5.3: Series solutions near an ordinary point, part II

A power series solution exists in a neighborhood of x_0 when the solution is analytic at x_0. I.e, the solution is of the form $y = \Sigma_{n=0}^{\infty} a_n(x-x_0)^n$ where this series has a nonzero radius of convergence about ~~x_0~~.

That is $f(x) = \Sigma_{n=0}^{\infty} \frac{f^{(n)}(\cancel{x_0})}{n!}(x-x_0)^n$ for x near x_0.

Thus there are constants $a_n = \frac{f^{(n)}(x_0)}{n!}$ such that,

$$f(x) = \Sigma_{n=0}^{\infty} a_n(x-x_0)^n.$$

When do we know an analytic solution exists? I.e, when is this method guaranteed to work?

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

Then $y''(x) = -[\frac{Q}{P}y' + \frac{R}{P}y]$

$y'''(x) = -[(\frac{Q}{P})'y' + \frac{Q}{P}y'' + \frac{R}{P}'y + \frac{R}{P}y']$

If $f(x) = \Sigma_{n=0}^{\infty} a_n(x-x_0)^n$ is a solution where $a_n = \frac{f^{(n)}(x_0)}{n!}$, then $a_0 = f(x_0), a_1 = f'(x_0)$

$2!a_2 = f''(x_0) = -[\frac{Q}{P}f'(x_0) + \frac{R}{P}f(x_0)] = -[\frac{Q}{P}a_1 + \frac{R}{P}a_0]$

$3!a_3 = f'''(x_0) = -[(\frac{Q}{P})'f'(x_0) + \frac{Q}{P}f''(x_0) + \frac{R}{P}'f(x_0) + \frac{R}{P}f'(x_0)]$

To find a_n we could continue taking derivative including derivatives of $\frac{Q}{P}$ and $\frac{R}{P}$ (but much easier to plug series into equation – ie 5.2 method).

Definition: The point x_0 is an *ordinary point* of the ODE,

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

if $\frac{Q}{P}$ and $\frac{R}{P}$ are analytic at x_0. If x_0 is not an ordinary point, then it is a *singular point*.

⇒ analytic soln

Theorem 5.3.1: If x_0 is an ordinary point of the ODE $P(x)y'' + Q(x)y' + R(x)y = 0$, then the general solution to this ODE is

$$y = \Sigma_{n=0}^{\infty} a_n(x-x_0)^n = a_0\phi_0(x) + a_1\phi_1(x)$$

where ϕ_i are power series solutions that are analytic at x_0. The solutions ϕ_0, ϕ_1 form a fundamental set of solutions. The radius of convergence for each of these series solutions is at least as large as the minimum radii of convergence of the series for $\frac{Q}{P}$ and $\frac{R}{P}$.

Theorem: If P and Q are polynomial functions with no common factors, then $y = Q(x)/P(x)$ is analytic at x_0 if and only if $P(x_0) \neq 0$. Moreover the radius of convergence of $Q(x)/P(x)$ is

$$min\{||x_0 - x|| \mid x \in \mathbf{C}, P(x) = 0\}$$

where $||x_0 - x||$ = distance from x_0 to x in the complex plane.

Ex: $\underbrace{x(x+1)}_{X(X+1)}y'' + \frac{x^2}{x^2+1}y' + \frac{x}{x-2}y = 0$ $X(X+1)$ $X(X+1)$

$y'' + \frac{x}{(x^2+1)(x+1)}y' + \frac{1}{(x-2)(x+1)}y = 0$ ⇐ simplify first remove common factors

Then $x_0 = -1, 2$ are singular points. All other points are ordinary points. $X^2+1=0 \Rightarrow X = \pm i = \pm\sqrt{-1}$

The zeros of the denominators are $x = \pm i, -1, 2$

Radius of convergence for the series solution to this ODE about the point x_0 if $x_0 \neq -1, 2$ is at least as large as minimum$\{\sqrt{x_0^2 + (\pm 1)^2}, |x_0 - (-1)|, |x_0 - 2|\}$

Domain includes

If $x_0 = 0$, radius of convergence ≥ 1 $(-1, 1)$ 0

If $x_0 = -3$, radius of convergence ≥ 2 −5 −3 −1 $(-5, -1)$

If $x_0 = 3$, radius of convergence ≥ 1 $(2, 4)$ 2 3 4

If $x_0 = \frac{1}{3}$, radius of convergence $\geq \sqrt{(\frac{1}{3})^2 + (\pm 1)^2} = \frac{\sqrt{10}}{3}$

choose any ordinary point

$\frac{1}{3} - \frac{\sqrt{10}}{3}$ $1/3$ $\frac{1}{3} + \frac{\sqrt{10}}{3}$