these results as the following theorem.

Theorem

The BVP:

$$\begin{aligned} [p(x)y']' + q(x)y &= 0 \text{ for } a < x < b \\ \alpha_1 y(a) + \beta_1 y'(a) &= 0 \\ \alpha_2 y(b) + \beta_2 y'(b) &= 0, \end{aligned}$$

where $\alpha_1^2 + \beta_1^2 \neq 0$ and $\alpha_2^2 + \beta_2^2 \neq 0$ has a nontrivial solution if and only if for any two linearly independent solutions y_1 and y_2 of the BVP,

$$\begin{vmatrix} \alpha_1 y_1(a) + \beta_1 y_1'(a) & \alpha_1 y_2(a) + \beta_1 y_2'(a) \\ \alpha_2 y_1(b) + \beta_2 y_1'(b) & \alpha_2 y_2(b) + \beta_2 y_2'(b) \end{vmatrix} = 0.$$

In this case all solutions are $u(x) = C y(x)$ where y is any nontrivial solution of the BVP and C is any constant.

Example

Find a nontrivial solution to the BVP problem if a nontrivial solution exists.

$$\begin{aligned} x^2 y''(x) + x y(x) - 4y(x) &= 0 \text{ for } 1 < x < 2 \\ 2y(1) + y'(1) &= 0 \\ y(2) + y'(2) &= 0 \end{aligned}$$

Solution

The ODE is Euler's equation for which two linearly independent solutions are $y_1(x) = x^2$ and $y_2(x) = x^{-2}$.

Suppose $y(x) = C_1 x^2 + C_2 x^{-2}$ then to satisfy the boundary conditions:

$$\begin{aligned} 0 &= 2y(1) + y'(1) = 2C_1 + 2C_2 + 2C_1 - 2C_2 \implies C_1 = 0 \\ 0 &= y(2) + y'(2) = \frac{C_2}{4} - \frac{2C_2}{8} \end{aligned}$$

which is true for any choice of C_2 .

Every nontrivial solution to the BVP has the form $y(x) = C/x^2$ where $C \neq 0$ is a constant.

<div data-bbox="23 1800 67 2150" data-label="Section-Header"> <h2>Lagrange's Identity</h2> </div> <div data-bbox="210 1655 248 2092" data-label="Section-Header"> <h3>Lemma (Lagrange's Identity)</h3> </div> <div data-bbox="255 1680 287 2092" data-label="Text"> <p>Let L be the operator defined as</p> </div> <div data-bbox="317 1494 354 1798" data-label="Equation-Block"> $L[y] = [p(x)y']' + q(x)y$ </div> <div data-bbox="384 1223 451 2092" data-label="Text"> <p>and let u and v be any twice continuously differentiable functions on (a, b), then</p> </div> <div data-bbox="481 1323 555 1968" data-label="Equation-Block"> $uL[v] - vL[u] = \frac{d}{dx} \left[p(x) \left(u(x) \frac{dv}{dx} - v(x) \frac{du}{dx} \right) \right].$ </div>	<div data-bbox="23 786 67 1095" data-label="Section-Header"> <h2>Green's Formula</h2> </div> <div data-bbox="210 633 248 1037" data-label="Section-Header"> <h3>Lemma (Green's Formula)</h3> </div> <div data-bbox="255 624 287 1037" data-label="Text"> <p>Let L be the operator defined as</p> </div> <div data-bbox="317 441 354 745" data-label="Equation-Block"> $L[y] = [p(x)y']' + q(x)y$ </div> <div data-bbox="384 165 451 1037" data-label="Text"> <p>and let u and v be any twice continuously differentiable functions on (a, b), then</p> </div> <div data-bbox="481 219 561 963" data-label="Equation-Block"> $\int_a^b (uL[v] - vL[u]) \, dx = \left[p(x) \left(u(x) \frac{dv}{dx} - v(x) \frac{du}{dx} \right) \right]_{x=a}^{x=b}.$ </div>
<div data-bbox="821 1850 865 2150" data-label="Section-Header"> <h2>Picone's Identity</h2> </div> <div data-bbox="991 1695 1029 2092" data-label="Section-Header"> <h3>Lemma (Picone's Identity)</h3> </div> <div data-bbox="1035 1249 1102 2092" data-label="Text"> <p>Suppose that $u(x)$ and $v(x)$ are solutions to the following ordinary differential equations:</p> </div> <div data-bbox="1133 1503 1165 1798" data-label="Equation-Block"> $[p_1(x)u']' + q_1(x)u = 0$ </div> <div data-bbox="1184 1496 1216 1798" data-label="Equation-Block"> $[p_2(x)v']' + q_2(x)v = 0.$ </div> <div data-bbox="1246 1433 1281 2092" data-label="Text"> <p>For all x such that $v(x) \neq 0$, Picone's Identity holds,</p> </div> <div data-bbox="1311 1202 1378 2092" data-label="Equation-Block"> $\left[\frac{u}{v} (p_1 u' v - p_2 u v') \right]' = (q_2 - q_1)u^2 + (p_1 - p_2)(u')^2 + \frac{p_2(u' v - uv')^2}{v^2}.$ </div>	<div data-bbox="821 620 865 1095" data-label="Section-Header"> <h2>Multiplicity of Eigenvalues</h2> </div> <div data-bbox="1023 795 1053 1037" data-label="Text"> <p>Consider the ODE:</p> </div> <div data-bbox="1083 201 1120 983" data-label="Equation-Block"> $L[y](x) + \lambda r(x)y(x) = [p(x)y'(x)]' + (q(x) + \lambda r(x))y(x) = 0.$ </div> <div data-bbox="1163 893 1197 1037" data-label="Section-Header"> <h3>Definition</h3> </div> <div data-bbox="1201 221 1340 1037" data-label="Text"> <p>An eigenvalue λ is said to be simple if there is only one linearly independent eigenfunction ϕ corresponding to λ. If there exist k linearly independent eigenfunctions corresponding to λ, the eigenvalue is said to be of multiplicity k.</p> </div>

<div data-bbox="23 1473 67 2150" data-label="Section-Header"> <h2>Eigenvalues of Sturm-Liouville BVPs</h2> </div> <div data-bbox="229 1953 261 2092" data-label="Section-Header"> <h3>Theorem</h3> </div> <div data-bbox="268 1200 335 2092" data-label="Text"> <p>All eigenvalues of the regular Sturm-Liouville boundary value problem with separated boundary conditions:</p> </div> <div data-bbox="363 1319 488 1973" data-label="Equation-Block"> $[p(x)y'(x)]' + (q(x) + \lambda r(x))y(x) = 0 \text{ for } a < x < b$ $\alpha_1 y(a) + \beta_1 y'(a) = 0$ $\alpha_2 y(b) + \beta_2 y'(b) = 0,$ </div> <div data-bbox="518 1514 557 2092" data-label="Text"> <p>with $\alpha_1^2 + \beta_1^2 \neq 0$ and $\alpha_2^2 + \beta_2^2 \neq 0$ are simple.</p> </div>	<div data-bbox="23 409 67 1093" data-label="Section-Header"> <h2>Inner Products and Weight Functions</h2> </div> <div data-bbox="236 891 268 1037" data-label="Section-Header"> <h3>Definition</h3> </div> <div data-bbox="274 197 411 1037" data-label="Text"> <p>Let $f(x)$ and $g(x)$ be two integrable functions on the interval $[a, b]$, and let $\rho(x)$ be a positive, continuous function on $[a, b]$. The weighted inner product of f and g with respect to ρ on $[a, b]$ denoted as $\langle \cdot, \cdot \rangle_\rho$ is</p> </div> <div data-bbox="442 407 520 777" data-label="Equation-Block"> $\langle f, g \rangle_\rho = \int_a^b f(x)g(x)\rho(x) \, dx.$ </div>
<div data-bbox="821 1901 865 2150" data-label="Section-Header"> <h2>Orthogonality</h2> </div> <div data-bbox="976 1953 1008 2092" data-label="Section-Header"> <h3>Theorem</h3> </div> <div data-bbox="1015 1438 1046 2092" data-label="Text"> <p>Suppose $y_\lambda(x)$ and $y_\mu(x)$ are solutions to the BVP:</p> </div> <div data-bbox="1077 1319 1201 1973" data-label="Equation-Block"> $[p(x)y'(x)]' + (q(x) + \nu r(x))y(x) = 0 \text{ for } a < x < b$ $\alpha_1 y(a) + \beta_1 y'(a) = 0$ $\alpha_2 y(b) + \beta_2 y'(b) = 0,$ </div> <div data-bbox="1232 1218 1337 2092" data-label="Text"> <p>corresponding to eigenvalues $\nu = \lambda$ and $\nu = \mu$ respectively. If $\lambda \neq \mu$, then $y_\lambda(x)$ and $y_\mu(x)$ are orthogonal with respect to the weight function $r(x)$.</p> </div> <div data-bbox="1367 1240 1436 2092" data-label="Text"> <p>Remark: eigenfunctions corresponding to distinct eigenvalues of a Sturm-Liouville boundary value problem are orthogonal.</p> </div>	<div data-bbox="821 701 865 1093" data-label="Section-Header"> <h2>Eigenvalues are Real</h2> </div> <div data-bbox="1015 898 1046 1037" data-label="Section-Header"> <h3>Theorem</h3> </div> <div data-bbox="1053 219 1085 1037" data-label="Text"> <p>The eigenvalues of the Sturm-Liouville boundary value problem:</p> </div> <div data-bbox="1115 264 1240 920" data-label="Equation-Block"> $[p(x)y'(x)]' + (q(x) + \nu r(x))y(x) = 0 \text{ for } a < x < b$ $\alpha_1 y(a) + \beta_1 y'(a) = 0$ $\alpha_2 y(b) + \beta_2 y'(b) = 0,$ </div> <div data-bbox="1270 206 1369 1037" data-label="Text"> <p>are all real and the corresponding eigenfunctions are real-valued functions (except possibly for a complex-valued constant multiplicative factor).</p> </div>

Homework

- ▶ Read Sections 7.1 and 7.2
- ▶ Exercises: 1–7