Mathematical Methods II

30 January 2012
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80% exam
20% CE- 3 assignments
Course
Fourier series
Fourier Transform
Complex Analysis

=> Introduce mathematical material, which allows us to describe physical concepts & solve physical systems accurately
=> Emphasis on <u>applications</u>
    Not focus on proofs

Fourier Series

30 January 2012
12:12

Step 1

Maths

Suppose f(x) is a periodic function

(x is a dimensionless real number)

With period 2π

$$f(x+2\pi)=f(x)$$

THEN (fourier's theorem)

$$f(x)=\frac{a_0}{2}+\sum_{n=1}^{\infty}(a_n\cos(nx)+b_n\sin(nx))$$

Where a_n, b_n are constants

(proof is non-trivial)

Proof by example

There are 3 ways to express this: (1)

$$f(x)=\frac{a_0}{2}+\sum_{n=1}^{\infty}A_n\cos(nx+\phi_n)$$

(2)

$$=\sum_{n=-\infty}^{\infty}c_n e^{inx}$$

(3)

SHOW forms are equivalent

- Need to remember

$$\sin(a+b)=\sin a\cos b+\cos a\sin b$$
$$\cos(a+b)=\cos a\cos b-\sin a\sin b$$

So

$$A_n\cos(nx+\phi_n)=A_n\cos nx\cos\phi_n-A_n\sin nx\ \sin\phi_n$$

So (2) $\equiv$ (1) provided

$$a_n=A_N\cos\phi_n$$
$$b_n=-A_n\sin\phi_n$$

Take eqn(b)/eqn(a)

Express this

$$\frac{b_n}{a_n}=-\frac{\sin\phi_n}{\cos\phi_n}=-\tan\phi_n$$

$$\Rightarrow \boxed{\phi_n=-\tan^{-1}\frac{b_n}{a_n}}$$

So

$$\sum_{n=-\infty}^{\infty}c_n e^{inx}=c_0+\sum_{n=1}^{\infty}\left(c_n e^{inx}+c_{-n}e^{-inx}\right)$$

$$=c_0+\sum_{n=1}^{\infty}\left((c_n+c_n)\cos nx+i(c_n-c_{-n})\sin nx\right)$$

So comparing (1) and (2)

$$c_0=\frac{a_0}{2}$$

$$c_n+c_{-n}=a_n$$
=eq(c)
$$c_n-c_{-n}=b_n$$
=eq(d)

Note $eq(c)-ieq(b)=(c_n+c_{-n})+(c_n-c_{-n})=a_n-ib_n$

$$\Rightarrow 2c_n = a)n - ib_n$$

$$c_n = \frac{1}{2}(a_n - ib_n)$$

Note: Fourier series works for both real and complex values f(x)

$f(x): \mathbb{R} \to \mathbb{C}$

In form (1) a complex f(x) corresponds to a complex $a_n \& b_n$

In form (3), a real f(x) $\boxed{c_n = c_{-n}^*}$

Formulate for $a_n \& b_n$

We will need the identity

$$I_{n,m} = \int_0^{2\pi} \sin(nx)\sin(mx)\,dx$$

n,m integers

Integrate[Sin[n*x]*sin[m*x],{x,0,2Pi}]

We use

$$\sin a \sin b = \cos(a-b) - \cos(a+b)$$

$$I_{n,m} = \frac{1}{2}\int_0^{2\pi} \{\cos\left((\mathrm{n}-\mathrm{m})\mathrm{x}\right) - \cos\left((\mathrm{n}+\mathrm{m})\mathrm{x}\right)\}dx$$

$$= \frac{1}{2}\left[\frac{\sin\left((n-m)x\right)}{n-m}\right]_0^{2\pi} - \frac{1}{2}\left[\frac{\sin\left((n+m)x\right)}{n+m}\right]_0^{2\pi}$$

$$= \frac{1}{2}(0-0) - \frac{1}{2}(0-0) = 0$$

$$I_{n,m} = 0$$

$$if\ m+n \neq 0 \ \&\ m-n \neq 0$$

$$m - n = 0 \to n = m$$

$$I_{n,m} = \int_0^{2\pi} \cos nx \cos nx\,dx$$

$$= \int_0^{2\pi} \cos^2 nx\,dx > 0$$

$$= \int_0^{2\pi} dx \frac{1}{2}(1 + \cos 2nx\,)$$

$$= \frac{1}{2}2\pi + \left[\frac{\sin 2nx}{2n}\right]_0^{2\pi}$$

For any periodic function

$f(x + 2\pi) = f(x)$

We can define $x \in [0,2\pi)$

OR $x \in (-\pi, \pi]$

Note

$$\int_0^{2\pi} f(x)dx = \int_{-\pi}^{\pi} f(x)dx$$

ALSO (exercise)

$$\int_{-\pi}^{\pi} \sin nx \sin mx = ?$$

$$\int_{-\pi}^{\pi} \sin nx \cos mx = 0$$

Return to Fourier series

$$f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n \cos nx + b_n \sin nx)$$

Take

$$\int_{-\pi}^{\pi} f(x)\cos mx\,dx = \int_{-\pi}^{\pi} dx \frac{a_0}{2}\cos mx + \sum_{n=1}^{\infty}\left(\int_{-\pi}^{\pi} a_n \cos nx \cos mx + b_n \sin nx \cos mx\,dx\right)$$

$$= 0 + \sum_{n=1}^{\infty} \pi \delta_{n,m} a_n + 0$$
$$= \pi a_m$$
So
$$\boxed{a_m = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos mx \, dx}$$
Exercise- check
$$b_m = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin mx \, dx$$
a_0?
Take
$$\int_{-\pi}^{\pi} f(x) dx$$
$$= \frac{a_0}{2} \int_{-\pi}^{\pi} 1 \, dx + \sum_{n=1}^{\infty} \int (a_n \cos nx + b_n \sin nx) dx = \pi a_0$$
$$a_0 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(x) dx$$

Comments on even + odd functions

EVEN
$$f(-x) = f(x)$$
ODD
$$f(-x) = -f(x)$$

Explicitly
$$h(x) = \frac{1}{2}\big(f(x) + f(-x)\big)$$
Explicitly even
$$g(x) = \frac{1}{2}\big(f(x) - f(-x)\big)$$
Explicitly odd
$$h(x) - g(x) = f(x)$$

Multiplying together
$$f(x) = f_1(x) f_2(x)$$

X	Even	Odd
Even	Even	Odd
Odd	Odd	Even

IF $f(x)$ is ODD
$$\int_{-\pi}^{\pi} f(x) dx = 0$$
IF $f(x)$ is even
$$\int_{-\pi}^{\pi} f(x) dx = 2 \int_{0}^{\pi} f(x) dx$$
Fourier series of even & odd functions simplify
If f(x) is an even function
$$\Rightarrow b_n = 0$$
$$\& \; f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos nx$$
Proof
$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} dx \, f(x) \sin(nx)$$
Even * odd=odd

$=0$

Since integral is odd

If f(x) is odd

$a_n - a_0 = 0$

$$\Rightarrow f(x) = \sum_{n=1}^{\infty} b_n \sin nx$$

Proof

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} dx\, f(x)\cos nx$$

Odd*even=odd

$= 0$

Since integral is odd

EXAMPLE

Periodic function with period 2π

$$f(x) = \begin{Bmatrix} 1 & x \in (0,\pi) \\ -1 & x \in (-\pi, 0) \end{Bmatrix}$$

"square wave"

So

$$b_n = \frac{2}{\pi}\int_0^{\pi} \sin(xn)\, dx$$

$$= \frac{2}{\pi}\left[-\frac{\cos nx}{n}\right]_0^{\pi}$$

$$= \frac{2}{\pi}\left(-\frac{\cos n\pi}{n} - \left(-\frac{\cos 0}{n}\right)\right)$$

$$= \frac{2}{\pi n}[1 - \cos(n\pi)]$$

$\cos(n\pi) = (-1)^n$

$$b_n = \frac{2}{\pi}\frac{1}{n}[1 - (-1)^n]$$

$$b_1 = \frac{4}{\pi}$$

$$b_2 = 0$$

$$b_3 = \frac{4}{\pi}\frac{1}{3}$$

$$b_4 = 0$$

$$b_5 = \frac{4}{\pi}\frac{1}{5}$$

So

$$f(x) = \frac{4}{\pi}\left[\sin(x) + \frac{1}{3}\sin(3x) + \frac{1}{5}\sin(5x) + \cdots\right]$$

$$= \frac{4}{\pi}\sum_{r=1}^{\infty}\frac{1}{2n-1}\sin\big((2n-1)x\big)$$

Define a bit better what we mean by f(x)=

Define

$$f_p(x) = \frac{a_0}{2} + \sum_{n=1}^{p}(a_n \cos nx + b_n \sin nx)$$

Note that f_p is continuious

Then

$f_p(x) \to f(x)$

As $p \to \infty$

"almost everywhere"

"almost everywhere"

≡except at points where measure is zero

Note

$$\int_{-\pi}^{\pi}\left(f(x)-f_p(x)\right)dx \to 0$$
IF f(x) is continuous
$f_p(x) \to f(x)$ everywhere

Suppose function is discontinuous at point (a)
Suppose
$$\lim_{x\to a^-} \square = f^-(a)$$
$$\lim_{x\to a^+} \square = f^+(a)$$
If

$$f(x)=\sum_{n=1}^{\infty}\frac{a}{\pi}\left(\frac{1-(-1)^n}{n}\right)\sin(nx)$$

$$\sin A\cos B=\frac{1}{2}(\sin(A+B)+\sin(A-B))$$
$$a_n=\frac{1}{\pi}\int_0^{\pi}\sin\left((n+1)x\right)+\sin\left((n-1)x\right)dx$$
$$=\frac{1}{\pi}\int_0^{\pi}\sin\left((n+1)x\right)-\sin\left((1-n)x\right)dx$$
$$=\frac{1}{\pi}\left(\left[-\frac{\cos(n+1)x}{n+1}\right]_0^{\pi}-\left[-\frac{\cos(n-1)x}{n-1}\right]_0^{\pi}\right)$$
$n\neq 1,-1$
$$=\frac{1}{\pi}\left(-\frac{[(-1)^{n+1}-1]}{n+1}-\left[-\frac{(-1)^{n-1}-1}{n-1}\right]\right)$$
$$=\frac{1-(-1)^{n+1}}{\pi}\left[\frac{1}{n+1}-\frac{1}{n-1}\right]$$
$$=\frac{1-(-1)^{n+1}}{\pi}\left[\frac{(n-1)-(n+1)}{(n+1)(n-1)}\right]$$
n=1 we have to do separately
n=1
$$a_1=\frac{2}{\pi}\int_0^{\pi}\sin x\cos x\,dx$$
$$=\frac{1}{\pi}\int_0^{\pi}\sin 2x\,dx$$
$$=1/\pi\left[-\frac{\cos 2x}{2}\right]_0^{\pi}$$
$$a_0=\frac{1}{\pi}\int_{-\pi}^{\pi}f(x)dx$$
$$=\frac{2}{\pi}\int_0^{\pi}\sin x\,dx$$
$$=\frac{2}{\pi}[-\cos(x)]_0^{\pi}=\frac{2}{\pi}[-\cos\pi+\cos 0]$$
$$=\frac{4}{\pi}$$
$|\sin x|=?$
"rectified ac-signal"

E6-triangle wave
$f(x)=x$
$-\pi\leq x\leq\pi$
$f(x+2\pi)=f(x)$
$f(x)$ is odd $\Rightarrow a_n=0, a_0=0$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} dx\, x \sin nx$$

$$\int_{-\pi}^{\pi} x \sin nx = \left[-\frac{\cos nx}{n} x\right]_0^{\pi} - \int_{-\pi}^{\pi} -\frac{\cos nx}{n} 1$$

$$= \left[\frac{\pi}{n}\cos(n\pi) - \left(-\frac{-\pi}{n}\cos(-nx)\right)\right] + \frac{1}{n}\int_{-\pi}^{\pi} \cos nx\, dx$$

$$b_n = \frac{\pi}{n}(-1)^n + \frac{1}{n}\left[\frac{\sin nx}{x}\right]_{-\pi}^{\pi}$$

<u>Extension to other periods</u>

Suppose

$f(x) = f(x - L)$

$f(t) = f(t + T)$

$x_{phy} \equiv x_{phy} + L$

Let

$$x_{maths} = 2\pi \frac{x_{phy}}{L}$$

x_{maths} is dimensionless &

$x_{maths} = x_{maths} + 2\pi$

$$f(x_{maths}) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos(nx_{maths}) + b_n \sin(nx_{maths})$$

$$= \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos\left(\frac{2\pi n}{L} x_{phy}\right) + b_n \sin\left(\frac{2\pi n}{L} x_{phy}\right)$$

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} dx_{maths} \cos(nx) + f(x_{maths})$$

$$a_n = \frac{2\pi}{\pi L}\int_{-\left(\frac{L}{2}\right)}^{\frac{L}{2}} dx_{phys} \cos\left(\frac{2\pi}{L}\, x_{phys}\right) f\left(x_{phys}\right)$$

Applications

Driven harmonic oscillator

Solution for sin/cos ⇒ general case

$$m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = F(t)$$

m-mass

b-viscous cons

k=restoration term

F(t)=driving force

⇒ $F(t + T) = F(t)$

T=period

⇒two parts to problem

A. Solve when F(t)=0

"Solving homogeneous part"

If $x_1(t)$ *and* $x_2(t)$ are solutions, then so is $x_1 + x_2$

2nd order linear differential equation

⇒Two linearly independent solutions

$x(t) = a_1 x_1(t) + a_2 x_2(t)$

B. Find a particular solution for $F(t) \neq 0$

$x_p(t)$

General solution is $x(t) = x_p(t) + a_1 x_1(t) + a_2 x_2(t)$

$$\frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} + w_0^2 x = f(t)$$

(*)

$$\gamma \equiv \frac{b}{m}$$

$$w_0^2 \equiv \frac{h}{m}$$

$$\hat{F} \equiv \frac{F}{m}$$

$([\gamma] = [t]^{-1}, [w_0^2] = [t]^{-2})$
trick Use a complex x*
$x(t) = x_r(t) + ix_i(t)$
If $x(t)$ satisfies (*)

Try a solution

$$x(t) = Ae^{i\alpha t}$$

In equation, which gives
$(ix)^2Ae^{i\alpha t} + \gamma i\alpha Ae^{i\alpha t} + \omega_0^2 Ae^{i\alpha t} = 0$
$[-\alpha^2 + i\alpha\gamma + \omega_0^2]Ae^{i\alpha t} = 0$
So
$\alpha^2 - i\alpha\gamma - \omega_0^2 = 0$

For a good solution

$$\left[ax^2 + bx + c \Rightarrow x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}\right]$$

$$\left(\alpha - \frac{i\gamma}{2}\right)^2 - \left(\frac{i\gamma}{2}\right)^2 - \omega_0^2 = 0$$

$$\left(\alpha - \frac{i\gamma}{2}\right)^2 = \omega_0^2 - \frac{\gamma^2}{4}$$

$$\alpha - \frac{i\gamma}{2} = \pm\sqrt{\omega_0^2 - \frac{\gamma^2}{4}}$$

$$\alpha = \frac{i\gamma}{2} \pm \sqrt{\omega_0^2 - \frac{\gamma^2}{4}} = \frac{\gamma}{2} \pm \bar{\omega}$$

$$\omega_0^2 - \frac{\gamma^2}{4} \geq 0$$

$$x(t) = Ae^{i\alpha t} = Ae^{-\frac{\gamma t}{2}}e^{\pm i\bar{\omega}}$$

Real solution

$$e^{-\frac{\gamma t}{2}}[a_1 \sin\bar{\omega}t + a_2 \cos\bar{\omega}t] = x(t)$$

$$A\cos(\bar{\omega}t + \phi)\, e^{-\left(\frac{\gamma t}{2}\right)}$$

$$\omega_0^2 - \frac{\gamma^2}{4} < 0$$

$$\alpha = \frac{i\gamma}{2} \pm i\sqrt{\frac{\gamma^2}{4} - \omega_0^2} = i\alpha_\pm$$

$e^{i\alpha t} \Rightarrow e^{-\alpha_+ t}\ or\ e^{-\alpha_- t}$
Particular solution
For

$$F(t) = F_0\cos(\omega t) = Re|F_0 e^{i\omega t}$$

Try $x(t) = Ae^{i\omega t}$
Substitute in
$-\omega^2 Ae^{-i\omega t} + i\omega\gamma Ae^{i\omega t} + \omega_0^2 Ae^{i\omega t} = \hat{F}_0 e^{i\omega t}$
$\Rightarrow A[-\omega^2 + i\omega\gamma + \omega_0^2] = \hat{F}_0$

To satisfy this, A must be complex!

Note

$$-\omega^2 + i\omega\gamma + \omega_0^2 = re^{i\theta} = r\cos\theta + i\sin\theta\, r$$

$$\Rightarrow r^2 = (\omega_0^2 - \omega^2)^2 + (\gamma\omega)^2 = r = \sqrt{(\omega_0^2 - \omega^2)^2 + (\gamma\omega)^2}$$

$$\tan\theta = \frac{\omega\gamma}{\omega_0^2 - \omega^2}$$

So

$$A = A_0 e^{i\delta}$$

$$A_0 = \frac{\hat{F}_0}{r}$$
$$\delta = -\omega$$
$$A_0(\omega) = \frac{\hat{F}_0}{[(\omega^2 - \omega_0^2)^2 + (\gamma\omega)^2]^{\frac{1}{2}}}$$
$$\tan\delta = \frac{\omega\gamma}{\omega^2 - \omega_0^2}$$
$$\omega^2 \ll \omega_0^2 \; \delta \sim 0$$

LET

$$x \equiv \omega/\omega_0$$
$$\omega = x\omega_0$$
$$A(x) = \frac{\hat{F}_0}{\omega_0^2\left[(x^2-1)^2 + \frac{\gamma^2}{\omega_0^2}x^2\right]^{\frac{1}{2}}}$$

Define

$$Q \equiv \frac{\omega_0}{\gamma}$$
$$A(x) = \frac{\hat{F}_0}{\omega_0^2\left[(x^2-1)^2 + \frac{x^2}{Q^2}\right]^{\frac{1}{2}}}$$

Q dimensionless !

$$A(x=1) = \frac{\hat{F}_0}{\omega_0^2\left[\frac{1}{Q^2}\right]^{\frac{1}{2}}} = \frac{\hat{F}_0 Q}{\omega_0^2}$$

Suppose we have a general periodic F(t)

e.g. square wave

e.g.

$$F(t) = \frac{F_0}{m}\left[\sin\omega t + \frac{1}{3}\sin 3\omega t + \frac{1}{5}\sin 5\omega t + \cdots\right]$$
$$\Rightarrow x(t)$$
$$= A_1(\omega)\cos(\omega t + \delta_1) + \frac{1}{3}A_1(3\omega)\cos(3\omega t + \delta_3)$$
$$+ \frac{1}{5}A_1(5\omega)\cos(5\omega t + \delta_5) \dots$$

Forced oscillation

$F = F_0\cos(\omega t)\, x(t)\colon A\cos(\omega t + \delta) + transients$

$$A(x,Q) = \frac{1}{\left[(x^2-1)^2 + \frac{x^2}{Q^2}\right]^{\frac{1}{2}}}$$
$$x = \omega/\omega_0$$
$$Q = \frac{\omega_0}{\gamma}$$

$F(t)$=Square waves

$$F(t) = F_0\left(\sin\omega t + \frac{1}{3}\sin 3\omega t + \frac{1}{5}\sin 5\omega t\right)$$
$$F(t) = F_0[A(\omega,Q)\sin\omega t + \frac{1}{3}A(3\omega,Q)\sin 3\omega t + \frac{1}{5}A(5\omega,Q)\sin 5\omega t$$

Response is NOT a square wave

For small x, amplitude of response has a resonance when $\omega = \omega_0$

But also if $3\omega = \omega_0$, we have a large resonance due to $A(3\omega,Q) = Q$

ω_0 get resonances: $\omega = \omega_0, \frac{\omega_0}{3}, \frac{\omega_0}{5}$

In general, get resonances $\omega = \frac{\omega_0}{n}, n = 1,2,3,\dots$

With relative co-efficient b_n

At small x

$$A(x,Q) = \frac{1}{\left[(x^2-1)^2 + \frac{x^2}{Q^2}\right]^{\frac{1}{2}}} \approx 1$$

So response just resembles fourier series and response has same shape as force

$A(x,Q) \rightarrow 1 \; as \; x \rightarrow 1$

<u>Application: Kallza-clein theories</u>

Recall

Particle in spacetime

$$\psi(x,t) = \exp\left[\frac{i(Et-px)}{\hbar}\right]$$

ψ =eigenstate of $i\hbar\frac{\delta}{\delta x} \equiv \hat{p}_x$

$$i\hbar\frac{\delta}{\delta x}\psi = P_x\psi$$

$$-i\hbar\frac{\delta}{\delta t}\psi = E\psi$$

Relativistically,

$$E^2 - |p|^2c^2 = m^2c^4$$

$$p^{\mu}_{\mu p} = m^2c^4$$

$$p_\mu p^\mu \equiv \left(p_0^2 - \sum_{i=x,y,z} p_i^2\right)$$

$$p_0 = \frac{E}{c}$$

Consider spacetime to be 5-dimensional

Idea Kallza-Klein

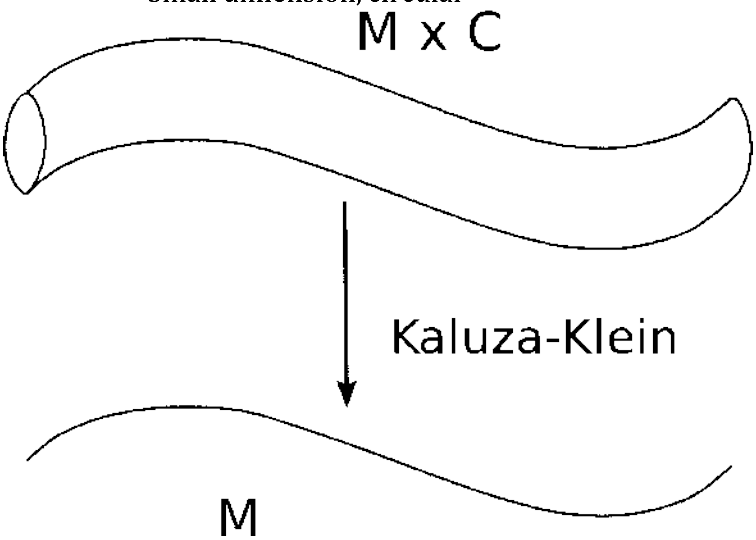
⇒1 time +4 spaces

-Extra dimension was condact

$0 \leq x_5 \leq 2\pi R$

(R small)

Small dimension, circular



From "a distance", space-time looks 4-dimensional

Consider a 5-D quantum particle

$$\frac{i}{\hbar}\left(Et - \underline{p}\underline{x} - p_5x_5\right)$$

$$\Psi = (\underline{x}, t, x_5) = e^{\frac{i}{\hbar}(Et - \underline{p}\underline{x} - p_5x_5)}$$

$$\hat{\text{p}}_\text{x}\Psi(\underline{x}, t, x_5) = \hat{p}_x\Psi$$

$$\boxed{it\frac{\delta}{\delta x_5}\psi = p_5\psi}$$

Since

$$0 \le x_5 \le 2\pi R$$

$$\psi(\underline{x}, t, x_5) = \sum_{n=-\infty}^{\infty} c_n(\underline{x}t) e^{\frac{i\hbar x_5}{R}}$$

Comparing to particle

$$\frac{P_5}{\hbar} \equiv \frac{n}{R}$$

Or

$$p_5 = \frac{\hbar}{R} \times n$$

=momentum in 5th d is quantized

=> in kallza klein electric charge recognised as 5th momentum

hgo

Momentum in 5th dimension is quantized in units of $\frac{\hbar}{R}$

$$\Rightarrow \hat{p}_5 e^{\frac{i\hbar x_5}{R}} = i\hbar \frac{\delta}{\delta x_5} e^{\frac{i\hbar x_5}{R}}$$

Gravity in 5-D

Gravity in 4-D +electromagnetism $[-Q \equiv R_5] = -\frac{\hbar n}{R}$

Note

$\sum P_N P^N = m^2$

n=1,2,3,4,5

$E^2 - p^2c^2 - p_5^2c^2 = m_0^2c^4$

p=3 momentum

$E^2 - |p|^2c^2 = m^2c^4 + p_5^2c^2 = m^2c^4 + \hbar^2n^2c^2/R^2$

=a 5-d particle looks like an infinite power of states in 4-D

Note

$\hbar = 6.6 \times 10^{-22} MeVs$

$c = 3 \times 10^8 m/\,s$

If

$r = 10^{-10}$

$$\frac{\hbar c}{R} = \frac{6.6 \times 10^{-22} MeVs \times 3 \times 10^8 m/\,s}{10^{-10}} = 1.96 \times 10^{-3} MeV$$

For $R = 10^{-15} m$

$$\frac{\hbar c}{R} = 1.96 \times 10^2 MeV$$

⇒ R<nuclear size

LHC experiment will search for masses up to ~TeV probably down to $10^{-19} m$

Kaluza-klein= very nice/beautiful idea, but no evidence observed in nature

Can "all" forces be viewed as gravity in higher dimensions??

Needs D=11 to work!

[11-D supergravity was very popular in 1980's]

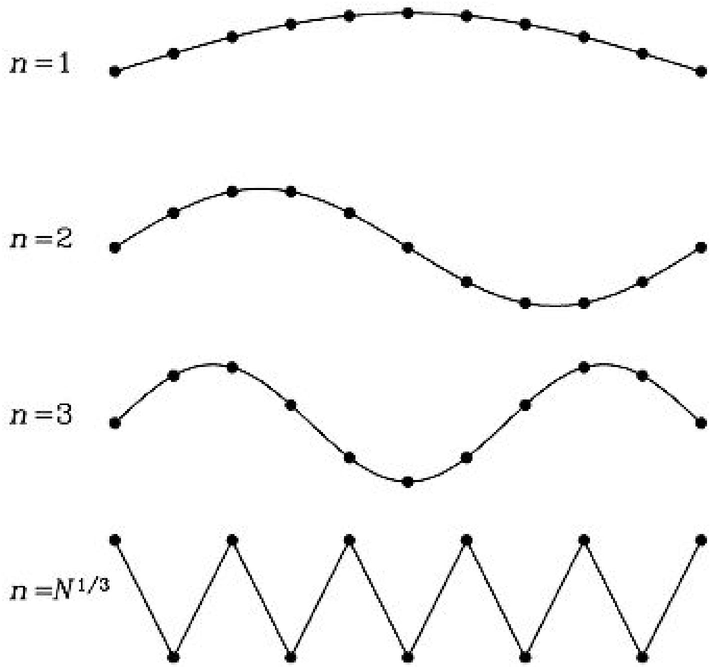
K-K is an alternate way to acquire mass

If $m_0^2 = 0$ $THEN$ $m^2 > 0$ for $n > 0$

Aside: New problem

20 February 2012
12:26

Phonons on a lattice



- Points $x = Na, N = -\infty, \dots, a$
- Displacement defined $f(x) = Na$
- Consider a wave

  $f(x) = A\sin(kx - \omega t)$

  Note $R \equiv R'$

  $A\sin(kx - nt) = A\sin(k'x - \omega t)'$

  At $x = Na$

  $k'a = ka + 2\pi n$

  $k' = k + \dfrac{3\pi N}{a}$
- R only defined $-\frac{\pi}{a} < k < \frac{\pi}{a}$
- Known as brillouin zone
- $\omega(k)$ ≡dispersion relation

  Compare

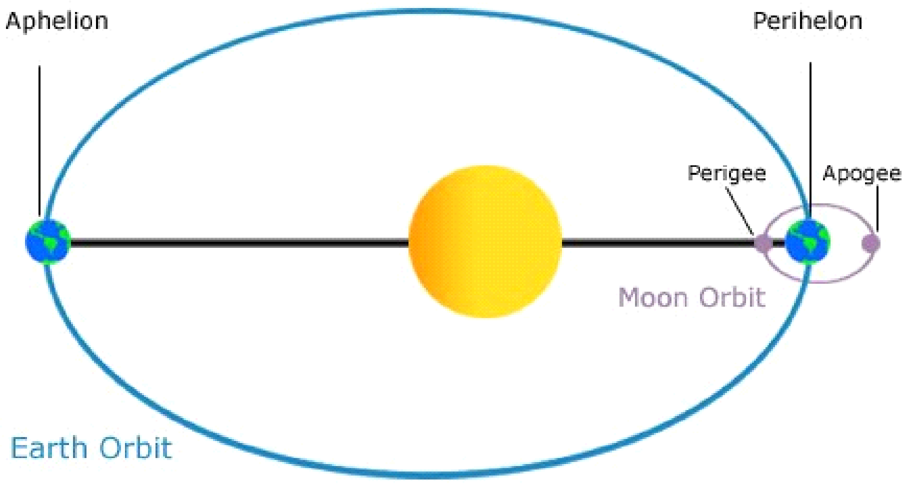
k-k	Phonons
$0 \le x \le R$	$x = Na$
$p = \dfrac{\hbar n}{R}$	$R \in \left[\dfrac{0{,}2\pi}{a}\right]$

Harmonic analysis (not exactly fourier)

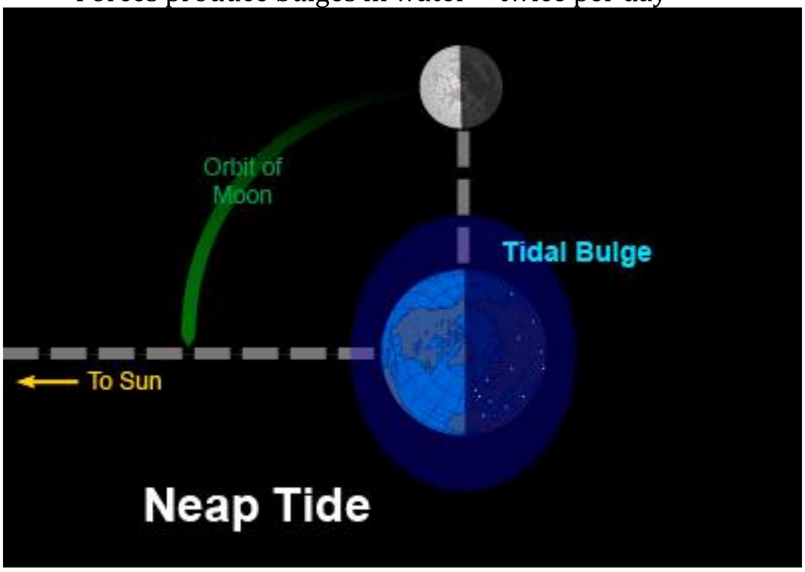
20 February 2012
12:44

Example: tide

The physics of tides is quite complicated



- Forces produce bulges in water ⇒twice per day



- It is important that the system is moving. This would not work if the system is static

Look at this from the viewpoint of the water

- Upward force which is periodic
- $F(t) = F_1 \cos(\omega_1 t) + F_2 \cos(\omega_2 t)$

Model tides by

$$m\ddot{x} + b\dot{x} + kx = F(t)$$

Not a periodic problem unless

$$\frac{\omega_1}{\omega_2} = \frac{n}{m}$$

Force is not periodic

$F(t) = F_1\cos(\omega_1 t) + F_2\cos(\omega_2 t + \epsilon_2)$
We expect a response

$x(t) = A_1\cos(\omega_1 t + \delta_1) + A_2\cos(\omega_2 t + \delta_2)$

$A_1, A_2, \delta_1, \delta_2$

Tidal constants
Are extracted from data

$\omega_1 \& \omega_2$

$\omega = \frac{\pi}{T}$

For sun, T=0.5 days=12 hours
For moon, force has T=12.42 hrs

$W_{sun} = 0.523hr^{-1}$
$W_{moon} = 0.5059hr^{-1}$
$M_{sun} = 1.98 \times 10^{30}kg$
$M_{moon} = 7.3 \times 10^{22}kg$
~~

$$\frac{\text{Force of earth by sun}}{\text{Force of earth by moon}} = \frac{\frac{GM_eM_s}{R_S^2}}{\frac{GM_eM_m}{R_m^2}} = \frac{M_s}{M_m} \times \left(\frac{R_M}{R_s}\right)^2 = 2.5 \times 10^7 \times \frac{1}{400^2} = \frac{2.5 \times 10^7}{1.6 \times 10^8}$$

$= 1.5 \times 10^2$

Tidal forces

How much a fore varies across an object
Tidal force=$(F_1 - F_2)$
~~

$$\frac{\text{tidal force of earth by sun}}{\text{tidal force of earth by moon}} = \left(\frac{M_S}{M_m}\right)\left(\frac{R_m}{R_S}\right)^3 \sim \frac{150}{400} \sim \frac{1}{2.6}$$

Strongest tidal force due to moon (by a small factor)

What does this look like?

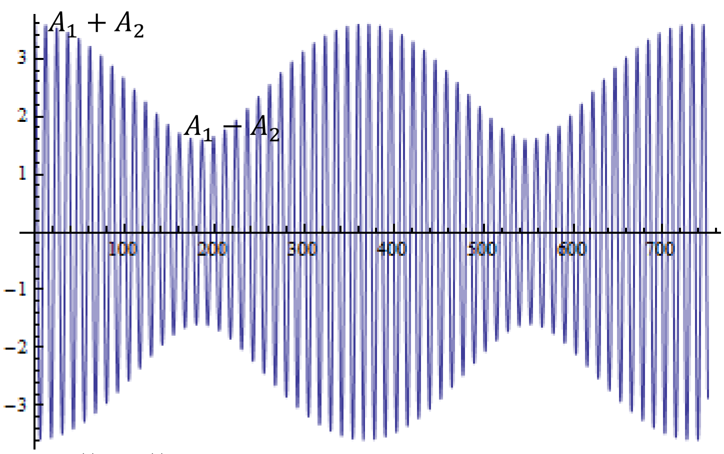
Special case: $A_1 = A_2$
$x(t) = A_1[\cos(\omega_1 t + \delta_1) + \cos(\omega_2 t + \delta_2)]$

$\cos A + \cos B$

$2A_1\cos\left(\frac{(A+B)}{2}\right)\cos\left(\frac{A-B}{2}\right)$

$= 2A_1\cos\left(\left(\frac{\omega_1+\omega_2}{2}\right)t + \left(\frac{\delta_1+\delta_2}{2}\right)\right)\cos\left(\left(\frac{\omega_1-\omega_2}{2}\right)t + \left(\frac{\delta_1-\delta_2}{2}\right)\right)$

Suppose $\omega_1 + \omega_2 \gg \omega_1 + \omega_2$
For us, $\omega_1 = 0.5059, \omega_2 = 0.523$
BUT $A_1 \neq A_2$ $(A_1 > A_2)$



$\frac{\omega_1 - \omega_2}{2} = 0.008853hr^{-1}$

$\Rightarrow T = \frac{2\pi}{\square} = 709.7\ hours = 29.57\ days$

"envelope" occurs every 29.57 days
Small oscillations occur twice daily

Other effects

Elliptical orbits

$F(t) = F_0 \cos(\omega_1 t)\,[1 + \alpha \cos(\omega_3 t)]]$

T_3=365.25 days=4383hrs

$W_3 = 0.00143hrs^{-1}$

α small

Effect of w3 oscillation is

$F(t) = F_0 \cos(\omega_1 t) + F_0 \alpha \cos\big((\omega_1 + \omega_3)t\big) + F_0 \alpha \cos\big((\omega_1 - \omega_3)t\big)$

⇒ response also has extra harmonic components

$x(t)_{extra} = A_3 \cos\big((\omega_1 - \omega_3)t + \delta_3\big) + A_4 \cos\big((\omega_1 + \omega_3)t + \delta\big)$

⇒ take these & other effects into account by adding more constants into response

⇒ tides can be predicted to $<$1%

Fourier Transform

27 February 2012
12:11

- Use Fourier techniques for non-periodic functions
- Start with complex Fourier series

$$f(x) = \sum_{n=-\infty}^{\infty} C_n e^{inx}$$

$$c_n = \frac{1}{2\pi}\int_{-\pi}^{\pi} f(x)e^{-inx}$$

Minus sign important

- For period $2\pi L$

$$f(x) = \sum_{n=-\infty}^{\infty} C_n e^{\frac{in}{L}x}$$

$$C_n = \frac{1}{2\pi L}\int_{-\pi L}^{\pi L} f(x)e^{-\frac{in}{L}x}dx$$

- We want $L \to \infty$

Use

$$\hat{f}\left(\frac{n}{L}\right) = C_n$$

$$f(x) = \sum_{n=-\infty}^{\infty} \hat{f}\left(\frac{n}{L}\right) e^{\frac{in}{L}x}$$

$$\hat{f}\left(\frac{n}{L}\right) = \frac{1}{2\pi L}\int_{-\pi L}^{\pi L} f(x)e^{-\frac{in}{L}x}$$

Define

$$\tilde{f}\left(\frac{n}{L}\right) = \sqrt{2\pi}L\hat{f}\left(\frac{n}{L}\right)$$

$$\hat{f}\left(\frac{n}{L}\right) = \frac{1}{\sqrt{2\pi}}\frac{1}{L}\tilde{f}\left(\frac{n}{L}\right)$$

$$f(x) = \frac{1}{\sqrt{2\pi}}\frac{1}{L}\sum_{n=-\infty}^{\infty} \tilde{f}\left(\frac{n}{L}\right) e^{\frac{in}{L}x}$$

(*)

$$\tilde{f}\left(\frac{n}{L}\right) = \frac{1}{\sqrt{2\pi}}\int_{-\pi L}^{\pi L} f(x)e^{-\frac{inx}{L}}$$

- Recognise (*) as discretization of integral

So

$$\int_{A}^{B} \tilde{f}(p)e^{ipx}$$

Discretised is

$\sum \tilde{f}(n\Delta x)e^{ip(n\Delta x)}$

With

$$\Delta x = \frac{1}{L}$$

So as $L \to \infty$

$$f(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} \tilde{f}(p)e^{ipx}$$

(1)

$$\hat{f}(p) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} f(x)e^{-ipx}$$

(2)

2 is presented as a definition

1 is a result

Function $\tilde{f}(p)$ is the fourier transform of $f(x)$

$f(x) \mapsto \tilde{f}(p)$

Means $\tilde{f}(p)$ is the Fourier transform of f(x)

Properties

1. If $f(x) \mapsto \tilde{f}(p) | g(x) \mapsto \tilde{g}(p)$

   Then

   $\alpha f(x) + \beta g(x) \mapsto \alpha f(p) + \beta g(p)$

2. If $f(x) \mapsto \tilde{f}(p)$

   Then

   $\bar{f}^*(x) \mapsto \tilde{\bar{f}}^\star(p) = \tilde{\bar{f}}(-p)$

   $$\tilde{\bar{f}}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx\, \bar{f}(x) e^{-ipx}$$

   $$= \frac{1}{\sqrt{2\pi}} \left(\int_{-\infty}^{\infty} \tilde{f}(p) \right)$$

   $$\tilde{\bar{f}}(-p)$$

3. If $f(x) \mapsto \tilde{f}(p)$

   Then

   $f(x-a) \mapsto e^{-ipa} \tilde{f}(p)$

   Let $f(x) = f(x-a)$

   $$\tilde{g}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx\, f(x-a) e^{-ipx}$$

   Let $y = (x-a); x = y + a$

   $dy = dx$

   $x = \pm\infty, y = \pm\infty$

   $$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dy f(y) e^{-ipy} e^{-ipa}$$

   $$= e^{-ipa} \times \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dy\, f(y) e^{-ipy} = e^{ipa} \tilde{f}(p)$$

4. If $f(x) \mapsto \tilde{f}(p)$

   $$f(\alpha x) \mapsto \frac{1}{|\alpha|} \tilde{f}\left(\frac{p}{\alpha}\right)$$

   Proof

   Let $g(x) = f(\alpha x)$

   $$\tilde{g}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx f(\alpha x) e^{-ipx}$$

   Let $y = \alpha x, dy = \alpha dx$

   $$3. \tilde{f}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \frac{dy}{\alpha} f(y)\, e^{-i\frac{py}{\alpha}}$$

   If $\alpha > 0m\ x = \pm\infty, y = \pm\infty$

   $$= \frac{1}{\alpha} \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dy\, f(y) e^{-i\left(\frac{p}{\alpha}\right)y}$$

   $$= \frac{1}{\alpha} f\left(\frac{p}{\alpha}\right)$$

   $$= \tilde{g}(p) = \frac{1}{\alpha}\, \tilde{f}\left(\frac{p}{\alpha}\right), a > 0$$

   $a < 0, x = \pm\infty \Rightarrow y = \mp\infty$

   $$\int_{-\infty}^{\infty} dx \to \int_{\infty}^{-\infty} \frac{dy}{\alpha} = -\frac{1}{\alpha} \int_{-\infty}^{\infty} dy$$

   $$\tilde{g}(p) = -\frac{1}{\alpha} f\left(\frac{p}{\alpha}\right), \alpha < 0$$

   So

   $$\tilde{g}(p) = \frac{1}{|\alpha|} \tilde{f}\left(\frac{p}{\alpha}\right)$$

Example

$f(x) = e^{-\alpha x^2}$

Gaussian

Width = $1/\sqrt{\alpha}$

Point α where $f(x) = e^{-1}$

Small α, wide spread

Large α, narrow

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx\, e^{-\alpha x^2} e^{ipx}$$

Step 1 Need

$$I(\alpha) = \int_{-\infty}^{\infty} dx\, e^{-\alpha x^2} \left[\tilde{f}(0) = \frac{1}{\sqrt{2\pi}} I(\alpha)\right]$$

Find it by considering

$$I_2 = \int_{-\infty}^{\infty} dy \int_{-\infty}^{\infty} e^{-(x^2+y^2)}$$

→ 2d integrals

$Note: e^{-\alpha(x^2+y^2)} = e^{-\alpha x^2} e^{-\alpha y^2}$

$$I_2 = \int_{-\infty}^{\infty} dx\, e^{-\alpha x^2} \int_{-\infty}^{\infty} dy\, e^{-\alpha y^2} = I^2(\alpha)$$

Recap

$f(x) = e^{-\alpha x^2}$

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx\, e^{-ipx} f(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx\, e^{-ipx} e^{-\alpha x^2}$$

<u>Aside:</u>

$$I(\alpha) = \int_{-\infty}^{\infty} dx\, e^{-\alpha x^2}$$

$$I_2 = \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy\, e^{-\alpha(x^2+y^2)} = I^2(\alpha)$$

Changing to (r, θ) coordinates, $x^2 + y^2 = r^2$

$$\int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \to \int_{0}^{\infty} dr \int_{0}^{2\pi} d\theta$$

$$I_2 = \int_{0}^{\infty} dr \int_{0}^{2\pi} d\theta\, r e^{-\alpha r^2} = 2\pi \int_{0}^{\infty} dr\, r e^{-\alpha r^2}$$

Let U= αr^2

$r = 0 \Rightarrow u = 0$

$r = \infty \Rightarrow u = \infty$

$du = 2\alpha r dr$

$$= 2\pi \int_{0}^{\infty} \frac{du}{2\alpha} e^{-u}$$

$$\frac{\pi}{\alpha} [-e^{-u}]_0^{\infty} = \frac{\pi}{\alpha}$$

$$\Rightarrow I(\alpha) = \sqrt{\frac{\pi}{\alpha}}$$

28 February 2012
14:11

Now

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} dx\, e^{-\alpha x^2} e^{-ipx}$$

We "complete the square" of $-\alpha^2 - ipx$

$$= -\alpha\left(x + \frac{ip}{2\alpha}\right)^2 + \alpha\left(\frac{iP}{2\alpha}\right)^2 = -\alpha\left(x + \frac{ip}{2\alpha}\right)^2 - \frac{p^2}{4\alpha}$$

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}} e^{-\frac{p^2}{4\alpha}} \int_{-\infty}^{\infty} dx\, e^{-\alpha\left(x+\frac{ip}{2\alpha}\right)^2}$$

Let $y = x + \frac{ip}{2\alpha a}$

$dy = dx$

$x = \pm\infty \Rightarrow y = \pm\infty$

$$= \frac{1}{\sqrt{2\pi}} e^{-\frac{p^2}{4\alpha}} \int_{-\infty}^{\infty} dy e^{-\alpha y^2} = \frac{1}{\sqrt{2\pi}}\sqrt{\frac{\pi}{\alpha}} e^{-\frac{p^2}{4\alpha}} = \frac{1}{\sqrt{2\alpha}} e^{-\frac{p^2}{4\alpha}}$$

Example

$$f(x) = \begin{cases} 1 & |x| \le a \\ 0 \text{ otherwise} \end{cases}$$

Fourier transform of Gau sian, width $= \frac{1}{\sqrt{\alpha}}$, is a Gausian with width $2\sqrt{\alpha}$

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} dx f(x) e^{-ipx}$$

$$= \frac{1}{\sqrt{2\pi}}\int_{-a}^{a} dx\, e^{-ipx} = \frac{1}{\sqrt{2\pi}}\left[\frac{e^{-ipx}}{-ip}\right]_{x=-a}^{x=a}$$

$$= \frac{1}{\sqrt{2\pi}}\frac{1}{-ip}\left[e^{-ipa} - e^{ipa}\right] = \frac{1}{\sqrt{2\pi}}\frac{2\sin pa}{p} = \frac{2a}{\sqrt{2\pi}}\frac{\sin(pa)}{pa} = \frac{2a}{\sqrt{2\pi}}\operatorname{sinc} pa$$

$\frac{\sin x}{x}$ $at\ x = 0\ is?$

We can use L'Hopitals theorem

$$\frac{f(x)}{g(x)} \to^{x\to 0} \lim_{x\to 0}\frac{f'(x)}{g'(x)}$$

In this case

$$\lim_{x\to 0}\frac{\cos x}{1} = 1$$

Example

$$f(x) = \begin{cases} |x-d| \le a & f(x) = 1 \\ |x+d| \le a & f(x) = 1 \\ 0 & \text{otherwise} \end{cases}$$

Note

$f(x) = f_0(x-d) + f_0(x+d)$

f_0 was example previously looked at

So

$$\tilde{f}(p) = \tilde{f}_0(p)e^{ipd} + \tilde{f}_0(p)e^{-ipd}$$

$$= \tilde{f}_0(p) \times 2\cos(pd)$$

$$= \square(\frac{4}{\sqrt{\pi}}\frac{\sin p\alpha}{\alpha}\cos pd$$

For $d \gg \alpha\ \hat{f}(p)$

Any function can be approximated by step functions

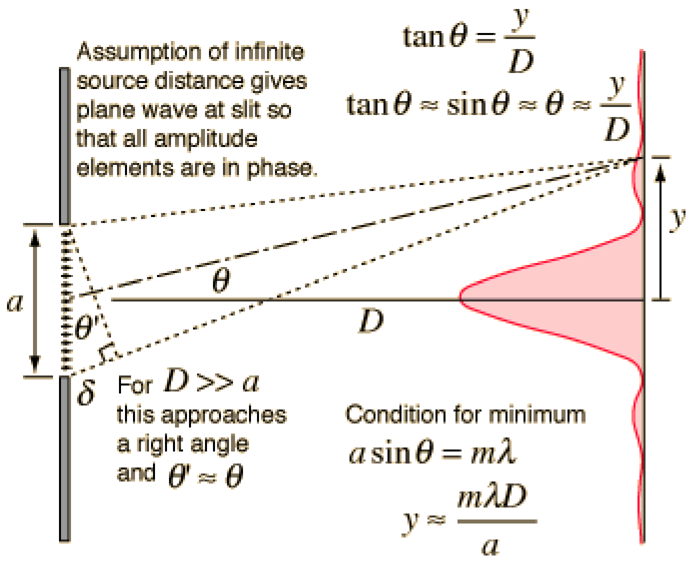
Application

=Fraunhofer diffraction

Diffraction Fraunhoffer ≡ light & screen are effectively at ∞

Fresnel ≡ they are not

Consider diffraction through a slit (specialisation of 2-d problem)
To calculate light at Ym we imagine every point a is a source of light & then we combine resultant



Light is a wave that oscillates

$$\sim \sin(\omega t - kx)$$

$$\cos\left(\omega t - \frac{2\pi}{\lambda}x_t\right)$$

$$= Re\left[e^{-\left(\omega t - \frac{2\pi}{\lambda}x_t\right)}\right]$$

Distance of travel $x_T = r - d = r - x\theta$

So adding waves

$$\int_{-a}^{a} dx\, e^{i\left(\omega t - \frac{2\pi}{\lambda}x_t\right)} e^{\frac{i2\pi x\theta}{\lambda}}$$

$$= e^{i\left(\omega t - \frac{2\pi}{\lambda}\theta\right)} \times \int_{-a}^{a} dx\, e^{\frac{i2\pi x\theta}{\lambda}}$$

f(x)=source
A(θ)=image on screen

$$A(\theta) = \int_{-\infty}^{\infty} dx\, f(x) e^{-i2\pi\frac{\theta}{\lambda}x}$$

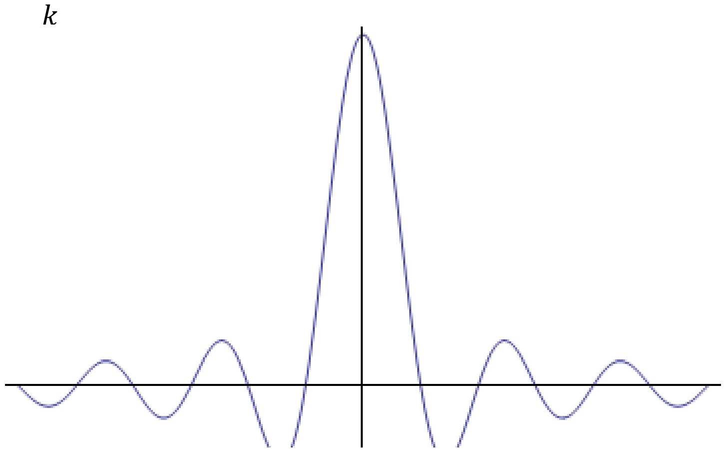
$$= \tilde{f}\left(2\pi\frac{\theta}{\lambda}\right)$$

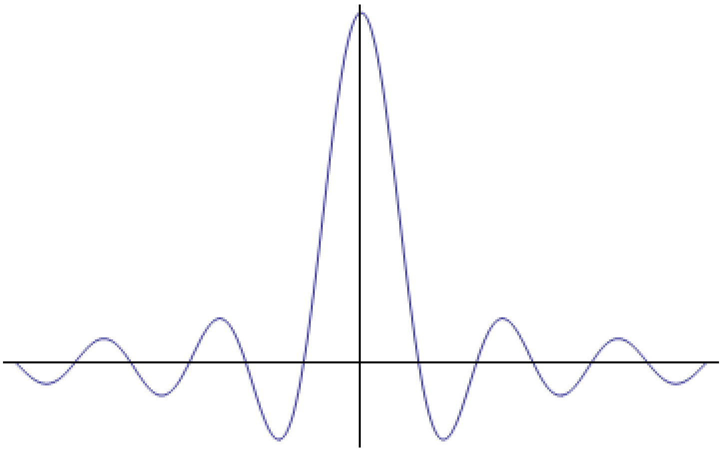
$$f(x) \equiv transmission =$$

e.g. f(x)= square wave from -a to a
We get a pattern

$$\tilde{f}\left(2\pi\frac{\theta}{\lambda}\right)$$

$$\frac{\sin(ka)}{k}$$

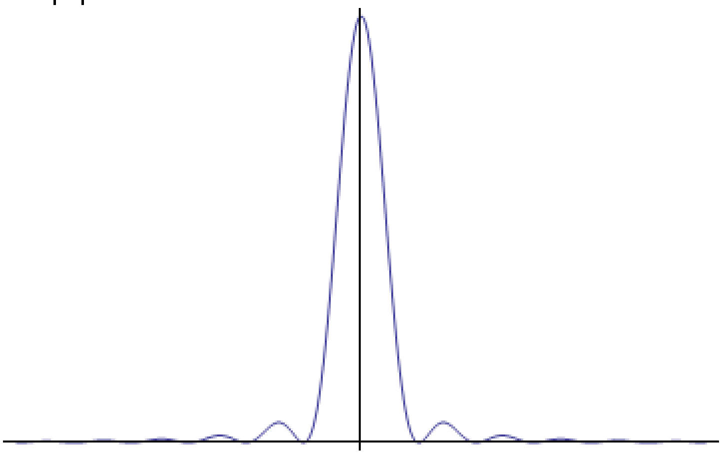




$\theta_{\text{first minimum}} = \frac{\lambda}{2a}$

Intensity of light

$I \propto |A|^2$



Q: how large is secondary maximum?

A. Find by taking derivative

$\left[\frac{\sin x}{x}\right]'$

$\Rightarrow \frac{\cos x}{x} + \sin x - \frac{1}{x^2} = 0$

$\Rightarrow \frac{\cos x}{x} = \frac{\sin x}{x^2}$

$\Rightarrow x = \tan x$

Solve numerically

2nd maximum has height, (intensity)=0.047

Double slit= single slit + single slit with phase shift

Solution

$\left(e^{ikd} + e^{-ikd}\right) \times \frac{\sin ka}{k}$

$= \frac{2 \cos kd \times \sin ka}{k}$

$k \Rightarrow 2\pi \frac{\theta}{\lambda}$

Q: how large is secondary maximum

$f_{\text{Screen Image}} \to \tilde{f}_{\text{Intensity pattern}}$

$f_{\text{Screen Image}} \leftarrow \tilde{f}_{\text{Intensity pattern}}$

Can get from one to the other

Multi Dimensional Fourier Transform

12 March 2012
10:39

$$\tilde{f}(p_1, p_2) \equiv \frac{1}{\left(\sqrt{2\pi}\right)^2} \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dy \; e^{i(p_1 x + p_2 y)} f(x, y)$$

Application ∴ diffraction

$$A(\theta, \phi) = \tilde{f}\left(\frac{2\pi\theta}{\lambda}, \frac{2\pi\phi}{\lambda}\right)$$

Example

$$f(x, y) = \begin{cases} 0 & \\ 1 \quad if & |x| < a \\ \quad And & |y| < b \end{cases}$$

$$\tilde{f}(p_1, p_2) = \tilde{f}_a(p_1) * \tilde{f}_b(p_2) = \frac{\sin p_1 a}{p_1} * \frac{\sin p_2 b}{p_2}$$

So

$$\sim \frac{\sin\left(\frac{2\pi\theta}{\lambda} a\right)}{\frac{2\pi a}{\lambda}} \frac{\sin\left(\frac{2\pi\phi}{\lambda} b\right)}{\frac{2\pi b}{\lambda}}$$

Properties of Fourier Transform

Suppose

$$f(x) \mapsto \tilde{f}(p)$$

$$x f(x) \mapsto i \frac{d}{dp} \tilde{f}(p)$$

$$\frac{d f(x)}{dx} \mapsto ip \, \tilde{f}(p)$$

Proof

Let $g(x) = x f(x)$

$$\tilde{g}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx \; e^{-ipx} x f(x)$$

$$\frac{d}{dp}\left[e^{-ipx}\right]$$

$$\left[\frac{1}{-i} = i\right]$$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx \; i \frac{d}{dp} e^{-ipx} \; f(x)$$

$$= i \frac{d}{dp}\left[\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx \; e^{-ipx} f(x)\right]$$

$$= i \frac{d}{dp} \tilde{f}(p)$$

Next

$$\left(\frac{df}{dx} \to ip\tilde{f}(p)\right)$$

Proof

$$f(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dp \; e^{ipx} \tilde{f}(p)$$

$$\frac{df}{dx} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dp \, \frac{d}{dx} [e^{ipx} \tilde{f}(p)$$

So

$$\frac{df}{dx} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dp \; ip \; e^{ipx} \tilde{f}(p)$$

So

$$\frac{df}{dx} \mapsto ip\tilde{f}(p)$$

E.g.

$$e^{-\frac{x^2}{2}} \mapsto e^{-\frac{p^2}{2}}$$

$$xe^{-\frac{x^2}{2}} \mapsto \frac{d}{dp} e^{-\frac{p^2}{2}} = -ipe^{-\frac{p^2}{2}}$$

$$x^2 e^{-\frac{x^2}{2}}$$

$$= x * xe^{-\frac{x^2}{2}} \mapsto i\ dp\ \left[-ipe^{-\frac{p^2}{2}}\right] = (-p^2 + 1)e^{-\frac{p^2}{2}}$$

$$x^N e^{-\frac{x^2}{2}} \mapsto H_N(p)e^{\frac{-p^2}{2}}$$

$H_N(p)$= hermite polynomials

Validity of Fourier transform

$\tilde{f}(p)$ is a well defined function if

$$\int_{-\infty}^{\infty} dx |f(x)|^2 < \infty$$

(*)

Note

$$f(x) \to 0\ as\ x \to \pm\infty$$

Dirac δ- function

13 March 2012
14:03

{Dirac Delta}

We want to use Fourier transform when (*) doesn't hold
Not a function
$\delta(x)$ is a <u>measure</u> (or distribution)
A measure has well defined integrals
If μ is a measure
$\int dx\, \mu(x) f(x) =$ well defined
$\delta(x)$ Basic defining property

$$\int_{-\infty}^{\infty} dx\, \delta(x) f(x) = f(0)$$

$\delta(x)$ is a limit of normal functions

$$\text{e.g. } \delta = \begin{cases} \frac{1}{2a} & -a < x < a \\ 0 & otherwise \end{cases}$$

$\delta_a(x) \to \delta(x) as\ a \to 0$

NB

$$\delta(x) = \begin{cases} \infty & x = 0 \\ 0 & otherwise \end{cases}$$

Poorly defined
Consider

$$I_a = \int_{-\infty}^{\infty} dx\, \delta_a(x) f(x)$$

Look at integral

$$I_a = 2a \times \frac{1}{2a} f(\zeta)$$

$f(\zeta), -a < \zeta < a$
As $a \to 0, f(\zeta) \to f(0)$
i.e.

$$\lim_{a \to 0} \delta_a(x) \to \delta(x)$$

Note

$$\delta_\alpha(x) \equiv \sqrt{\frac{\pi}{\alpha}} e^{-\alpha x \zeta}$$

$\alpha \to 0$
$\delta_\alpha(x) \to \delta(x)$
Note

$$\tilde{\delta}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx\, e^{-ipx} \delta(x) = \frac{1}{\sqrt{2\pi}}$$

Note

$$\delta(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dp\, e^{ipx} \tilde{\delta}(p)$$

$$\boxed{\delta(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{ipx} dp}$$

$\delta(x-a)$: $\int_{-\infty}^{\infty} dx\, f(x) f(x-a) = f(a)$
$\delta(x-a) \mapsto ?$

$$\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} dx\, e^{-ipx}\delta(x-a) = \frac{a}{\sqrt{2\pi}}$$

$$f(x)\delta(x) = f(0)\delta(x)$$

As a distribution

Proof

$$\int_{-\infty}^{\infty} dx\,\big(f(x)\delta(x)\big)g(x) = \int_{-\infty}^{\infty} dx\, f(x)g(x)\delta(x) = f(0)g(0)$$

$$\int_{-\infty}^{\infty} dx\, f(0)\delta(x)g(x) = f(0)g(0)$$

A

Also

$$\delta(ax) = \frac{1}{|a|}\delta(x)$$

Proof

$$\int_{-\infty}^{\infty} dx f(x)\delta(ax)$$

Let $x' = \alpha x$

$$\alpha dx = dx'$$

$$dx = \frac{1}{\alpha}dx$$

IF

$$a > 0, x = \pm\infty \Rightarrow x' = \pm\infty$$

$$= \frac{1}{\alpha}\int_{-\infty}^{\infty} dx' f\left(\frac{x'}{\alpha}\right)\delta(x') = \frac{1}{\alpha}f(0)$$

Suppose f(x) is periodic $f(x+2\pi) = f(x)$

$$f(x) = \sum_{n=-\infty}^{\infty} c_n e^{inx}$$

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} dx\, e^{-ipx}\sum c_n e^{inx}$$

$$= \sum_{n=-\infty}^{\infty}\frac{c_n}{\sqrt{2\pi}}\int_{-\infty}^{\infty} dx\, e^{-i(p-n)x}$$

$$= \sum_{n=-\infty}^{\infty} c_n\sqrt{2\pi}a\delta(p-n)$$

Recap

$$\int_{-\infty}^{\infty} dx\, \delta(x)f(x) = f(0)$$

$$\tilde{\delta}(o) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} dx\, e^{-ipx}\,\delta(x) = \frac{1}{\sqrt{2\pi}}$$

$$\delta(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} dp\, e^{ipx}\,\tilde{\delta}(p) = \frac{1}{2\pi}\int_{-\infty}^{\infty} dp\, e^{ipx}$$

Example

$$Let\ f(x) = x = x*1 \mapsto (\square)\frac{\delta}{\delta p}\delta p$$

$$\tilde{f}(p) = \frac{1}{\sqrt{\square}}$$

What does

$$\frac{d\delta(x)}{\mathrm{dx}}$$

Mean?

Now

$$\int_{-\infty}^{\infty} dx\, f(x)\frac{d}{dx}\delta(x) = [f(x)\delta(x)]_{-\infty}^{\infty} - \int_{-\infty}^{\infty}\frac{d}{dx}f(x)\delta(x)dx$$

$$= f'(0)$$

Use of δ function

Result

$$\int_{-\infty}^{\infty} |f(x)|^2 \, dx = \int_{-\infty}^{\infty} \left|\tilde{f}(p)\right|^2 dp$$

RHS

$$= \int_{-\infty}^{\infty} dp \, \tilde{f}(p) \tilde{f}(p)^*$$

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx \, e^{-ipx} f(x)$$

$$\tilde{f}^*(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx' \, e^{ipx'} f^*(x')$$

Important to label dummy variables separately

$$= \frac{1}{2\pi} \int_{-\infty}^{\infty} dp \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dx' e^{ip(x'-x)} f(x) f^*(x')$$

$$= \frac{1}{2\pi} \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dx' \, f(x) f^*(x') \int_{-\infty}^{\infty} dp \, e^{ip(x'-x)}$$

$$\int_{-\infty}^{\infty} dp \, e^{ip(x'-x)} = 2\pi \delta(x'-x)$$

$$= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} dx dx' f(x) f^*(x') \delta(x'-x)$$

$$= \int_{-\infty}^{\infty} dx f(x) \int_{-\infty}^{\infty} dx' f^*(x') \delta(x'-x)$$

$$\int_{-\infty}^{\infty} dx' f^*(x') \delta(x'-x) = f^*(x)$$

$$= \int_{-\infty}^{\infty} dx \, f(x) f^*(x) = LHS$$

Notation

13 March 2012
14:19

$|S\rangle = \sum_{i=1}^{n} C_i \, |i\rangle$

$\psi_S = \sum_{i=1}^{n} c_i \psi_i$

ψ_i =eigenstates of an operator

$c_i = \int d^3x \, \psi_i^* \psi = \langle \psi_i \mid \psi \rangle$

Application: Quantum mechanics

$iC_i = (if)\langle j|i\rangle = \delta_{ij}$

$\int \psi_j^* \psi_i = \delta_{ij}$

We can extend to case when we have an infinite, countable set of states

$|s\rangle = \sum_{i=1}^{\infty} C_i \mid i\rangle$

Suppose we move to continuous infinity

$\mid S\rangle = \int_{-\infty}^{\infty} dx \, C_x \mid x\rangle$

Important case: expand in terms of eigenstates of $\hat{x}$

$\mid S\rangle = \int dx \, C(x) \mid x\rangle$

$C_x \rightarrow C(x)$

$\hat{x} \mid x\rangle = x \mid x\rangle$

$\equiv \psi(x)$

We can also expand $\mid s\rangle$ in terms of eigenstates of momentum

$\mid S\rangle = \int dp \tilde{\psi}(p) \mid p\rangle$

$\hat{p} \mid p\rangle = p \mid p\rangle$

$\hat{x}, \hat{p}$ are operators

$\hat{x}\psi(x) = x\psi(x)$

$\hat{p}\psi(x) = i\hbar \frac{\delta}{\delta x} \psi(x)$

Momentum eigenstate is

$\psi(x) = e^{-ip\frac{x}{\hbar}}$

$\hat{p}\psi(x) = i\hbar \frac{\delta}{\delta x} e^{-ip\frac{x}{\hbar}} = i\hbar - \frac{ip}{\hbar} e^{-ip\frac{x}{\hbar}}$

$= P\psi(x)$

=Eigenstate of $\hat{p}$

Note $\psi(x)$ is NOT normalizable!

A. Put universe in a box

   $-M \leq x \leq M$

   $\psi(x)$ is normalizable

   $\int_{-M}^{M} |\psi|^2 < \infty$

   We can calculate "everything" at finite M, & set M to infinity at last line

B. Use wave packets as a fundamental state

   $\psi(x)$ is a Gaussian at x_0 with width Δx

   And we have $\psi(p)$ a Gaussian of width ΔP

C. Use δ −functions

   Accept $\psi(x)$ being a measure rather than function

   $\int_a^b |\psi(x)|^2$= probability of finding particle between a and b

   $|\psi(x)|^2 \Delta x$ = probability of finding particle between x & Δx

Since $\psi(x)$ inside $\int$ perhaps a measure is OK

$$\psi_S = \sum_{i=1}^{n} c_i \psi_i$$

ψ_i =eigenstates of an operator

$$c_i = \int d^3x\, \psi_i^* \psi = \langle \psi_i \mid \psi \rangle$$

For a free particle, particle can be in state x

$$\hat{x} \mid x\rangle = x \mid x\rangle$$

$$\psi(x) \equiv c_i$$

Eigenstates of momentum

$$e^{-\frac{ipx}{\hbar}} = \psi_p(x)$$

$$\hat{p} = i\hbar \frac{\delta}{\delta x}\, \psi_p(x) = p\psi_p(x)$$

Let $\psi_{p_1}(x)$& $\psi_{p_2}(x)$ be wavefunctions which are eigenstates of momentum

Recap for

$$\psi = \sum_n c_n \psi_n$$

$$\int \psi_n^* \psi_m = \delta_{n,m}$$

$$\int dx\, \psi_{p_1}^*(x) \psi_{p_2}(x)$$

$$= \int_{-\infty}^{\infty} dx\, e^{\frac{ip_1 x}{\hbar}} e^{-\frac{ip_2 x}{\hbar}}$$

$$= \int_{-\infty}^{\infty} dx\, e^{\frac{i(p_1 - p_2)x}{\hbar}}$$

$$= \cdots$$

$$= 2\pi \times \hbar \times \delta(p_1 - p_2)$$

x-representation	p-representation
$\psi(x)$	$\psi'(p)$
$\hat{x}\psi = x\psi$	$\hat{p}\psi' = p\psi'$
$\hat{p}\psi = i\hbar \frac{\delta}{\delta x}\psi$	$\hat{x}\psi'(p) = ?$ $\leftarrow i\hbar\, \frac{\delta}{\delta p}$
$\psi_p = e^{-\frac{ipx}{\hbar}}$ Eigenfunction of $\hbar$ Eigenvectors of x	Eigenstates of x? $\tilde{\psi}(p)$ $= \delta(p - p_0)$ $\times 2\pi\hbar$ $= \frac{\hbar}{2\pi}\delta(p_0 - p)$

$\psi(x)$&$\psi'(p)$ are related by being fourier transform of each other ($\hbar = 1$)

$$\psi'(p) = \tilde{\psi}(p)$$

Recall that

$$\psi \mapsto \tilde{\psi}$$

$$x\psi \mapsto \sim \frac{\delta}{\delta p}\tilde{\psi}$$

$$\frac{\delta \psi}{\delta x} \mapsto \sim px\tilde{\psi}$$

For

$\psi_p = e^{\frac{ip_0 x}{\hbar}}$

What is $\tilde{\psi}(p)$

$$\psi(p) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{\frac{ip_0}{\hbar}x} e^{-\frac{ip}{\hbar}x}$$

$$= \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} e^{\frac{i(p_0-p)}{\hbar}x}$$

Similarly eigenstate of x (with value x_0) is

$$\frac{\hbar}{\sqrt{2\pi}}\delta(x - x_0) = \psi(x)$$

Example

$$f(x) = \begin{Bmatrix} \cos(k_0 x) & |x| \le L \\ 0 & otherwise \end{Bmatrix}$$

"wave train"

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} dx\, e^{-ipx} f(x)$$

$$= \frac{1}{\sqrt{2\pi}}\int_{-L}^{L} dx\, e^{-ipx}\cos(k_0 x)$$

Trick use

$$\cos(k_0 x) = \frac{1}{2}(\, e^{ik_0 x} + e^{-ik_0 x})$$

$$= \frac{1}{2\sqrt{2\pi}}\int_{-L}^{L}\left(e^{-i(p+k_0)x} + e^{-i(p-k_0)x}\right)dx$$

$$= \frac{1}{2\sqrt{2\pi}}\left\{\left[\frac{e^{-i(p+k_0)x}}{-i(p+k_0)}\right]_{-L}^{L} + \left[\frac{e^{-i(p-k_0)x}}{-i(p-k_0)}\right]_{-L}^{L}\right\}$$

$$= \frac{1}{2\sqrt{2\pi}}\left\{\frac{e^{-i(p+k_0)L} - e^{-i(p+k_0)(-L)}}{-i(p+k_0)} + \frac{e^{-i(p-k_0)L} - e^{-i(p-k_0)(-L)}}{-i(p-k_0)}\right\}$$

Use $\frac{e^{i\alpha} - e^{-i\alpha}}{2i} = \sin\alpha$

$$= \frac{1}{\sqrt{2\pi}}\left[\frac{\sin\left((p+h_0)L\right)}{p+k_0} + \frac{\sin(p-k_0)L}{p-k_0}\right]$$

...

$$= \frac{L}{\sqrt{2\pi}} \times [\mathrm{sinc}(p+k_0)L + \mathrm{sinc}(p-k_0)L]$$

Function crosses axis at

$$(p - k_0)L = \pi$$

$$p - k_0 = \frac{\pi}{L}$$

$$p = k_0 + \frac{\pi}{L}$$

As L shortens pulse/fourier transform widens

Note peak at $p = -k_0 \& p = k_0$

Because

$$\cos(k_0 x) = \frac{1}{2}\left(e^{ik_0 x} = e^{-ik_0 x}\right)$$

Peaks have width $\frac{\pi}{L}$

Peaks with long width, $L \to 0$

Peaks with short widths $L \to large$

<u>Convolutions</u>

Take 2 functions $f(x), g(x)$

Convolution

$$h(x) = (f * g)x$$

$$h(x) = \int_{-\infty}^{\infty} dx' f(x') g(x - x')$$

Applications

$\Rightarrow^{signal} \Big|_{\text{screen f(x)}} \Big|_{g(x)}$ ⇒ output is some convolution of original signal

Properties

$f * g = g * x$

Proof

$$LHS = f * g(x) - \int_{-\infty}^{\infty} dx' f(x') g(x - x')$$

Let

$y = x - x'$

$dy = -dx'$

$x' = +\infty \Rightarrow y = i\infty$

$x' = x - y$

$$f * g(x) = \int_{\infty}^{-\infty} -dy\, f(x-y) g(y)$$

$$= \int_{-\infty}^{\infty} dy\, g(y) f(x-y) = g * f(x)$$

$f * \delta(x) = f$

$$(f * \delta)(x) = \int_{-\infty}^{\infty} dx' f(x') \delta(x - x') = f(x)$$

Proof

If

$h(x) = f * g$

And

$f \mapsto \tilde{f}$

$g \mapsto \tilde{g}$

$h \mapsto \tilde{h} = \sqrt{2\pi} \tilde{f}(p) \tilde{g}(p)$

Proof

$$\tilde{h}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx\, e^{-ipx} h(x)$$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} dx' g(x') f(x - x') e^{-ipx}$$

Reorder integrators

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx' g(x') \int_{-\infty}^{\infty} dx f(x - x') e^{-ipx}$$

Let $y = x - x' \Rightarrow dy = dx, x = y + x'$

$x = \pm\infty \Rightarrow y = \pm\infty$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx' g(x') \int_{-\infty}^{\infty} dy\, f(y) e^{-ip(y+x')}$$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx' g(x') e^{-ipx'} \int_{-\infty}^{\infty} dy\, f(x) e^{-ipy} = \sqrt{2\pi} \tilde{f}(p)$$

$$\int_{-\infty}^{\infty} dx' g(x') e^{-ipx'} = \sqrt{2\pi} \tilde{g}(p)$$

So

$\tilde{h}(p) = \sqrt{2\pi} \tilde{f}(p) \tilde{g}(p)$

Strategy to disentangle a convolution (knowing f or g)

$$f * g \rightarrow_{FT} \tilde{f}(p) = \frac{\widetilde{f * g}}{\tilde{g}(p)} \rightarrow \tilde{f}(p) \rightarrow_{FT} f(p)$$

Result

If

$f \mapsto \tilde{f}(p), g \mapsto \tilde{g}(p)$

If

$h(x) = f(x) g(x), h \mapsto \tilde{h} \Rightarrow \tilde{f} * \tilde{g}$

Suppose

$\tilde{h}(p) \equiv \tilde{f}(p) * \tilde{g}(p)$

Then

$$h(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dp\ e^{ipx} \tilde{h}(p)$$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dp\ e^{ipx} \int_{-\infty}^{\infty} dp' \tilde{f}(p') \tilde{g}(p - p')$$

Changing order of integrator, and define $q \equiv p - p'$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dp' \tilde{f}(p') \int_{-\infty}^{\infty} dq\ \tilde{g}(q) e^{i(p'+q)x}$$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dp' f(p') e^{ip'x} \int_{-\infty}^{\infty} dq\ \tilde{g}(q) e^{iqx}$$

$$\int_{-\infty}^{\infty} dp' f(p') e^{ip'x} = f(x)$$

$$\int_{-\infty}^{\infty} dq\ \tilde{g}(q) e^{iqx} = g(x)$$

$$\tilde{h}(p) = \sqrt{2\pi} \tilde{f}(p) * \tilde{g}(p)$$

Complex analysis

20 March 2012
14:25

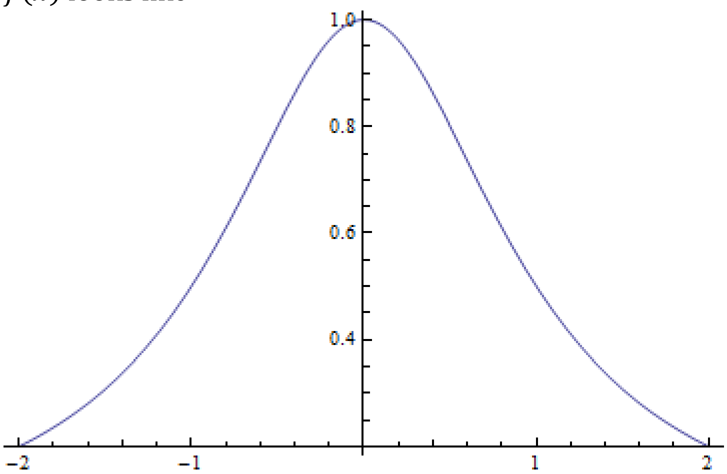
"complex valued complex functions"

Real valued function of real variable	$f\mathbb{R} \to \mathbb{R}$
Complex valued functions of real variables	$f\mathbb{R} \to \mathbb{C}$

$f(x) = f_1(x) + if_2(x)$
Useful
in waves (As a trick)
In QM $\psi(x)$

Complex valued functions of complex variables	$f\mathbb{C} \to \mathbb{C}$

If $z = x + iy$
$f(x) = f_1(x,y) + if_2(x,y)$
At present it is a useful trick/technique
Can help to understand real functions
e.g. $f(x) = \frac{1}{1+x^2}$
Consider taylor expansion
$$\left(\frac{1}{1-x} = 1 + x + x^2 + x^3\right)$$
$f(x) = 1 - x^2 + x^4 - x^6 +$
Converges $|x| < 1$
Diverges $|x| \geq 1$
$f(x)$ looks like



$f(x)$ has no bad behaviour at x=1
Consider
$f\mathbb{C} \to \mathbb{C}$
$$f(z) = \frac{1}{1+z^2}$$
$f(z)$ has a singularity at $1 + z^2 = 0$, or $z^2 = -1, z = \pm i$
If $z = iy$
$$f(x) = \frac{1}{1-y^2}$$
We can understand the behaviour of f(x) better by studying f(z)
Hot topic in particle physics
Studying f if k_1, k_2 can be complex is a remarkably useful technique

Allows us to do really really hard integrals

Complex numbers

26 March 2012
12:06

Complex number

$Z = x + iy, -\infty < x, y < \infty$

$= re^{i\theta}, 0 \le r < \infty, 0 \le \theta < 2\pi \; (-\pi < \theta \le \pi)$

$Z^* = x - iy = re^{-i\theta}$

$ZZ^* = |Z|^2 = r^2 = x^2 + y^2$

$\frac{1}{Z} = \frac{Z^*}{ZZ^*} = \frac{Z^*}{|Z|^2}, e.g. \frac{1}{i} = -i$

$Z_1 Z_2 = (x_1 + iy_1)(x_2 + iy_2) = (x_1x_2 - y_1y_2) + i(y_1x_2 + y_2x_1) = r_1r_2e^{i(\theta_1+\theta_2)}$

$|Z_1Z_2| = |Z_1||Z_2|$

For $Z = x + iy$

$x = Real(Z) = \frac{Z + Z^*}{2}$

$y = Imagenary(x) = \frac{Z - Z^*}{2i}$

Regions on the complex plane

$\{Z: |Z - Z_0| \le a\}$

a=real number

Functions

f(z) is a complex function

$f: \mathbb{C} \to \mathbb{C}$

Limits

$\lim_{z \to z_0} f(z) = \omega_0$

Means as z gets closer to x_0 from any direction, $f(z)$ gets close to ω_0

$\forall \epsilon, \exists a$ st $|f(z) - \omega_0| < \epsilon$ for $z \in \{z: |z - z_0| < a\}$

Differentiation

Consider

$\lim_{z \to z_0} \frac{f(z) - f(z_0)}{z - z_0}$

If this exists then f(z) is differentiable/Holomorphic/analytic

At z_0 we denote the limit by $f'(z_0)$

e.g. any polynomial is holomorphic $f(z) = a_0 + a_1 z - \cdots a_n z^n$

Take something that is not holomorphic

e.g. f(z)=Re(z)

$\Rightarrow Consider$

$\frac{f(z) - f(0)}{z - 0}$

Consider the limit along real axis, z=x

$\frac{f(z) - f(0)}{z - 0} = \frac{x - 0}{x - 0} = 1$

Consider the limit along imaginary axis z=iy

$\frac{f(z) - f(0)}{z - 0} = \frac{0}{iy} = 0$

$\Rightarrow$ two different limits imply function is not holomorphic

Also,

$Im(z) = \frac{z - Re(z)}{i} = -iz + iRe(z)$

Also, Z^* is not holomorphic

$\left(Re(z) = \frac{1}{2}(z + z^*) \right)$

$|z|^2 = zz^*$ is not holomorphic

E.G. $Z^n = f(z)$

$\frac{f(z) - f(z_0)}{z - z_0} = \frac{z^n - z_0^n}{z - z_0} = \frac{(z - z_0)}{z - z_0}(z^{n-1} + z^{n-2}z_0 + \cdots + z_0^{n-1})$

$= z^{n-1} + z^{n-2}z_0 + \cdots + z^{n-1}z_0$

So limit

$= nz_0^{n-1}$

e.g. complex function

$e^z = e^x e^{iy}$

$e^{z'} = e^z \left(\frac{df}{dz} = f\right)$

e.g.

$f(z) = \frac{1}{z}$

=holomorphic except at z=0

$f' = -\frac{1}{z^2}$

= singular at z=0

="pole" at z=0

Rational function

$$f(z) = \frac{\sum_{n=0}^{r_2} a_n z^n}{\sum_{n=1}^{r_1} b_n z^n} = \frac{(a_0 + a_1 z + \cdots + a_n z^n)}{(b_0 + b_1 z + \cdots + b_n z^n)}$$

Singularities occur when

$$\sum b_n z^n = 0$$

Or

$b_{r_1}(z - z_1)(z - z_2)(z - z_3) \ldots (z - z_r)$

e.g. $z^2 + 1 = (z + i)(z - i)$

NB. Real polynomial

$$P(x) = \prod_{i=1}^{m} (x - x_i) x_0 \times \prod_{j=1}^{n} (x^2 + bx + c)$$

IF z_i appears once, it is a "simple pole"

e.g.

$$f(z) = \frac{1}{(z-1)(z-2)(z-3)}$$

Simple poles at $z = 1,2,3$

$$\frac{1}{(z+1)^2(z-1)}$$

Simple pole at z=1

But pole of degree 2 at z=-1

e.g. Log(z)

Define this by

$e^{\log z} = z$

Let $z = re^{i\theta} = x + iy$

$\log(z) = f + ig$

$e^{f+ig} = re^{i\theta}$

Pr

$e^f = r$

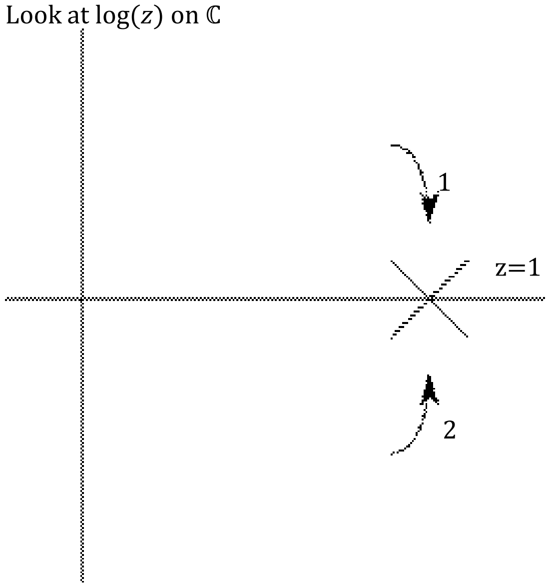
$e^{ig} = e^{i\theta}$

$f = \log|z|$

$g = \arg(z)$

$Log\ (z) = \log|z| + i \arg(z)$

Look at $\log(z)$ on $\mathbb{C}$



1. Approach from above

   $\log z = i\theta \to 0$
2. Approach from below

   $\log z = i\theta \to 2\pi i$

Log(z) is not continuous at z=1!
Not continuous at any point on real +ve axis
Log(z) is not good on real axis
We could choose $-\pi < \theta' < \pi$

$\log' z = \log(|z|) + i\theta'$
Cut on -ve real axis
Functions with cuts are tricky
e.g. $f(z) = \sqrt{z}$

$z = re^{i\theta}, 0 \le \theta \le 2\pi$

$\Rightarrow f(z) = \sqrt{r}e^{i\frac{\theta}{2}}$

Has a cut on real axis

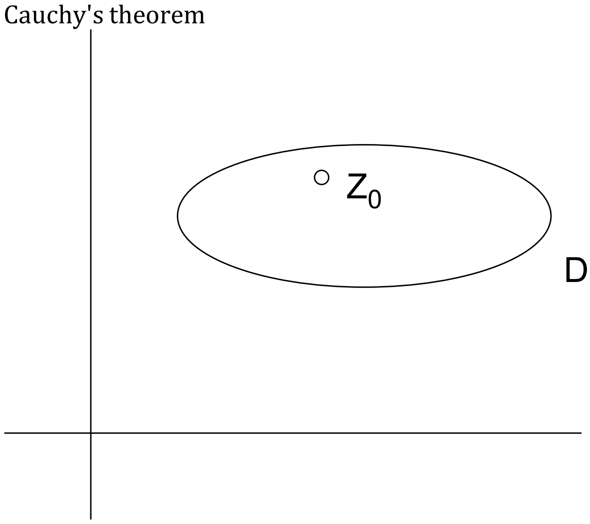
We can change position of cut, BUT not its existence
e.g.

$$\sin z = \frac{e^{iz} - e^{-iz}}{2i}$$

$$\cos z = \frac{e^{iz} + e^{-iz}}{2}$$

Give holomorphic functions everywhere

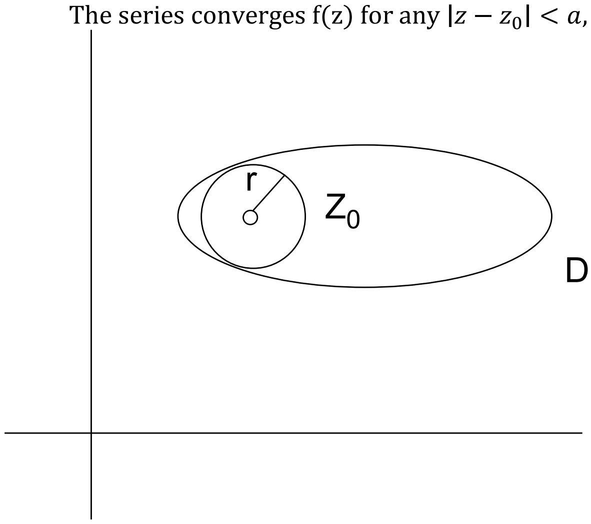
Cauchy's theorem



f(z) is holomorphic on D & $z_0 \subset D$
Then f(z) can be expanded

$$f(z) = \sum_{n=0}^{\infty} C_n (z - z_0)^n$$

The series converges f(z) for any $|z - z_0| < a$, where a is largest disc fitting into D



=Taylor series converges for z in disc

e.g

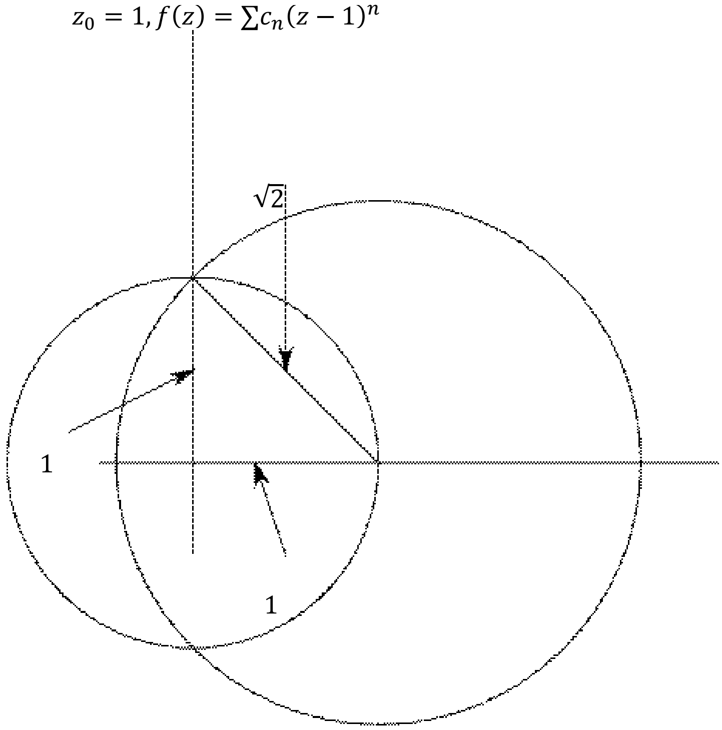
$$f(z) = \frac{1}{1+z^2}$$

Holomorphic except at $z = \pm i$

For $z_0 = 0, a = 1$ & $radius\ of\ convergence = 1$

For

$z_0 = 1, f(z) = \sum c_n (z-1)^n$



A curve, γ, is a continuous mapping from [a,b] to $\mathbb{C}, z = \gamma(t), t \in [a,b]$

$\gamma(t)$ is the parameterisation, $\gamma \& \gamma'$ are same if set of points $\{\gamma(t)\} = \{\gamma'(t)\}$

e.g.

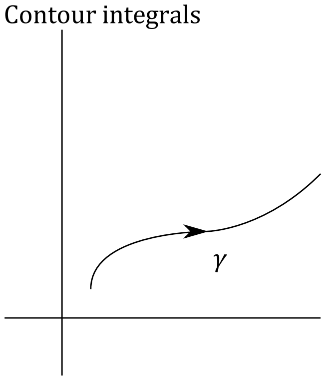
$\gamma_1(t) = 1 + it, t \in [0,1]$

$\gamma_2(t) = 1 + it^2, t \in [0,1]$

= these are two parameterisations of the same curve

e.g. $\gamma(t) = 2e^{it}, t \in [0,2\pi]$

Contour integrals



$$\int_\gamma f(z)dz \equiv depends\ upon\ z\ \&\ \gamma$$

$$\int_\gamma f(z)dz = \int_a^b dt\, f\left(z\big(\gamma(t)\big)\right)\gamma'(t)$$

e.g.

$f(z) = (1+z^2), \{\gamma(t) = 1 + it, t \in [0,1]\}$

$$\int_\gamma f(z)dz = \int_0^1 (1 + (1+it)^2).idt$$

$$= i\int_0^1 dt\,[1 + 1 + 2it - t^2]$$

$$= i\left|2t = \frac{2it^2}{2} - \frac{t^3}{3}\right|_0^1 = i\left|2 + i - \frac{1}{3}\right| = -1 + \frac{5}{3}i$$

$$= \int_\gamma f(z)dz$$

Is parameterization invariant

e.g. $f(z) = 1 + z^2 \{\gamma(t) = 1 + it^2, t \in [0,1]\}$

$$\int_0^1 (1 + (1 + it^2)^2 . 2it\, dt$$

$$2i \int_0^1 t(1 + 1 + 2it^2 - t^4)$$

$$= 2i \left| \frac{2t^2}{2} + \frac{2it^4}{4} - \frac{t^5}{5} \right|_0^1$$

$$= 2i - 1 - \frac{1}{3} i = -1 + \frac{5}{3} i$$

e.g.

$\gamma(t) = Re^{it}, 0 \le t \le 2\pi$

=circle of radius R

="anticlockwise" means +ve direction in θ

$f(z) = z^n, n \ge 0\ integer$

$$\int_\gamma f(z)dz = \int_0^{2\pi} dt\big(Re^{it}\big)iRe^{it} = iR^{n+1} \int_0^{2\pi} e^{i(n+1)t}dt = iR^{n+1} \left| \frac{e^{i(n+1)t}}{1(n+1)} \right|_0^{2\pi}$$

$$= \frac{iR^{n+1}}{i(n+1)} [1 - 1] = 0$$

$$f(z) = \frac{1}{z^n}, n \ne 1$$

$$\int_\gamma f(z)dz = \int_0^{2\backslash pi} dt\ \left(\frac{e^{-int}}{R}\right) iRe^{it} = 0$$

$$f(z) = \frac{1}{z}$$

$$\int_\gamma f(z)dz = \int_0^1 dt\ \frac{1}{Re^{it}}(iRe^{it}) = i \int_0^{2\pi} dt\ 2\pi i$$

$$\int_\gamma f(z)dz = 2\pi i\ \delta_{n,-1}$$

Function gives nothing unless n=-1

Cauchy's integral theorem

$f(z)$ holomorphic on D

γ is in D closed simple contour

$$\int_\gamma f(z)dz = 0$$

- Proof (Not a proof, but reason)

  A small circular region

  $$\int_\gamma f(z)dz = 0$$

  $f(z) = z^n, n = any + ve\ integer$

  Trivial extension to a polynomial

  For a general holomorphic function

  $$f(z) = \sum_{n=0}^{\infty}{}' c_n (z - z_0)^n$$

  In a small region

  $$f_N(z) = \sum_{n=0}^{N}{}' c_n (z - z_0)^n$$

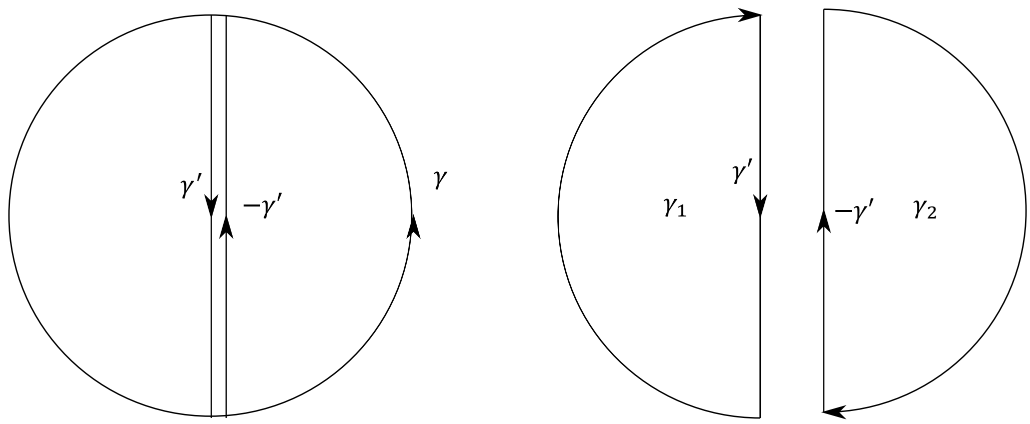
  satisfies

  $$\int_\gamma f_N(z)dz = 0$$

- Note: γ has a direction. Contour reversed is $-\gamma$

  $$\int_\gamma f(z)dz = -\int_{-\gamma} f(z)dz$$

  $$\Rightarrow \int_a^b dt = -\int_b^a dt$$



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$$\int_\gamma f(z)dz = \sum_{CEUS} \int_{\gamma_1} f(z)dz$$

Since cauchy's works for γ_i, it works for γ

Cauchy's residue theorem

γ closed, simple, anticlockwise [+ve direction]

$$\int_\gamma f(z)dz = 2\pi i \times \sum_{z_i\ inside\ \gamma} Res(f, z_i)$$

$Res(f, z_i) \equiv residue\ of\ f\ at\ z_i$

$Res(f, z_i) = \lim_{z \to z_i} (z - z_i) f(z)$

$Res(f, z_i) \equiv$"size" of singularity

Example

$$f(z) = \frac{1}{a^2 + z^2}$$

A +ve real number

f(z) holomorphic except $a^2 + z^2 = 0$

$z^2 = -a^2$

$z = \pm ia^2$

$$Res(f, ia) = \lim_{z \to ia} (z - ia) \frac{1}{z^2 + a^2}$$

$$\lim_{z \to ia} (z - ia) \frac{1}{(z - ia)(z + ia)} = \lim_{z \to ia} \frac{1}{(z + ia)} = \frac{1}{2ia} = \frac{-i}{2a}$$

$$Res(f, -ia) = \lim_{z \to ia} (z + ia) \frac{1}{z^2 + a^2}$$

$$\lim_{z \to ia} (z + ia) \frac{1}{(z - ia)(z + ia)} = \lim_{z \to ia} \frac{1}{(z - ia)} = -\frac{1}{2ia} = \frac{i}{2a}$$

$$\int_{\gamma_1} f(z)dz = 2\pi i\ Res(f, ia)$$

$$2\pi i * -\frac{i}{2a} = \frac{\pi}{a}$$

$$\int_{\gamma_2} f(z)dz = 2\pi i[Res(f, ia) + Res(f, -ia)] = 0$$

$$\int_{\gamma_3} f(z)dz = 0$$

Consider $\gamma' \equiv$ new contour

$$\int_{\gamma'} f(z)dz = 0$$

Near z_i,

$$f(z) \approx \frac{Res(f, z_i)}{z - z_i}_{small} \quad as\ z \to z_i$$

& we know

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$$0 = \int_\gamma f(z)dz = \int_\gamma f(z)dz - 2\pi i \sum Res(f, z_i)$$

$$\int_{\gamma} f(z)dz = 2\pi i \sum_i{}' Res(f, z_i)$$

Note: we can distort contours

$$\int_{\gamma_1} f(z)dz = \int_{\gamma_2} f(z)dz$$

If f(z) is holomorphic on shaded region

$\gamma_1 - \gamma_2 \equiv$

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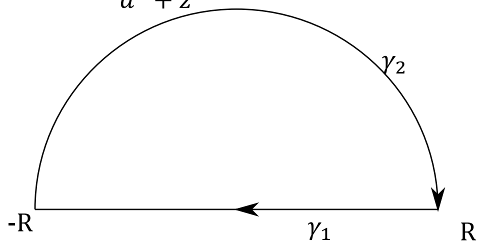
Consider

$$I = \int_{-\infty}^{\infty} dx \frac{1}{a^2 + x^2}$$

We must choose f(z) & γ

Choose

$$f(z) = \frac{1}{a^2 + z^2}$$



$\gamma = \gamma_1 + \gamma_2$

Note

$$\int_{\gamma_1} f(z)dz$$

$$\gamma_1 = \{ \begin{matrix} z = x, & -R \le x \le R \\ \gamma' = 1 & \end{matrix}$$

$$= \int_{-R}^{R} \frac{dx}{a^2 + x^2} = I_R$$

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$$\int_{\gamma} f(z)dz = 2\pi i \sum_i{}' Res(f, z_1) = 2\pi i \, Res(f, z = i, a), R > a$$

$$= 2\pi * -\frac{i}{2a} = \frac{\pi}{a}$$

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Note: IF

$$\int_{\gamma_2} f(z)dz \to 0 \; as \; R \to \infty$$

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Theorem

If

$|f(z)| \le M \; on \; \gamma$

$$\left| \int_{\gamma} f(z)dz \right| \le M \times L$$

$L \equiv length \; \gamma$

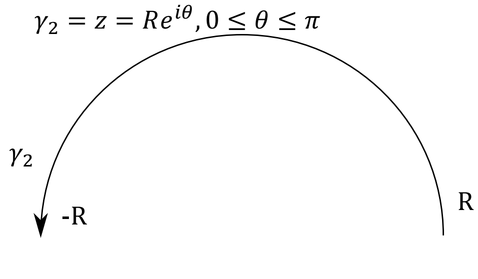
$L \equiv \int_a^b dt |\gamma'(t)| \equiv$ normal definition of length

This is just

$$|a_1 + a_2 + a_3| \le |a_1| + |a_2| + |a_3|$$

Theorem

$\gamma_2 = z = Re^{i\theta}, 0 \le \theta \le \pi$



On $\gamma_2 |z| = R$
On γ_2

$$f(z) = \frac{1}{a^2 + z^2}$$

$$|f(z)| = \frac{1}{|a^2 + z^2|} \leq \frac{1}{|z|^2 - |a|^2} = \frac{1}{R^2 - a^2}$$

$$\left| \int_{\gamma_2} f(z) dz \right| \leq \frac{\pi R}{R^2 - a^2}$$

$R \to \infty$
$this \to 0$
So

$$\lim_{R \to \infty} \square$$

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This technique works

$$\int_{-\infty}^{\infty} \frac{p^m(x)}{p^n(x)} dx$$

Provided $n-, \geq 2$

$$\left[\text{Note } \int^{\infty} \frac{p^m(x)}{p^n(x)} \sim \int^{\infty} \frac{1}{x^{n-m}} \text{ converges only if } n-m>1\right]$$

$$[\text{Note } \int_1^A \frac{dx}{x} = [\ln x]_1^A = \ln A \to \infty \; as \; A \to \infty$$

2) $p^n(z) = 0$ only for z not purely real

⇒in this case

$$\int_{-\infty}^{\infty} \frac{1}{x} dx$$

Is also not well defined

Example

What is fourier transform of

$$\frac{1}{x^2+a^2}?$$

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} dx \frac{e^{-ipx}}{x^2+a^2}$$

Choose

$$g(z) = \frac{e^{-ipz}}{z^2+a^2}$$

$$\int_{\gamma} g(z)dz = 2\pi i \sum_{z_i \text{ in } \gamma} Res(f, z_i)$$

g(z) has poles at $z = \pm ia$

$$Res(f, ia) = \lim_{z\to ia} z_i$$

$$= \lim_{z\to ia} (z-ia) \frac{e^{-ipz}}{(z-ia)(z+ia)}$$

$$= \frac{e^{-ip.ia}}{2ia} = -\frac{i}{2a} e^{pa}$$

$$Res(f, z=-ia) = \lim_{z\to ia} \frac{(z+ia)e^{-ipz}}{(z-ia)(z+ia)} = \frac{e^{-ip.-ia}}{-2ia} = \frac{i}{2a} e^{-pa}$$

Look at

$$\int_{\gamma_2} f(z)dz \, , z = Re^{i\theta} = R\cos\theta + iR\sin\theta$$

$$f(z) = \frac{e^{ipz}}{z^2+a^2} = \frac{e^{ipR\cos\theta + Rp\sin\theta}}{z^2+a^2}$$

$$|f(z)| = \frac{e^{Rp\sin\theta}}{|z^2+a^2|} \leq \frac{e^{Rp\sin\theta}}{R^2-a^2} \leq \frac{1}{R^2-a^2}, IF \; p<0$$

Choose

$$IF \; p<0, \left|\int_{\gamma_2} f(z)dz\right| \leq \frac{\pi L}{R^2-a^2} \to 0 \; as \; R \to \infty$$

So

$$\int_{\gamma} f(z)dz = 2\pi i \times -\frac{i}{2a} e^{Pa} = \frac{\pi}{a} e^{Pa}$$

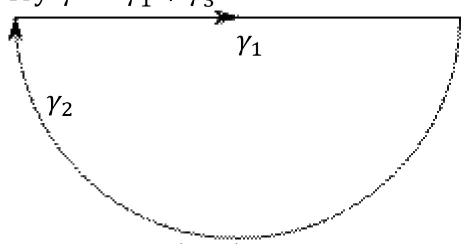
So

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}} \times \frac{\pi}{a} e^{Pa}$$

If P<0

$P > 0$

Try $\gamma' = \gamma_1 + \gamma_3$



$z = Re^{i(2\pi - t)}, t \in (0, \pi)$

$$\int_\gamma f(z)dz = -2\pi i \, Res(f, z = -ia)$$

$-$ sign since γ' is clockwise (negative)

$$= -2\pi i. \frac{1}{2a} e^{-pa} = \frac{\pi}{a} e^{-pa}$$

On $\gamma_3, z = R\cos(2\pi - t) + iR\sin(2\pi - t)$

$|e^{-ipz}| = e^{pR\sin(2\pi - t)} \leq 1$

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$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}} \frac{\pi}{a} e^{-pa}, p > 0$$

$$\tilde{f}(p) = \frac{1}{\sqrt{2\pi}} \frac{\pi}{a} e^{pa}, p < 0$$

$$\tilde{f}(p) = \sqrt{\frac{\pi}{2}} \times \frac{e^{-|p|a}}{a}$$

e.g.6

$$f(x) = \frac{\cos(x)}{x^2 + a^2}$$

$$f(z) = \frac{e^{iz} + e^{-iz}}{z^2 + a^2} = f_1(z) + f_2(z)$$

$$f_1(z) = \frac{e^{iz}}{z^2 + a^2}$$

$$f_2(z) = \frac{e^{-iz}}{z^2 + a^2}$$

Example

$$\int_0^{2\pi} d\theta F(\cos\theta, \sin\theta)$$

e.g.

$$\int_0^{2\pi} \frac{dx}{2 + \cos A}$$

We want

$$\int_\gamma f(z)dz = I$$

Choose γ

Circular contour of r=1

$z = e^{i\theta}, 0 \leq \theta \leq 2\pi$

ON contour

$$\cos A = \frac{(e^{i\theta} + e^{-i\theta})}{2} = \frac{1}{2}\left(z + \frac{1}{z}\right), \sin\theta = \frac{1}{2i}\left(z - \frac{1}{z}\right)$$

Note

$$\gamma'(\theta)d\theta = ie^{i\theta}d\theta$$

So

$$\int \frac{dz}{z} \times (\square) \Rightarrow \int \frac{d\theta ie^{i\theta}}{e^{i\theta}} \times (\square) = i \int d\theta(\square)$$

So

$$\int_\gamma \frac{dz}{iz} F\begin{pmatrix} \cos A \Rightarrow \frac{1}{2}\left(z + \frac{1}{z}\right) \\ \sin A \Rightarrow \frac{1}{2}\left(z - \frac{1}{z}\right) \end{pmatrix}$$

$$\Rightarrow \int_0^{2\pi} d\theta F(\cos\theta, \sin\theta)$$

Eg

$$\int_0^{2\pi} \frac{d\theta}{2 + \cos\theta}$$

γ circle radius 1

$$f(z) = \frac{1}{iz} \frac{1}{2 + \frac{1}{2}\left(z + \frac{1}{z}\right)} = -i \frac{1}{2z + \frac{1}{2}z^2 + \frac{1}{2}}$$

$$= -\frac{2i}{4z + z^2 + 1}$$

Ex1

$$\int_\gamma f(z) = 2\pi i \sum Res(f, z_i)$$

f(z) has poles

$$z^2 + 4z + 1 = 0$$
$$(z + 2)^2 - 4 + 1 = 0$$
$$(z + 2)^2 = 3$$
$$z = -2 \pm \sqrt{3}$$

$$\int_\gamma f(z)dz = 2\pi i Res\left(f, z = -2 + \sqrt{3}\right)$$

Res

$$= \lim_{z \to -2+\sqrt{3}} \left(z - \left(-2 + \sqrt{3}\right)\right) \frac{-2i}{\left(z - \left(-2 + \sqrt{3}\right)\right)\left(z - \left(-2 - \sqrt{3}\right)\right)}$$

$$= -\frac{2i}{-2 + \sqrt{3} - \left(-2 - \sqrt{3}\right)} = -\frac{2i}{2\sqrt{3}} = -\frac{i}{\sqrt{3}}$$

$$\int f(z)dz = 2\pi i \times -\frac{i}{\sqrt{3}} = \frac{2\pi}{\sqrt{3}}$$