PHYS 3031 Course Notes

Mathematical Methods in Physics II

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PHYS 3031 Mathematical Methods in Physics II

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1 Series

1.1 Convergence Condition for Positive Series $\sum\limits_{n=1}^{\infty} a_n$

Necessary condition: $\lim_{N\to\infty} a_N = 0$

Hierarchy: $N! > a^N > N^b > \ln N$

Stirling's Formula $\ln N! \approx N \ln N - N \approx N \ln N$

Comparison Test 1 $\sum a_n < \sum b_n$, b converges $\to a$ converges

Comparison Test 2 (Integral Test) $\sum a_n \& \int a(n)\mathrm{d}n$ share the same fate

Ratio Test $\lim_{n\to\infty} \frac{a_{n+1}}{a_n} = \rho$, $\rho > 1 \to$ Diverges, $\rho < 1 \to$ Converges

Extended (Special) Comparison Test $\lim_{n\to\infty} \frac{a_n}{b_n} = 1$, then $\sum a_n \& \sum b_n$ share the same fate

1.2 Convergence Condition for Alternating Series $\sum\limits_{n=1}^{\infty} (-1)^n a_n$

If $a_n > 0, \lim_{n\to\infty} a_n = 0$, this series may diverge.

(1) Absolute Convergence: If $\sum a_n$ converges, then $\sum (-1)^n a_n$ converges

(2) Convergence Condition: $\lim_{n\to\infty}$ and $a_n > a_{n+1}$

(3) Diverge: If $a_n < a_{n+1}$, then the series diverges

1.3 Power Series $\sum_{n=0}^{\infty} a_n (x - x_0)^n \to f(x)$

Convergent condition for x: $\lim_{n\to\infty} \left| \frac{a_{n+1}}{a_n} (x - x_0) \right| < 1$

1.4 Asymptotic Series

For functions $f(z)$ and $\phi(z) \neq 0$ defined in $\mathring{U}(z_0)$, we say that $f(z) = O(\phi(z))$ at $z \to z_0$ if $f(z)/\phi(z)$ is bounded, and that $f(z) = o(\phi(z))$ at $z \to z_0$ if $f(z)/\phi(z) \to 0$.

If for $\forall m$, when $z \to z_0$,

$$f(z) - \sum_{n=0}^{m} a_n \phi_n(z) = o(\phi_m(z))$$

we say that $\sum_{n=0}^{m} a_n \phi_n(z)$ is an asymptotic series for $f(z)$, even though the series may not converge:

$$f(z) \sim \sum_{n=0}^{m} a_n \phi_n(z)$$

2 Taylor Expansion $\sum_{n=0}^{\infty} a_n (x - x_0)^n$

$$\sin x = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)!} x^{2n+1} \qquad \cos x = \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n)!} x^{2n} \qquad \tan x = x + \frac{x^3}{3} + \frac{2x^5}{15} + \frac{17x^7}{315} + ... \qquad e^x = \sum_{n=0}^{\infty} \frac{x^n}{n!}$$

$$\arctan x = \int_0^x \sum_{n=0}^{\infty} (-t^2)^n \mathrm{d}t = \sum_{n=0}^{\infty} \frac{(-1)^n x^{2n+1}}{2n+1}, \text{ where } |x| < 1$$

2.1 Leibniz Rule

$$\frac{\mathrm{d}^{(M)}}{\mathrm{d}x^M}(u \cdot v) = \left(\frac{\mathrm{d}u}{\mathrm{d}x}\frac{\partial}{\partial u} + \frac{\mathrm{d}v}{\mathrm{d}x}\frac{\partial}{\partial v}\right)^M (u \cdot v) = \sum_{n=0}^{M} C_M^n \left(\frac{\mathrm{d}^{(M-n)}u}{\mathrm{d}x^{(M-n)}}\right)\left(\frac{\mathrm{d}^{(n)}v}{\mathrm{d}x^n}\right)$$

2.2 Error Estimation when N Terms are Kept

$$f(x) \approx \sum_{n=0}^{N} (-1)^n a_n (x - x_0)^n \qquad b_n \equiv a_n (x - x_0)^n > 0$$

2.2.1 Alternating Series $S = \sum_{n=0}^{\infty} (-1)^n b_n$

Maximum possible error for $f(x)$ is
$$b_{N+1} = a_{N+1}\big|x - x_0\big|^{N+1}$$

2.2.2 "Positive" Series $S = \sum_{n=0}^{\infty} a_n(x - x_0)^n, a_n(x - x_0)^n > 0$

If it converges when $\big|x - x_0\big| < 1$, and $\big|a_{n+1}\big| < \big|a_n\big|$, then

$$S - S_N < \frac{\big|a_{N+1}\big|\big|x - x_0\big|^{N+1}}{1 - \big|x - x_0\big|}$$

Note: In practice, Taylor Expansion is useful when $\big|x - x_0\big| << 1$, and an upper limit of error ϵ to be tolerated is given, even if the series converges for any value of $(x - x_0)$.

2.3 L'Ĥopital's Rule

Theorem 1: $\lim_{x \to x_0} \frac{f(x)}{g(x)} \xrightarrow[g(x_0)=0]{f(x_0)=0} \frac{0}{0} \implies \lim_{x \to x_0} \frac{f(x)}{g(x)} \longrightarrow \frac{f'(x)}{g'(x)}$

Theorem 2: $\lim_{x \to x_0} \frac{f(x)}{g(x)} \xrightarrow[g(x_0)=0]{f(x_0)=0} \frac{\infty}{\infty} \implies \lim_{x \to x_0} \frac{f(x)}{g(x)} \longrightarrow \frac{f'(x)}{g'(x)}$(proved by the inverse of the fraction)

3 Complex Analysis

Convergence of the Complex Series $\sum^{\infty} c_n = \sum^{\infty} a_n + i\sum^{\infty} b_n \implies a_n$ and b_n both converges.

Complex Power Series $\sum^{\infty} c_n z^n = f(z)$ with convergence region $\lim_{n \to \infty}\big|\frac{c_{n+1}}{c_n}z\big| < 1$.

Euler's Formula: $e^z = \cos z + i\sin z$ help solving the inverse trigonometric functions.

3.1 Complex Functions $f(z) = f(x + iy) = u(x,y) + iv(x,y)$

Analytic Function

Property: $f'(z) = \lim_{\Delta z \to 0} \frac{f(z + \Delta z) - f(z)}{\delta z}$ is **unique** regardless how $\Delta z \to 0$.

Necessary and Sufficient Conditions:

Cauchy-Riemann Conditions in Cartesian Coordinate: $\partial_x u = \partial_y v, \quad \partial_y u = -\partial_x v$

Cauchy-Riemann Conditions in Polar Coordinate: $\partial_\theta u = -\rho\partial_\rho v, \quad \partial_\theta v = \rho\partial_\rho u$

Isolated Zeros

If f is analytic at z_0, then f has a zeo of order $m \geq 1$ at z_0 if

$$f(z_0) = f'(z_0) = \cdots = f^{(m-1)}(z_0) = 0$$

and $f^{(m)}(z_0) \neq 0$. Note that f becomes a **branch point** if m is not an integer, and that f is not analytic at that point.

Theorem: If $z = a$ is a zero of $f(z)$ which is not a constant at $\mathring{U}(a)$, then $\exists \rho > 0$, $f(z)$ doesn't have any zeros in the region $0 < |z - a| < \rho$.

3.2   Line Integrals

With the substitution of line $c : y = g(x)$, $\mathrm{d}y = g'(x)\mathrm{d}x$

$$\lim_{\delta z_n \to 0} \sum_{z_n \in c} f(z_n)\Delta z_n = \int_c f(z)\mathrm{d}z = \int_c f(x+iy)(\mathrm{d}x + i\mathrm{d}y) = \int_a^b f(x+ig(x))(1+ig'(x))\mathrm{d}x \implies \int_c f(z)\mathrm{d}z = -\int_{-c} f(z)\mathrm{d}z$$

Cauchy's Theorem for Analytic Functions:

$$\oint_C f(z)\mathrm{d}z = 0$$

Two Foundation Lemmas - Small & Big Arc Lemma

• Small Arc Lemma (小圆弧引理):

If $f(z)$ is continuous in $\mathring{U}(a)$, and $(z-a)f(z)$ approaches k consistently as $|z-a| \to 0$ within $\theta_1 \leq \arg(z-a) \leq \theta_2$, then

$$\lim_{\delta \to 0} \int_{C_\delta} f(z)\mathrm{d}z = ik(\theta_2 - \theta_1)$$

• Big Arc Lemma (大圆弧引理):

If $f(z)$ is continuous in $\mathring{U}(\infty)$, and $zf(z)$ approaches K consistently as $z \to \infty$ within $\theta_1 \leq \arg(z-a) \leq \theta_2$, then

$$\lim_{R \to \infty} \int_{C_R} f(z)\mathrm{d}z = iK(\theta_2 - \theta_1)$$

Cauchy's Integral Formula: $f(z)$ is analytic inside and on the contour, then for $\forall z_0$ inside the contour,

$$\implies f(z_0) = \frac{1}{2\pi i} \oint_C \frac{f(z)\mathrm{d}z}{z - z_0} \implies f(z_0) = \frac{1}{2\pi} \int_0^{2\pi} f(z_0 + Re^{i\theta})\mathrm{d}\theta \text{ (Mean Value Theorem 均值定理)}$$

i.e. Get full information inside by the information on the boundary only.

Note: If z_0 were outside the contour, then

• If f is analytic inside C, then $\frac{1}{2\pi i} \oint_C \frac{f(z)\mathrm{d}z}{z-z_0} = 0$

• If f is analytic outside C and $\lim_{z \to \infty} f(z) = K$, then $\frac{1}{2\pi i} \oint_C \frac{f(z)\mathrm{d}z}{z-z_0} = f(z_0) - K$

• The above two lemmas are NOT contradictory. In fact, if a complex function is analytic and bounded within $U(\infty)$, then it must be a constant function.

Liouville Theorem (in Complex Analysis) 刘维尔定理

Every bounded entire function must be constant. That is, every holomorphic function f for which there exists a positive number M such that $|f(z)| \leq M$ for all $z \in \mathbb{C}$ is constant. Equivalently, non-constant holomorphic functions on $\mathbb{C}$ have unbounded images.

Poisson's Formula

Idea: If $f(z = x + iy) = u(x, y) + iv(x, y)$ is analytic on the upper-half plane and that we only know the value of $u(x, 0)$ or $v(x, 0)$, we can first get the value of $f(x \in \mathbb{R})$, then apply the Cauchy's Integral Formula to get all the complex value on the upper-half plane:

$$f(z) = \frac{1}{\pi i} \int_{-\infty}^{\infty} \frac{u(\xi, 0)}{\xi - (x + iy)} \mathrm{d}\xi = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{v(\xi, 0)}{\xi - (x + iy)} \mathrm{d}\xi$$

$$f(z) = \frac{y}{\pi} \int_{-\infty}^{\infty} \frac{f(\xi)}{(\xi - x)^2 + y^2} \mathrm{d}\xi = \frac{1}{\pi i} \int_{-\infty}^{\infty} \frac{(\xi - x)f(\xi)}{(\xi - x)^2 + y^2} \mathrm{d}\xi$$
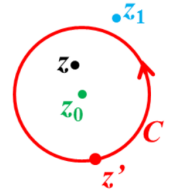
3.3 Taylor Series

Derivative of $f(z)$

$$f^{(n)}(a) \equiv \frac{\mathrm{d}^{(n)} f}{\mathrm{d}a^n} = \frac{n!}{2\pi i} \oint_C \frac{f(z)\mathrm{d}z}{(z - a)^{n+1}}$$

Taylor Series $f(z) = \sum a_n (z - z_0)^n$

Suppose $f(z)$ has a singular point at z_1, we can expand $f(z)$ at z_0:

$$f(z) = \frac{1}{2\pi i} \oint_C \frac{f(z')\mathrm{d}z'}{z' - z} = \frac{1}{2\pi i} \sum_{n=0}^{\infty} (z - z_0)^n \oint_C \frac{f(z')\mathrm{d}z'}{(z' - z_0)^{n+1}} = \sum_{n=0}^{\infty} a_n (z - z_0)^n$$

$$a_n \equiv \frac{1}{2\pi i} \oint_C \frac{f(z')\mathrm{d}z'}{(z' - z_0)^{n+1}} = \frac{1}{n!} \frac{\mathrm{d}^n f(z_0)}{\mathrm{d}z^n}$$

3.4 Lauren Series

Suppose $f(z)$ has a pole at z_0, define the hole as order $N \geq 1$ at z_0 if $\lim_{z \to z_0} (z - z_0)^N f(z)$ is finite and non-zero. ("Essential Pole" if such $N \to \infty$ like $e^{1/z}$ at $z = 0$)
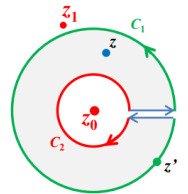
$f(z)$ can be expressed as

$$f(z) = \sum_{m=0}^{\infty} a_m (z - z_0)^m + \sum_{n=1}^{N} \frac{b_m}{(z - z_0)^n} \text{ as } \lim_{z \to z_0} (z - z_0)^N f(z) = b_N$$

$$f(z) = \frac{1}{2\pi i} \oint_{C_1} \frac{f(z')\mathrm{d}z'}{z' - z} + \oint_{C_2} \frac{f(z')\mathrm{d}z'}{z' - z} = I_1 + I_2$$

We have

$$a_n = \frac{1}{2\pi i} \oint_{C_1} \frac{f(z')\mathrm{d}z'}{(z' - z_0)^{n+1}} \quad b_1 = \frac{1}{2\pi i} \oint_{C_2} f(z')\mathrm{d}z' \quad b_{n+1} = \frac{1}{2\pi i} \oint_{C_2} f(z')(z' - z_0)^n \mathrm{d}z' \quad \text{(Not Useful)}$$

Note that when $f(z)$ is analytic at z_0, a_n becomes the same as the coefficient in Taylor Series, and $b_i \equiv 0$ for $\forall i$.

3.5 Residue Theorem 留数定理

We want to evaluate $\oint_C f(z)\mathrm{d}z$ around the pole. By applying the Lauren Series, one can prove that

$$\oint_C f(z)\mathrm{d}z = 2\pi i b_1$$

To find b_1, notice that $\lim_{z \to z_0}(z - z_0)^N f(z)$ is finite and all the other terms in the Lauren Series would disappear by taking $(N-1)$ times derivatives and taking $z = z_0$:

$$b_1 = \lim_{z \to z_0} \frac{g^{(M-1)}(z)}{(M-1)!}, \quad \text{where } g(z) \equiv (z - z_0)^M f(z), M \geq N$$

We then define the coefficient b_1 of the Lauren Series at the pole z_0 as $b_1(z_0) \equiv R(z_0)$, and refer as the **residue** of $f(z)$ at z_0
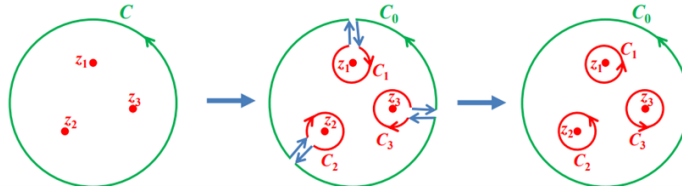
If $f(z)$ has singular points $z_1, z_2, \cdots, z_n$ inside contour C, then

$$\oint_C f(z)\mathrm{d}z = 2\pi i \sum_{n=1}^{N} R(z_n)$$

Noun	Explanation
Analytic (Holomorphic) Point	A point which the function has a derivative at and in a neighborhood around that point
Branch Point 分支点	A point such that all of its neighborhoods contain a point that has more than n values
Pole	A point of a function f if it is a zero of the function $1/f$ which is analytic
Regular Point	A point in the function's domain where the function is differentiable
Singularity 奇点	Essential Singularity: $\lim_{z \to z_0}(z - z_0)^N f(z)$ is always infinite Isolated Singularity: One that has no other singularities close to it Movable Singularity, Removable Singularity

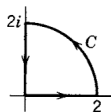Table 1: Explanation of Important Nouns

Homework 4

Problem 1

Evaluate the integral $\int_1^i z\,\mathrm{d}z$ along the indicated paths.
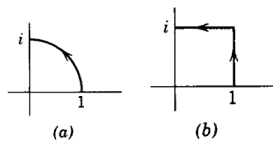
Solution.

Problem 2

Evaluate $\oint_C (\bar{z} - 3)\mathrm{d}z$ where C is the indicated closed curve along the first quadrant part of the circle $|z| = 2$, and the indicated parts of the x and y axes. Hint: Don't try to use Cauchy's theorem!

Solution.

Problem 3

Evaluate the following integrals:

(a) $\oint_C \frac{\sin 2z \, \mathrm{d}z}{6z - \pi}$ where C is the circle $|z| = 3$

(b) $\oint \frac{e^{3z} \, \mathrm{d}z}{z - \ln 2}$ if C is the square with vertices $\pm 1 \pm i$

Solution.

Problem 4

For each of the following functions, say whether the indicated point is regular, an essential singularity, or a pole, and if a pole of what order it is.

(a) $\frac{e^z - 1 - z}{z^2}$, $z = 0$

(b) $\frac{\sin z}{z^3}$, $z = 0$

(c) $\frac{z^2 - 1}{(z-1)^2}$, $z = 1$

(d) $\frac{\cos z}{(z - \pi/2)^4}$, $z = \pi/2$

Solution.

Problem 5

Find the residues of the following functions at the indicated points. Try to select the easiest of the methods outlined above. Check your results by computer.

(a) $\frac{1}{(3z+2)(2-z)}$ at $z = -\frac{2}{3}$ and $z = 2$

(b) $\frac{z+2}{4z^2-1}$ at $z = \frac{1}{2}$ and $z = -\frac{1}{2}$

(c) $\frac{\cosh z - 1}{z^7}$ at $z = 0$

(d) $\frac{e^{iz}}{(z^2+4)^2}$ at $z = 0$ and $z = \frac{1}{2}$

Solution.