Physics 464/511    Lecture J    Fall, 2016

We have considered various second order linear ordinary differential equations which emerge from separation of variables in many physics contexts. We have employed the concepts of weighted inner products and self-adjointness, and considered functions satisfying the self-adjoint differential equations

\[ \frac{d}{dx} \left[ p(x) \frac{du(x)}{dx} \right] + q(x) u(x) + \lambda w(x) u(x) = 0. \]

\[ \int^b_a w(x) x^n \, dx \]

Suppose we have a weight function \( w > 0 \) on \((a, b)\), with \( \int^b_a w(x) x^n \, dx \) defined for all positive \( n \in \mathbb{R} \). Then we can define a sequence of orthogonal polynomials \( f_n(x) \) of order \( n \) such that

\[ \int^b_a w(x) f_n(x) f_m(x) \, dx = h_n \delta_{mn}. \]

This can be done iteratively by a kind of Schmidt diagonalization.

One can show that the \( f \)'s obey a recursion relation \( f_{n+1} = (a_n + xb_n)f_n - c_n f_{n-1} \). The way to see this is to choose \( b_n \) such that the \( x^{n+1} \) term in \( f_{n+1} - xb_n f_n \) cancels. Note \( b_n \neq 0 \). Then \( f_{n+1} - xb_n f_n \) is a polynomial of order \( \leq n \), so \( = \sum_j \gamma_j f_j \). Then let

\[ \gamma_i = \frac{1}{h_i} \int w f_i (f_{n+1} - xb_n f_n) \, dx. \]

For \( i \leq n \), the first term vanishes directly. For \( i < n - 1 \), \( x f_i \) is of order \( < n \), so \( = \sum_{j=0}^{n-1} \delta_j f_j \), and so

\[ \gamma_i = -\frac{h_n}{h_i} \sum_{j=0}^{n-1} \delta_j \int w f_n f_j = 0 \quad \text{for } i < n - 1. \]

So the \( \gamma_i \) vanish except for \( a_n := \gamma_n \) and \( c_n := -\gamma_{n-1} \). And we have that any set of orthogonal polynomials obeys a recursion relation

\[ f_{n+1} = (a_n + xb_n)f_n - c_n f_{n-1}. \]

Consider our eigenvalue problem, known as the Sturm-Liouville equation, but with \( q(x) = 0 \):

\[ \frac{d}{dx} \left( p(x) \frac{dy}{dx} \right) + \lambda w(x) y(x) = 0. \]

We suppose \( p(a) = p(b) = 0 \), \( p(x) > 0 \) and \( w(x) > 0 \) on \((a, b)\).

Let us also assume there exists a complete set of orthogonal polynomials \( f_n \) which solve this equation with eigenvalues \( \lambda_n \). These are called the “classical” sets of orthogonal polynomials.

### Table of Self-Adjoint ODE’s

<table>
<thead>
<tr>
<th>Equation</th>
<th>( a )</th>
<th>( b )</th>
<th>( p(x) )</th>
<th>( q(x) )</th>
<th>( \lambda )</th>
<th>( w(x) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legendre</td>
<td>-1</td>
<td>1</td>
<td>( 1 - x^2 )</td>
<td>0</td>
<td>( \ell(\ell + 1) )</td>
<td>1</td>
</tr>
<tr>
<td>Associated</td>
<td>-1</td>
<td>1</td>
<td>( 1 - x^2 )</td>
<td>-( \frac{w^2}{1-x^2} ) ( \ell(\ell + 1) )</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Chebyshev I</td>
<td>-1</td>
<td>1</td>
<td>( \sqrt{1-x^2} )</td>
<td>0</td>
<td>( n^2 ) ( (1-x^2)^{-1/2} )</td>
<td>1</td>
</tr>
<tr>
<td>Chebyshev II</td>
<td>-1</td>
<td>1</td>
<td>( (1-x^2)^{3/2} )</td>
<td>0</td>
<td>( n(n+2) ) ( \sqrt{1-x^2} )</td>
<td>1</td>
</tr>
<tr>
<td>Ultraspherical or Gegenbauer</td>
<td>-1</td>
<td>1</td>
<td>( (1-x^2)^{\alpha+1/2} )</td>
<td>0</td>
<td>( n(n+2\alpha) ) ( (1-x^2)^{\alpha-1/2} )</td>
<td>1</td>
</tr>
<tr>
<td>Bessel</td>
<td>0</td>
<td>( a )</td>
<td>( x )</td>
<td>( -n^2/x ) ( a^2 ) ( x )</td>
<td>( \alpha ) ( e^{-x} )</td>
<td>1</td>
</tr>
<tr>
<td>Laguerre, ( 0 \leq \infty )</td>
<td>0</td>
<td>( \infty )</td>
<td>( xe^{-x} )</td>
<td>0</td>
<td>( \alpha ) ( e^{-x} )</td>
<td>1</td>
</tr>
<tr>
<td>Associated</td>
<td>Laguerre</td>
<td>( k \in \mathbb{N} )</td>
<td>( x^{k+1} e^{-x} )</td>
<td>0</td>
<td>( \alpha - k ) ( x^k e^{-x} )</td>
<td>1</td>
</tr>
<tr>
<td>Hermite</td>
<td>(-\infty )</td>
<td>( \infty )</td>
<td>( e^{-x^2} )</td>
<td>0</td>
<td>( 2\alpha ) ( e^{-x^2} )</td>
<td>1</td>
</tr>
<tr>
<td>Harmonic Osc.</td>
<td>(-\pi )</td>
<td>( \pi )</td>
<td>( 1 )</td>
<td>0</td>
<td>( n^2 ) ( 1 )</td>
<td>1</td>
</tr>
</tbody>
</table>
Then we can show the \( f'_n \) are an orthogonal set of polynomials with weight \( p(x) \).

For

\[
\int_a^b f_m \frac{d}{dx} \left( p(x) \frac{d f_n}{dx} \right) = -\lambda_n \int_a^b f_m w f_n = -\lambda_n \delta_{mn}
\]

\[
= f_m p(x) \frac{d f_n}{dx} \bigg|_a^b - \int_a^b f'_m(x) f'_n(x) p(x) \, dx
\]

so

\[
\int_a^b f'_m(x) f'_n(x) p(x) \, dx = \lambda_n \delta_{mn}
\]

[Note: this proves \( \lambda_n > 0 \) for \( n > 0 \)].

It turns out that all these classical polynomials reduce to three cases, according to whether the interval has finite or infinite endpoints.

<table>
<thead>
<tr>
<th>( a )</th>
<th>( b )</th>
<th>( w )</th>
<th>Name</th>
<th>( g = p/w )</th>
<th>Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\alpha,\beta}^n(x) )</td>
<td>(-1)</td>
<td>( 1 - x^n )</td>
<td>Jacobi</td>
<td>( 1 - x^2 )</td>
<td>( \alpha &gt; -1, \beta &gt; -1 )</td>
</tr>
<tr>
<td>( L_n^{(\alpha)}(x) )</td>
<td>0</td>
<td>( \infty )</td>
<td>( x^\alpha e^{-x} )</td>
<td>Generalized Laguerre</td>
<td>( x )</td>
</tr>
<tr>
<td>( H_n(x) )</td>
<td>(-\infty)</td>
<td>( \infty )</td>
<td>( e^{-x^2} )</td>
<td>Hermite</td>
<td>1</td>
</tr>
</tbody>
</table>

Notice that \( p(x) \) and \( w(x) \) are always closely related.

If \( f_n \) is a solution to \( \frac{d}{dx} g(x) w(x) \frac{dy}{dx} + \lambda_n w(x) g(y) = 0 \), we see immediately

\[
n = 0 \quad \lambda_0 = 0
\]

\[
n = 1 \quad f_1 = k_1 x + k'_1, \quad \frac{k_1}{w(x)} \frac{d}{dx} g(x) w(x) = -\lambda_1 f_1(x)
\]

In fact, this form can be generalized into an expression called Rodrigues’ Formula\(^1\)

\[
f_n(x) = \frac{1}{a_n w(x)} \frac{d^n}{dx^n} (wg^n).
\]  

(1)

It is not even obvious that \( f_n \) is a polynomial, but if you examine the cases you will see that each \( \frac{1}{w} \frac{d}{dx} w \) has or makes a simple pole where \( g \) has a zero, and when multiplied by \( g \) is proportional to \( x + \text{constant} \). Thus by induction \( f_n \) is a polynomial of order \( n \).

One also makes use of \( \frac{d^m}{dx^m} (wg^n) \rightarrow 0 \) for \( m < n \) to show that \( f_n \) is orthogonal to any polynomial of order \( < n \), so in particular \( \langle f_n, f_m \rangle = h_n \delta_{nm} \).

To see that \( f \) satisfies Eq. (1) note that \( \frac{d}{dx} g(x) w(x) = -\lambda_1 \frac{f_1(x)}{k_1} w(x) \).

Now

\[
\left( \frac{d}{dx} \right)^{n+1} g \frac{d}{dx} wg^n = g \left( \frac{d}{dx} \right)^{n+2} wg^n + (n+1) \frac{dg}{dx} \left( \frac{d}{dx} \right)^n wg^n
\]

\[+ \frac{n(n+1)}{2} \frac{d^2 g}{dx^2} \left( \frac{d}{dx} \right)^n w g^n. \]  

(2)

as \( g \) has no higher derivatives (\( g \) is quadratic).

Note \( g \frac{d}{dx} wg^n = \frac{d(wg)}{dx} g^n + (n-1)wg^n \frac{dg}{dx} = wg^n \left( -\lambda_1 \frac{f_1}{k_1} + (n-1) \frac{dg}{dx} \right) \)

The term in parenthesis is linear, so at most one of the \( n+1 \) derivatives acts on it, and

\[
\left( \frac{d}{dx} \right)^{n+1} g \frac{d}{dx} wg^n = \left[ -\lambda_1 \frac{f_1}{k_1} + (n-1) \frac{dg}{dx} \right] \left( \frac{d}{dx} \right)^n wg^n
\]

\[+ (n+1) \left( -\lambda_1 + (n-1) \frac{d^2 g}{dx^2} \right) \left( \frac{d}{dx} \right)^n wg^n. \]  

(3)

Equating the right hand sides of Eqs. (2) and (3) with \( a_n w f_n = \frac{d^n}{dx^n} (wg^n) \),

\[
\left\{ g \left( \frac{d}{dx} \right)^2 + \left( 2 \frac{dg}{dx} + \lambda_1 \frac{f_1}{k_1} \right) \frac{d}{dx} + (n+1) \left( \frac{2-n d^2 g}{2} + \lambda_1 \right) \right\} a_n w f_n = 0,
\]

or

\[
\left\{ gw \frac{d^2}{dx^2} + \left( 2g \frac{dw}{dx} + 2w \frac{dg}{dx} + \lambda_1 \frac{f_1}{k_1} \right) \frac{d}{dx} + \lambda_1 w \right\} f_n = 0
\]

with

\[
\lambda_n = g \frac{1}{w} \frac{d^2 w}{dx^2} + \left( 2g \frac{dw}{dx} + \lambda_1 \frac{f_1}{k_1} \right) \frac{1}{w} \frac{dw}{dx} + (n+1) \left[ \frac{2-n d^2 g}{2} + \lambda_1 \right].
\]

\(^1\)See Supplementary Notes “Rodrigues’ Formula and Orthogonal Polynomials”.

From \(-\frac{\lambda_1}{k_1} f_1 = \frac{1}{w} \frac{d}{dx} gw = g' + g \frac{1}{w} \frac{dw}{dx}\)

\[-\lambda_1 = g'' + g \frac{1}{w} \frac{d^2 w}{dx^2} - g \left( \frac{1}{w} \frac{dw}{dx} \right)^2 + g' \frac{1}{w} \frac{dw}{dx},\]

so \(\lambda_n = -\lambda_1 - g'' + (n + 1)\lambda_1 - (n + 1) \left( \frac{n}{2} - 1 \right) g'' = n\lambda_1 - \frac{1}{2} n(n-1)g''\) and

\(\left( \frac{d}{dx} p \frac{d}{dx} + \lambda_n w \right) f_n = 0.\)

The three classical polynomials we have considered have special cases, with different names and normalizations. Some important ones are

- Legendre: \(P_n(x) = P_n^{(0,0)}(x)\) occurs in the angular equations in spherical coordinates.

- Chebyshev: \(T_n(x) \propto P_n^{(-1/2,-1/2)}(x)\) is used in data fitting to minimize maximum errors.

- Gegenbauer: \(C_n^\alpha(x) \propto P_n^{(\alpha-1/2,\alpha-1/2)}(x)\) are the spherical harmonics in four dimensions.

- Laguerre: \(L_n = L_n^{(0)}\).

The associated Laguerre and the Hermite polynomials arise in the quantum mechanical bound states of the hydrogen atom and harmonic oscillator, respectively. They are also used in numerical analysis for some very efficient integration techniques.