Group Velocity and Phase Velocity (1A)

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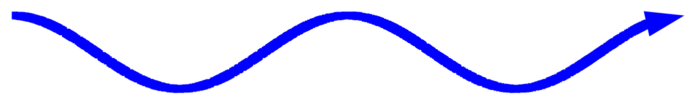
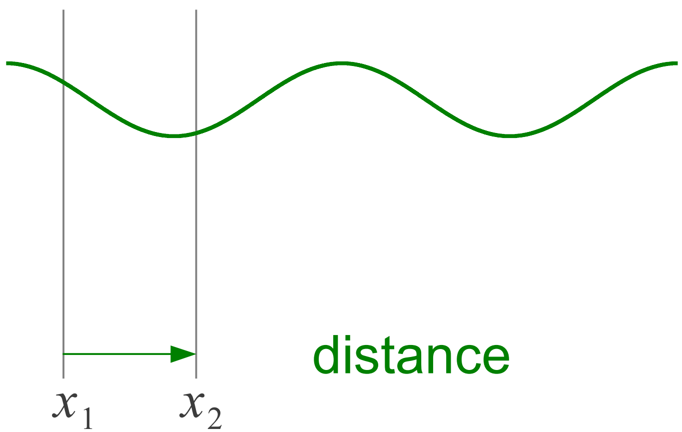
Wave Equation

$$A(t, t) = A_0 \cos(kx - \omega t)$$



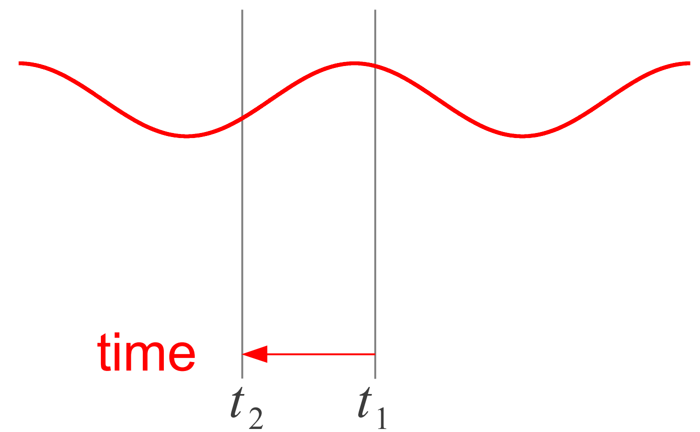
$A_0 \cos(kx - \omega t_0)$

At the snapshot of the time t_0



$A_0 \cos(kx_0 - \omega t)$

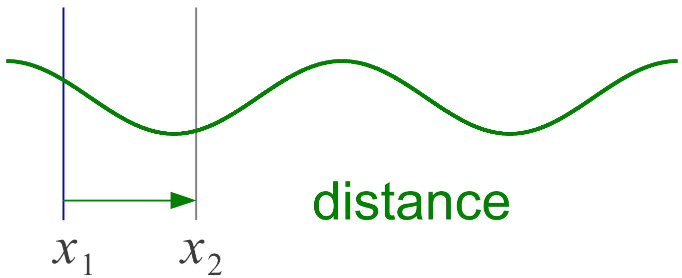
At the fixed site of the distance x_0



Wavelength, Frequency

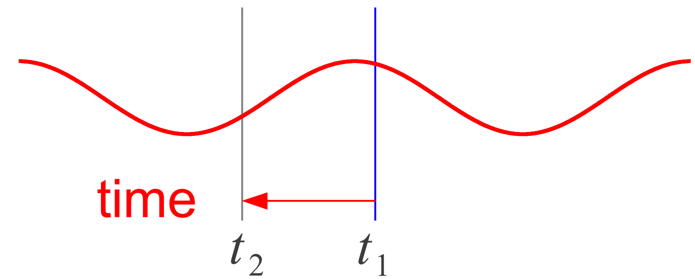
$A_0 \cos(k\,x - \omega t_0)$

At the snapshot of the time t_0



$A_0 \cos(k\,x_0 - \omega t)$

At the fixed site of the distance x_0



wavelength $\lambda = \dfrac{2\pi}{k}$

wave number $k = \dfrac{2\pi}{\lambda}$

frequency $f = \dfrac{\omega}{2\pi}$

period $T = \dfrac{2\pi}{\omega}$

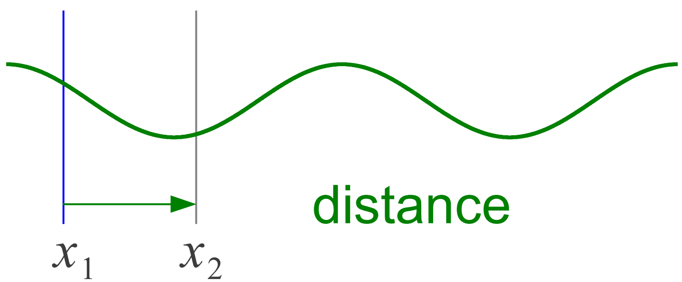
angular frequency $\omega = 2\pi f$

angular frequency $\omega = \dfrac{2\pi}{T}$

Wave Number, Angular Frequency

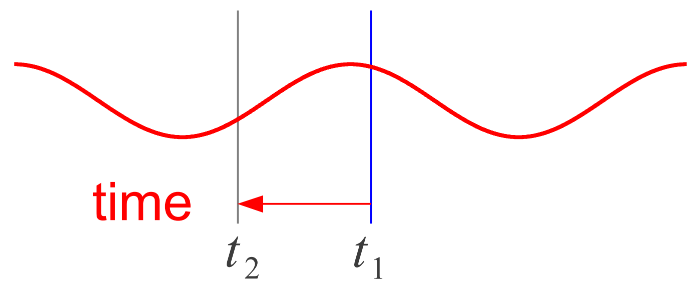
$A_0 \cos(k\,x - \omega\,t_0)$

At the snapshot of the time t_0



$A_0 \cos(k\,x_0 - \omega\,t)$

At the fixed site of the distance x_0



wave number $k = \dfrac{2\pi}{\lambda}$

radians per unit distance

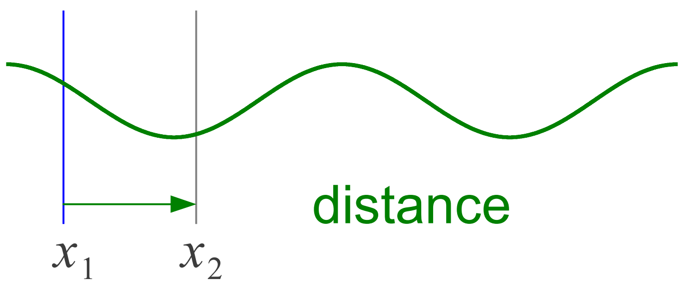
angular frequency $\omega = \dfrac{2\pi}{T}$

radians per unit time

Phase Velocity (1)

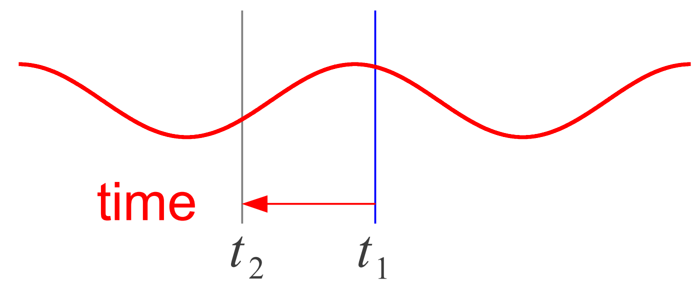
$$A_0 \cos(k\,x - \omega t_0)$$

At the snapshot of the time t_0



$$A_0 \cos(k\,x_0 - \omega t)$$

At the fixed site of the distance x_0



wave number $k = \dfrac{2\pi}{\lambda}$

radians per unit distance

angular frequency $\omega = \dfrac{2\pi}{T}$

radians per unit time

Phase Velocity $v_p = \dfrac{\lambda}{T} = \dfrac{2\pi/k}{2\pi/\omega} = \dfrac{\omega}{k}$

$$v_p = \frac{\omega}{k}$$

Phase Velocity (2)

Phase Velocity $v_p = \frac{\omega}{k}$

$$A\cos(kx - \omega t)$$

*Given time **t**,* ➡ ωt *oscillations*

*Corresponding distance **x**,* ➡ *the same oscillations*

$$kx = \omega t$$

$$v_p = \frac{x}{t} = \frac{\omega}{k}$$

Phase Velocity, Group Velocity

Phase Velocity $$v_p = \frac{\omega}{k}$$

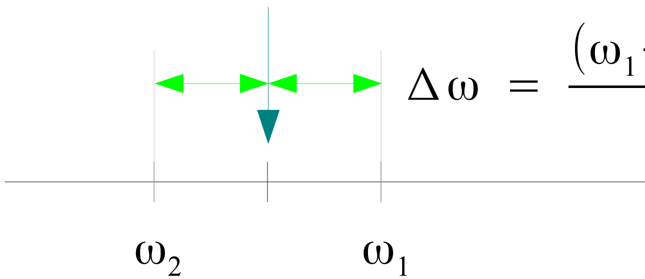
Group Velocity $$v_g = \frac{\partial \omega}{\partial k}$$

Group Velocity Explanation (1)

$$\omega_1 > \omega_2$$

$$\omega = \frac{(\omega_1 + \omega_2)}{2}$$

$$\Delta\omega = \frac{(\omega_1 - \omega_2)}{2}$$



$$\omega_1 = \omega + \Delta\omega$$

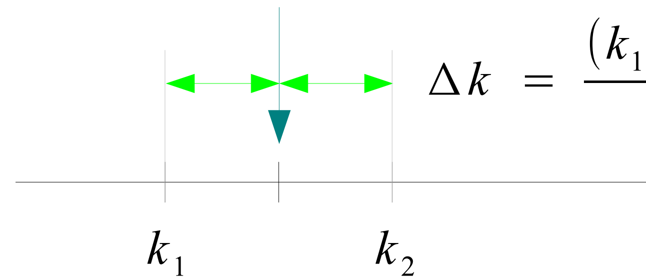
$$\omega_2 = \omega - \Delta\omega$$

$$e^{j(k_1 x - \omega_1 t)}$$

$$k_1 > k_2$$

$$k = \frac{(k_1 + k_2)}{2}$$

$$\Delta k = \frac{(k_1 - k_2)}{2}$$

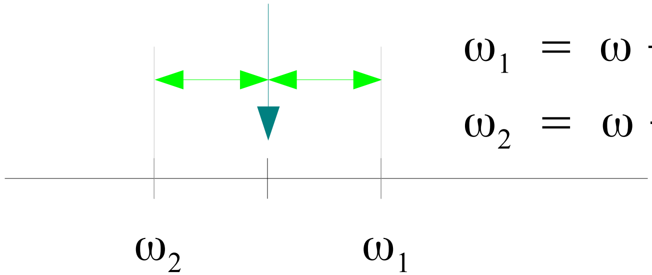


$$k_1 = k + \Delta k$$

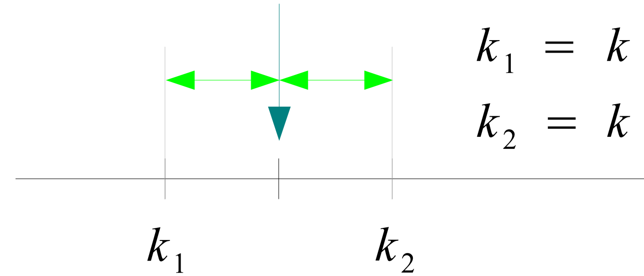
$$k_2 = k - \Delta k$$

$$e^{j(k_2 x - \omega_2 t)}$$

Group Velocity Explanation (2)



$$\omega_1 = \omega + \Delta\omega$$
$$\omega_2 = \omega - \Delta\omega$$



$$k_1 = k + \Delta k$$
$$k_2 = k - \Delta k$$

$$e^{j(k_1 x - \omega_1 t)} + e^{j(k_2 x - \omega_2 t)}$$

$$= e^{j\{(k + \Delta k)x - (\omega + \Delta\omega)t\}} + e^{j\{(k - \Delta k)x - (\omega - \Delta\omega)t\}}$$

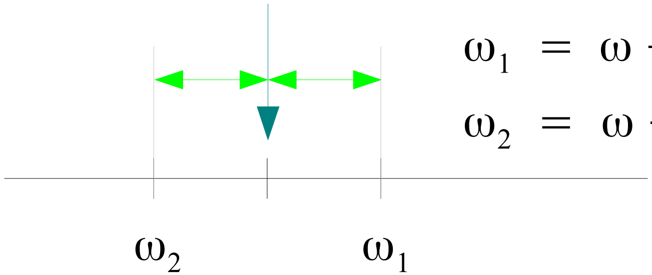
$$= e^{j\{(kx - \omega t) + (\Delta k x - \Delta\omega t)\}} + e^{j\{(kx - \omega t) - (\Delta k x - \Delta\omega t)\}}$$

$$= e^{j(kx - \omega t)}\left\{e^{j(\Delta k x - \Delta\omega t)} + e^{-j(\Delta k x - \Delta\omega t)}\right\}$$

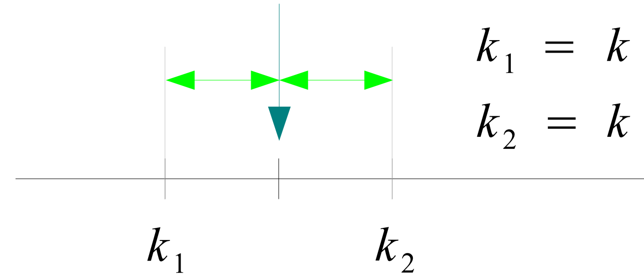
$$= 2\cos(\Delta k x - \Delta\omega t)\, e^{j(kx - \omega t)}$$

Envelope

Group Velocity Explanation (3)



$$\omega_1 = \omega + \Delta\omega$$
$$\omega_2 = \omega - \Delta\omega$$



$$k_1 = k + \Delta k$$
$$k_2 = k - \Delta k$$

$$e^{j(k_1 x - \omega_1 t)} + e^{j(k_2 x - \omega_2 t)}$$
$$= 2\cos(\Delta k\, x - \Delta\omega\, t)\, e^{j(k x - \omega t)}$$

Envelope

$\Delta k \ll k_1, \; k_2$ → *Small Wave number* → *Long Wavelength*

$\Delta\omega \ll \omega_1, \; \omega_2$ → *Small Frequency* → *Long Period*

Envelope Velocity $\quad v_g = \dfrac{\Delta\omega}{\Delta k}$

Group Velocity $\quad v_g = \dfrac{d\omega}{dk}$

Group Velocity & Fourier Transform (1)

A periodic function

$$f(\theta) = \sum_k a_k \sin(k\theta) + b_k \cos(k\theta)$$

$$a_k = \frac{1}{\pi}\int_{-\pi}^{+\pi} f(\theta)\sin(k\theta)\,d\theta \qquad b_k = \frac{1}{\pi}\int_{-\pi}^{+\pi} f(\theta)\cos(k\theta)\,d\theta$$

A non-periodic function

$$f(x) = \int_{-\infty}^{+\infty} F(k)\,e^{jkx}\,dk$$

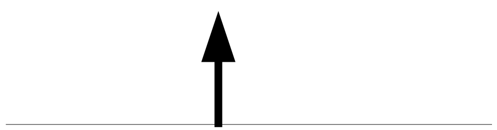
$$F(k) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} f(x)\,e^{-jkx}\,dx$$

Group Velocity & Fourier Transform (2)

A non-periodic function

$$f(x) = \int_{-\infty}^{+\infty} F(k)\, e^{jkx}\, dk \qquad F(k) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} f(x)\, e^{-jkx}\, dx$$

Infinite number of sine waves
Well-defined wavelength
Well-defined k (wave number)



Lots of sine waves of diff wavelengths
Short wave packet

A long wave packet

A small spread in k
Sharp peak

Group Velocity & Fourier Transform (3)

A non-periodic function

$$f(x) = \int_{-\infty}^{+\infty} F(k)\, e^{jkx}\, dk \qquad F(k) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} f(x)\, e^{-jkx}\, dx$$

A long wave packet

A small spread in k
Sharp peak at k_0

At some initial time $t = t_0$

$$f(x,0) = \int_{-\infty}^{+\infty} F(x) e^{jkx} dk$$

After time t

$$f(x,t) = \int_{-\infty}^{+\infty} F(x) e^{j(kx - \omega(k)t)} dk$$

$\omega(k)$ ***different wavelength components have different frequencies***

Taylor expansion to 1st order

$$\omega(k) = \omega_0 + \frac{d\omega}{dk}(k - k_0)$$

$$f(x,t) = \int_{-\infty}^{+\infty} F(x) e^{j(kx - (\omega_0 + \frac{d\omega}{dk}(k-k_0))t)} dk$$

Group Velocity & Fourier Transform (3)

A long wave packet

A small spread in k
Sharp peak at k_0

After time t

$$f(x,t) = \int_{-\infty}^{+\infty} F(x) e^{j(kx - \omega(k)t)} dk$$

Taylor expansion to 1st order

$$\omega(k) = \omega_0 + \frac{d\omega}{dk}(k - k_0)$$

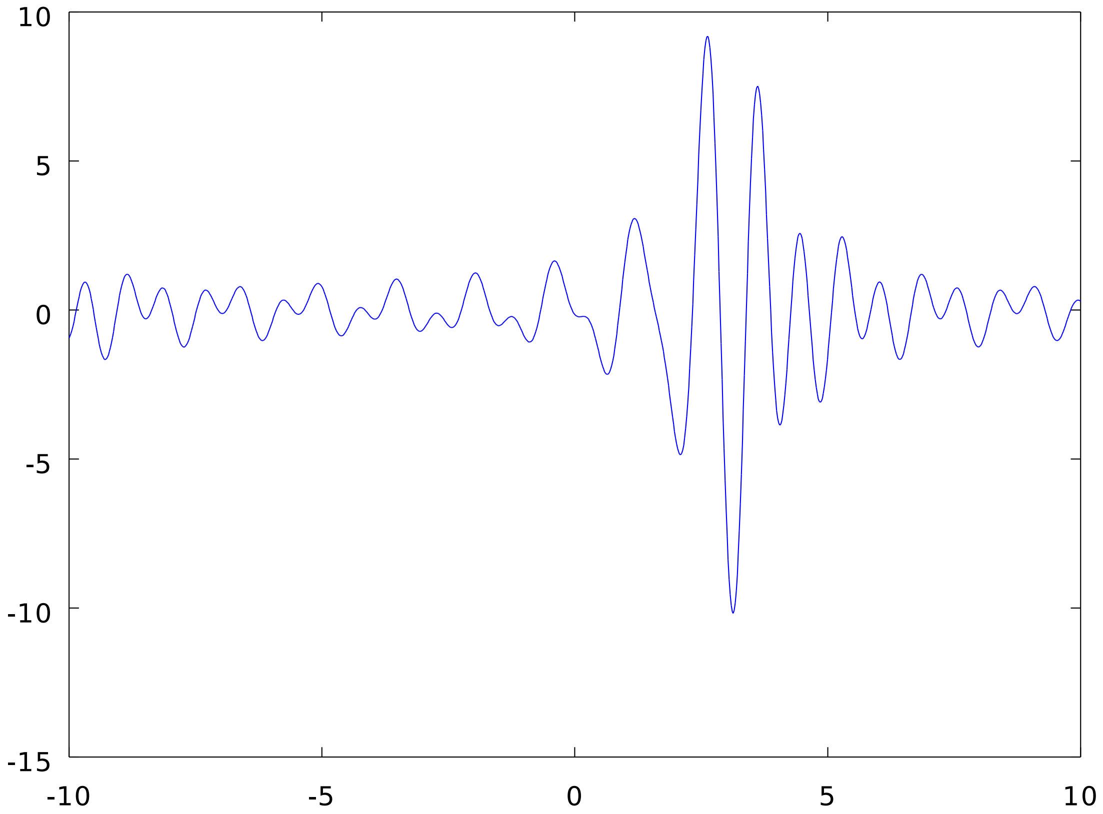
$$f(x,t) = \int_{-\infty}^{+\infty} F(k) e^{j(kx - (\omega_0 + \frac{d\omega}{dk}(k-k_0))t)} dk$$

$$= \int_{-\infty}^{+\infty} F(k) e^{j(k_0 x + kx - k_0 x - (\omega_0 + \frac{d\omega}{dk}(k-k_0))t)} dk$$

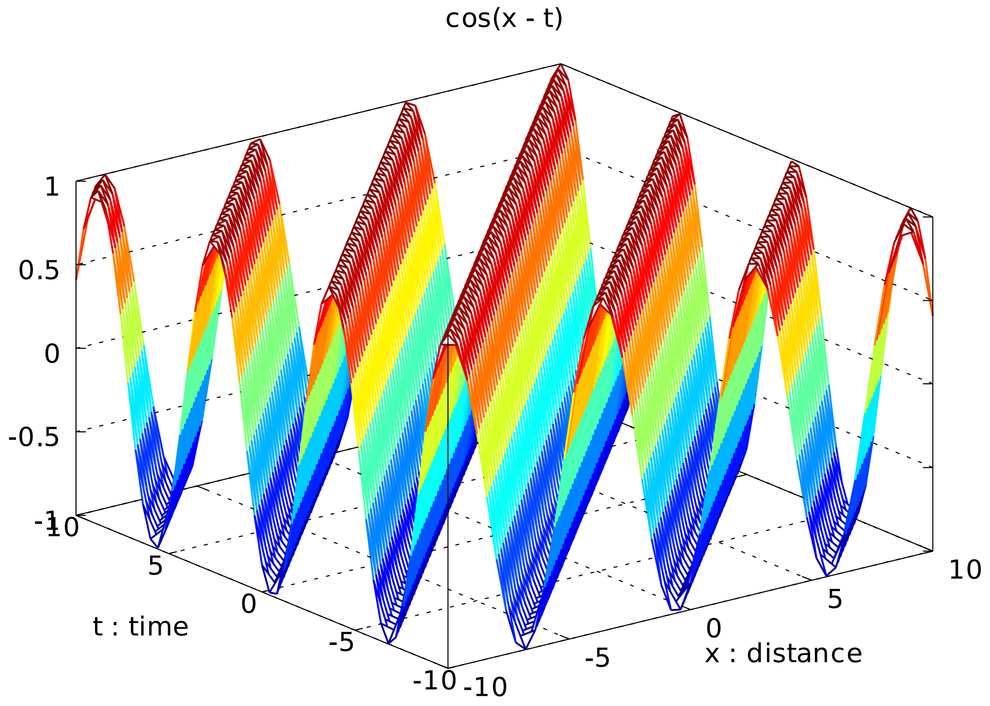
$$= e^{j(k_0 x - \omega_0 t)} \int_{-\infty}^{+\infty} F(k) e^{j((k-k_0)x - \frac{d\omega}{dk}(k-k_0)t)} dk$$

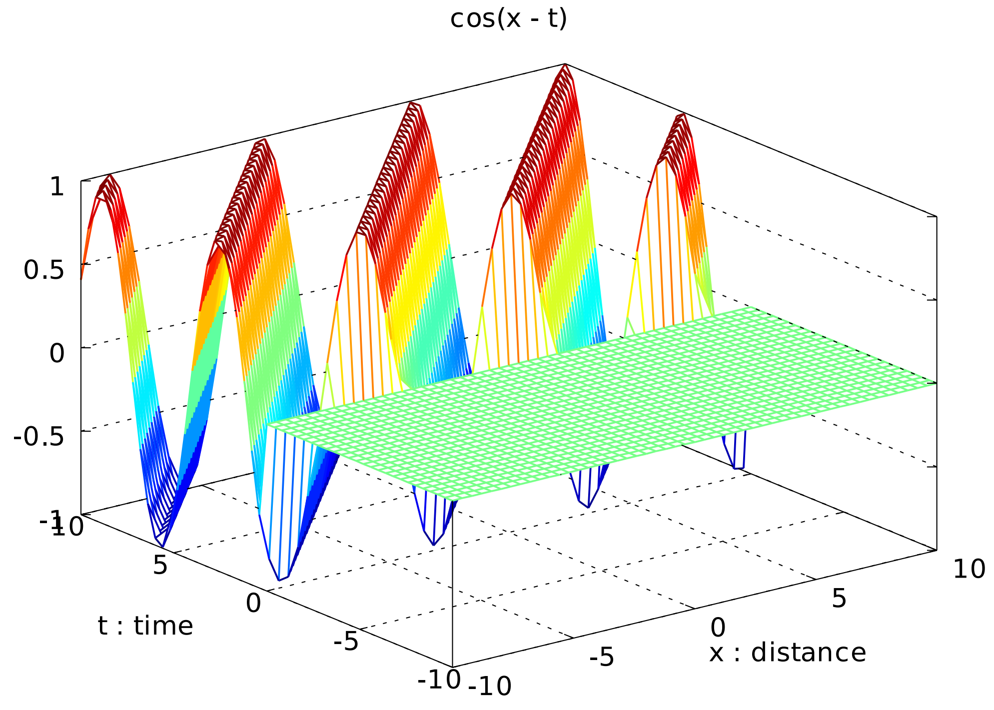
$$= e^{j(k_0 x - \omega_0 t)} \int_{-\infty}^{+\infty} F(k) e^{j(k-k_0)\left(x - \frac{d\omega}{dk}t\right)} dk$$

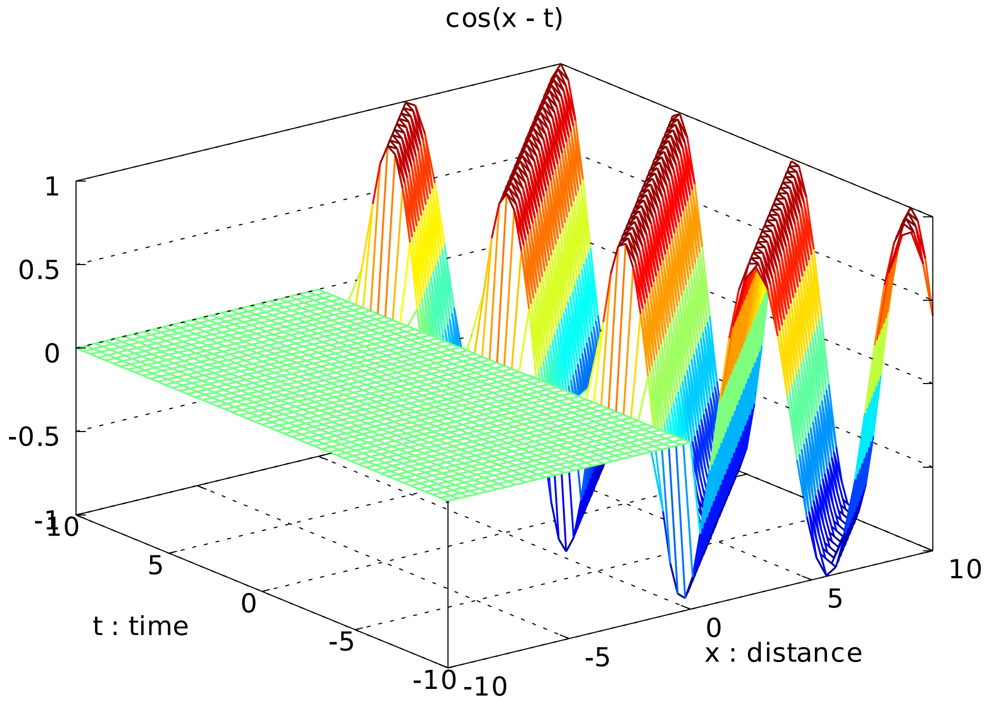
Group Velocity $\quad v_g = \dfrac{d\omega}{dk} \quad \Leftarrow \quad \left(x - \dfrac{d\omega}{dk} t\right)$



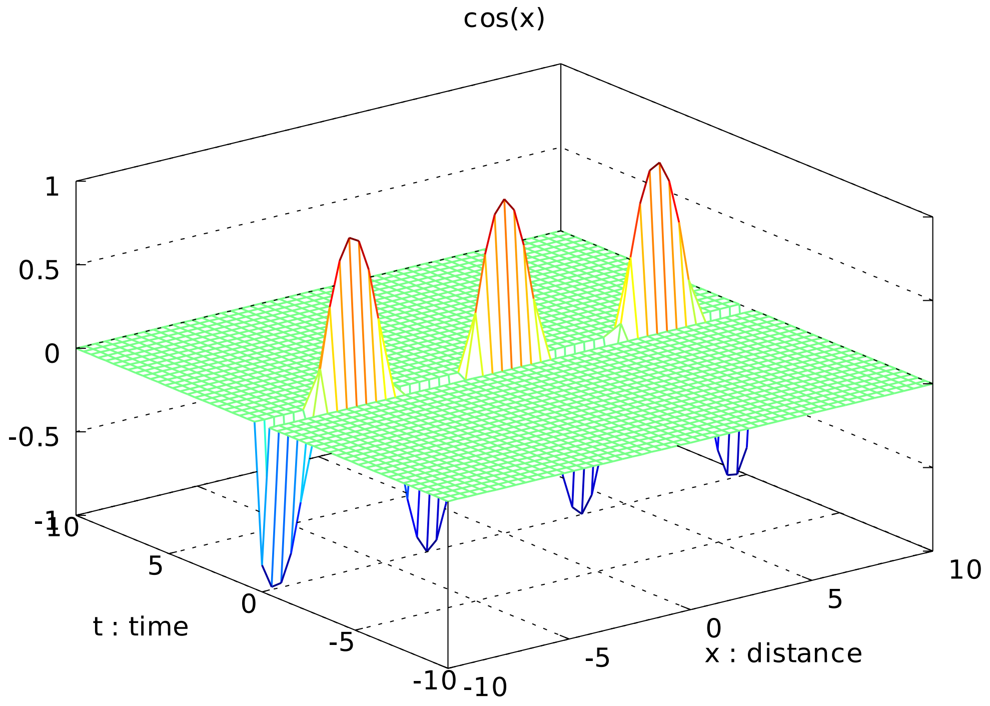

```
x = linspace(-10, +10, 1000);

y = zeros(1, 1000);
for k= 1.0:0.1:2.0
   y = y + cos(4*k*(x-k));
end
plot(x, y);
```

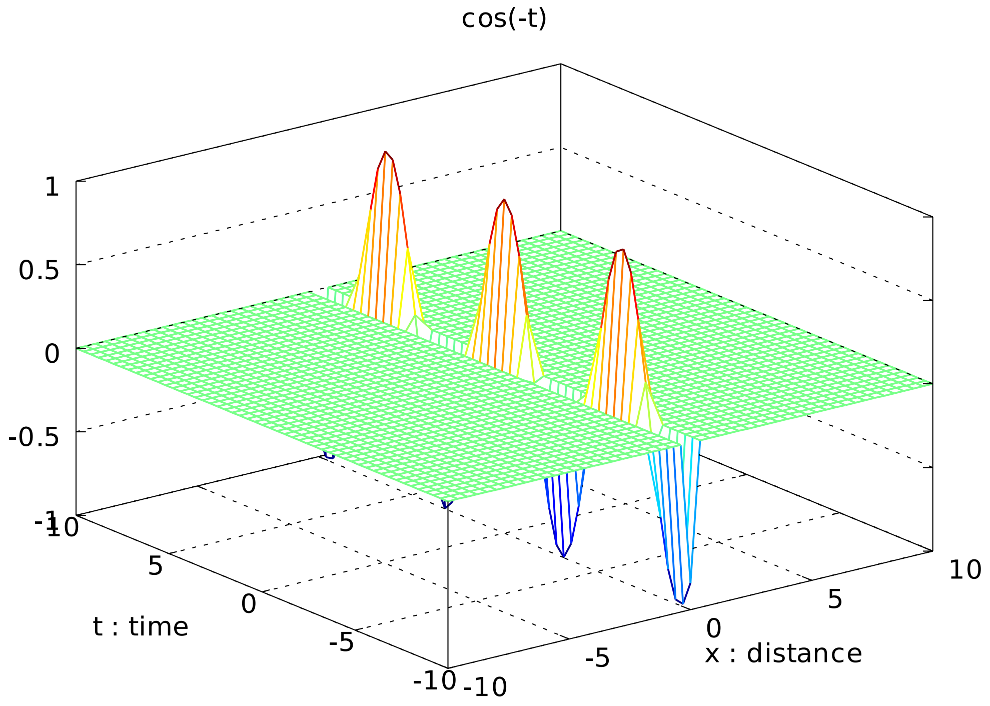

cos(x - t)
1
0.5
0
-0.5
-1
-10
5
0
-5
-10
t : time
-10
-5
0
5
10
x : distance


cos(x - t)
1
0.5
0
-0.5
-1
-10
5
0
-5
-10
t : time
-10
-5
0
5
10
x : distance



cos(x - t)
1
0.5
0
-0.5
-1
-10
5
0
-5
-10
t : time
-10
-5
0
5
10
x : distance


cos(x)
1
0.5
0
-0.5
-1
-10
5
0
-5
-10
t : time
-10
-5
0
5
10
x : distance


cos(-t)
1
0.5
0
-0.5
-1
10
5
0
-5
-10
t : time
-10
-5
0
5
10
x : distance

```
tx = ty = linspace(-10, 10, 51);
[xx, yy] = meshgrid(tx, ty);
tz = cos(xx-yy) ;
mesh(tx, ty, tz);
title("cos(x - t)");
xlabel("x : distance");
ylabel("t : time");
print -demf fig1.emf
```

```
tx = ty = linspace(-10, 10, 51);
[xx, yy] = meshgrid(tx, ty);
bb = [zeros(26, 51); ones(25, 51)];
tz = cos(xx-yy) .* bb;
mesh(tx, ty, tz);
title("cos(x - t)");
xlabel("x : distance");
ylabel("t : time");
print -demf fig2.emf
```

```
tx = ty = linspace(-10, 10, 51);
[xx, yy] = meshgrid(tx, ty);
bb = [zeros(51, 26) ones(51, 25)];
tz = cos(xx-yy) .* bb;
mesh(tx, ty, tz);
title("cos(x - t)");
xlabel("x : distance");
ylabel("t : time");
print -demf fig3.emf
```

```
tx = ty = linspace(-10, 10, 51);
[xx, yy] = meshgrid(tx, ty);
aa = zeros(51, 51);
aa(26,:) = ones(1, 51);
tz1 = cos(xx - yy) .* aa;
mesh(tx, ty, tz1);
title("cos(x)");
xlabel("x : distance");
ylabel("t : time");
print -demf fig4.emf
```

```
tx = ty = linspace(-10, 10, 51);
[xx, yy] = meshgrid(tx, ty);
aa = zeros(51, 51);
aa(:, 26) = ones(51, 1);
tz1 = cos(xx - yy) .* aa;
mesh(tx, ty, tz1);
title("cos(-t)");
xlabel("x : distance");
ylabel("t : time");
print -demf fig5.emf
```

References

[1] http://en.wikipedia.org/
[2] J.H. McClellan, et al., Signal Processing First, Pearson Prentice Hall, 2003
[3] http://www.mathpages.com/, Phase, Group, and Signal Velocity
[4] R. Barlow, www.hep.man.ac.uk/u/roger/PHYS10302/lecture15.pdf
[5] P. Hofmann, www.philiphofmann.net/book_material/notes/groupphasevelocity.pdf