Fourier Series & The Fourier Transform

What is the Fourier Transform?

Anharmonic Waves

Fourier Cosine Series for even functions

Fourier Sine Series for odd functions

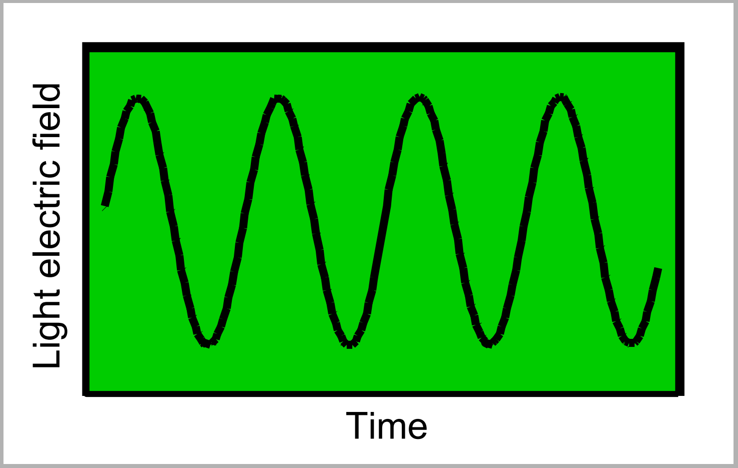
The continuous limit: the Fourier transform (and its inverse)

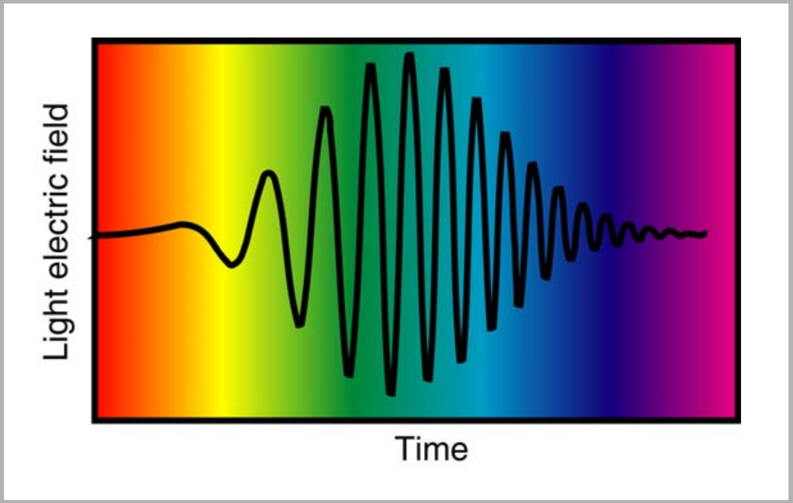
$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)\exp(i\omega t)\,d\omega \qquad F(\omega) = \int_{-\infty}^{\infty} f(t)\exp(-i\omega t)\,dt$$

What do we hope to achieve with the Fourier Transform?

We desire a measure of the frequencies present in a wave. This will lead to a definition of the term, the "spectrum."

Plane waves have only one frequency, ω.





This light wave has many frequencies. And the frequency increases in time (from red to blue).

It will be nice if our measure also tells us when each frequency occurs.

Lord Kelvin on Fourier's theorem

Fourier's theorem is not only one of the most beautiful results of modern analysis, but it may be said to furnish an indispensable instrument in the treatment of nearly every recondite question in modern physics.

Lord Kelvin

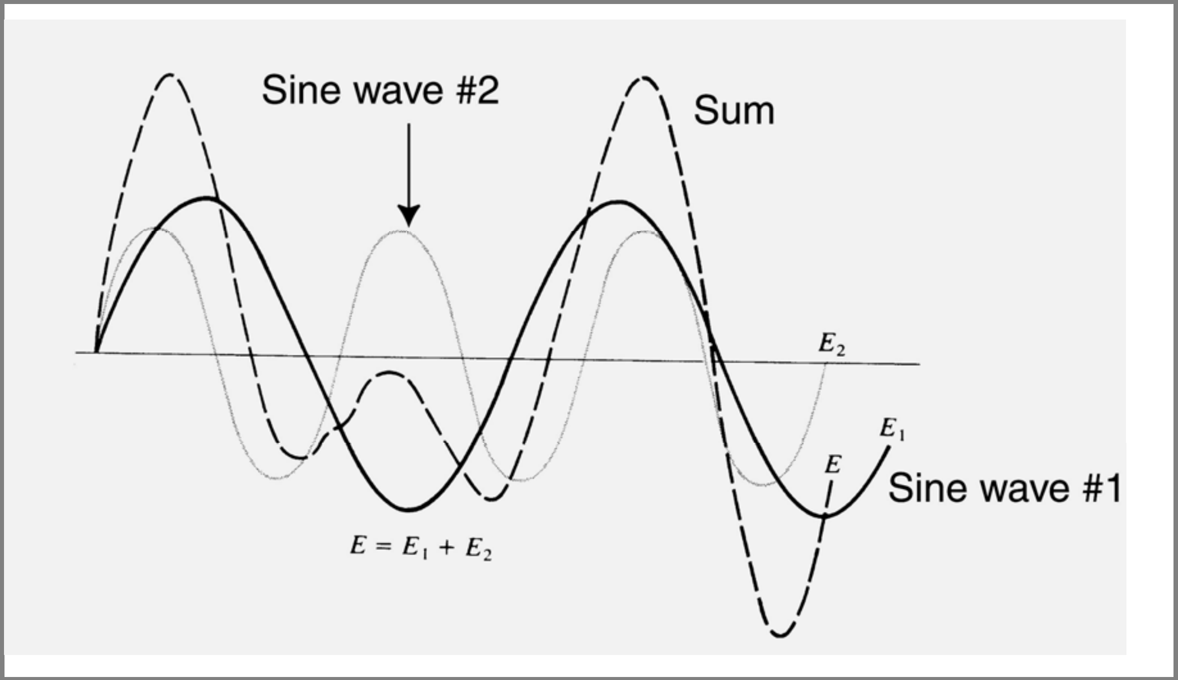
Joseph Fourier, our hero

Joseph Fourier, 21 March 1768–16 May 1830. (*By permission of the Bibliothèque Municipale de Grenoble.*)

Fourier was obsessed with the physics of heat and developed the Fourier series and transform to model heat-flow problems.

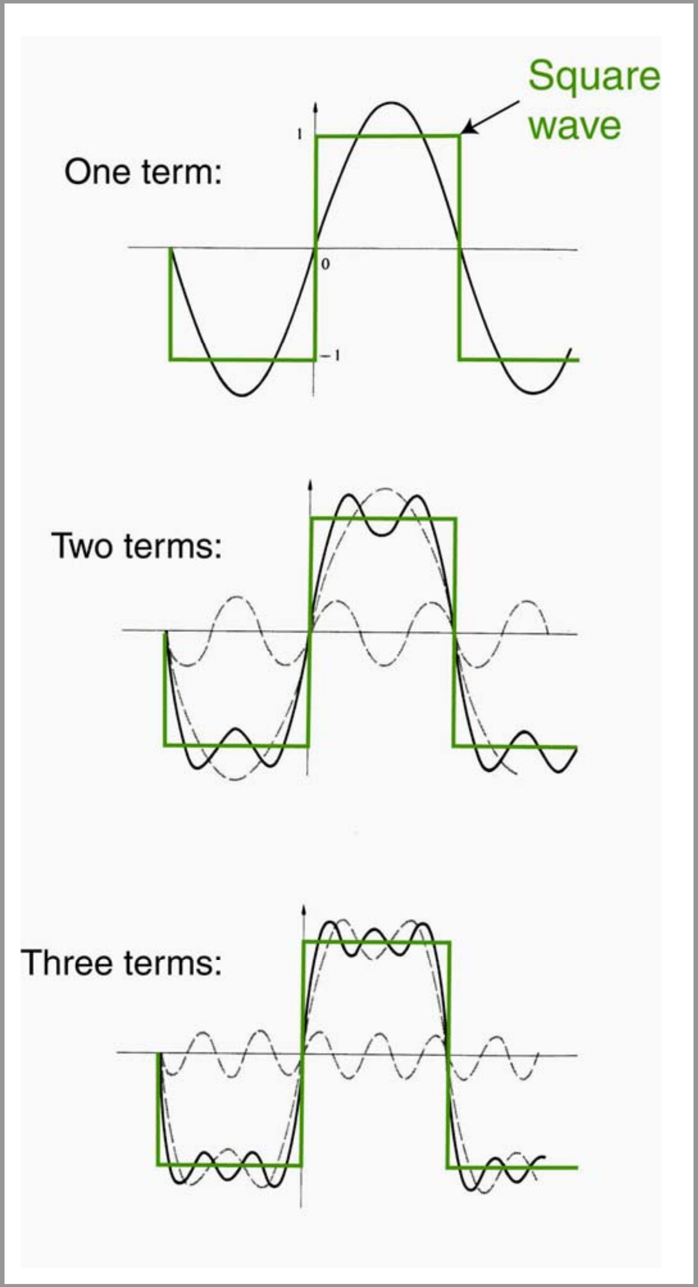
Anharmonic waves are sums of sinusoids.

Consider the sum of two sine waves (i.e., harmonic waves) of different frequencies:



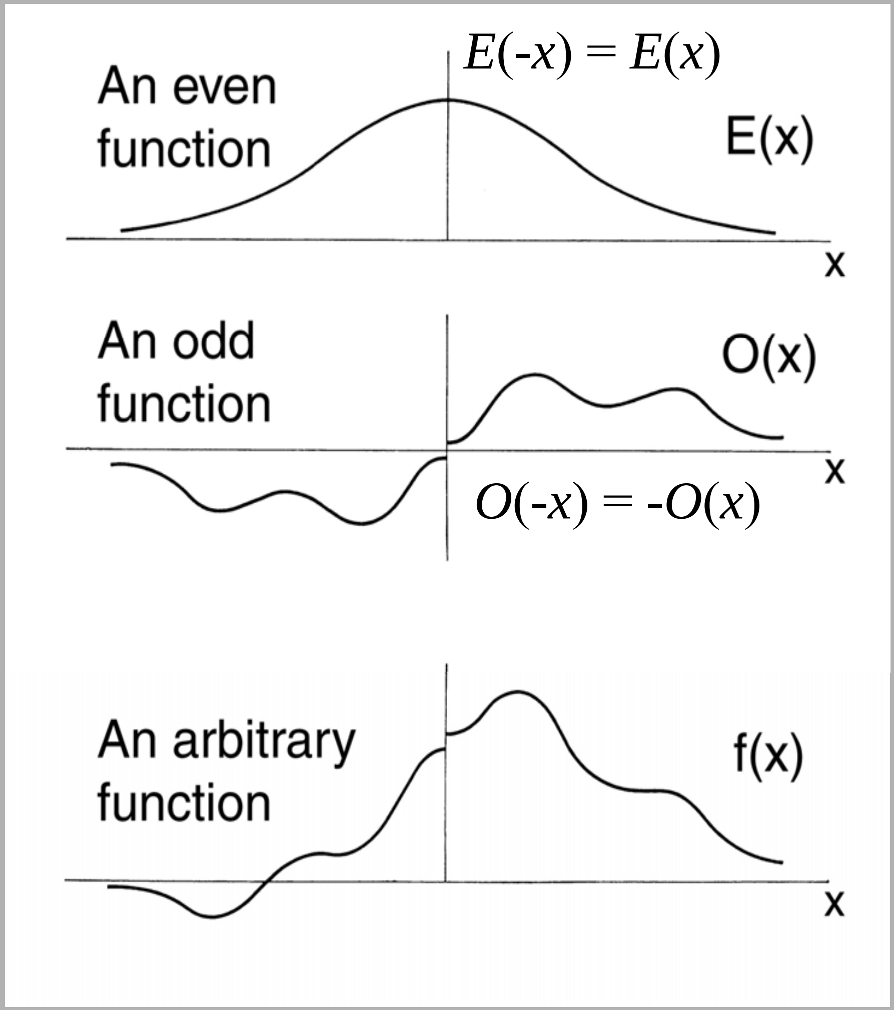
The resulting wave is periodic, but not harmonic.
Most waves are anharmonic.

Fourier decomposing functions



Here, we write a square wave as a sum of sine waves.

Any function can be written as the sum of an even and an odd function



$$E(x) \equiv [f(x) + f(-x)]/2$$

$$O(x) \equiv [f(x) - f(-x)]/2$$

$$\Downarrow$$

$$f(x) = E(x) + O(x)$$

Fourier Cosine Series

Because $\cos(mt)$ is an even function (for all m), we can write an even function, $f(t)$, as:

$$f(t) = \frac{1}{\pi}\sum_{m=0}^{\infty} F_m \cos(mt)$$

where the set $\{F_m; m = 0, 1, \dots\}$ is a set of coefficients that define the series.

And where we'll only worry about the function $f(t)$ over the interval $(-\pi,\pi)$.

The Kronecker delta function

$$\delta_{m,n} \equiv \begin{cases} 1 \text{ if } m = n \\ 0 \text{ if } m \neq n \end{cases}$$

Finding the coefficients, F_m, in a Fourier Cosine Series

Fourier Cosine Series: $$f(t) = \frac{1}{\pi}\sum_{m=0}^{\infty} F_m \cos(mt)$$

To find F_m, multiply each side by $\cos(m't)$, where m' is another integer, and integrate:

$$\int_{-\pi}^{\pi} f(t)\cos(m't)\,dt = \frac{1}{\pi}\sum_{m=0}^{\infty}\int_{-\pi}^{\pi} F_m \cos(mt)\cos(m't)\,dt$$

But: $$\int_{-\pi}^{\pi} \cos(mt)\cos(m't)\,dt = \begin{cases} \pi & \text{if } m = m' \\ 0 & \text{if } m \neq m' \end{cases} \equiv \pi\,\delta_{m,m'}$$

So: $$\int_{-\pi}^{\pi} f(t)\cos(m't)\,dt = \frac{1}{\pi}\sum_{m=0}^{\infty} F_m\,\pi\,\delta_{m,m'}$$ ← only the $m' = m$ term contributes

Dropping the ' from the m:

$$F_m = \int_{-\pi}^{\pi} f(t)\cos(mt)\,dt$$

← yields the coefficients for any $f(t)$!

Fourier Sine Series

Because $\sin(mt)$ is an odd function (for all m), we can write any odd function, $f(t)$, as:

$$f(t) = \frac{1}{\pi} \sum_{m=0}^{\infty} F'_m \sin(mt)$$

where the set $\{F'_m;\ m = 0, 1, \ldots\}$ is a set of coefficients that define the series.

where we'll only worry about the function $f(t)$ over the interval $(-\pi,\pi)$.

Finding the coefficients, F'_m, in a Fourier Sine Series

Fourier Sine Series: $$f(t) = \frac{1}{\pi}\sum_{m=0}^{\infty} F'_m \sin(mt)$$

To find F_m, multiply each side by $\sin(m't)$, where m' is another integer, and integrate:

$$\int_{-\pi}^{\pi} f(t)\sin(m't)\,dt = \frac{1}{\pi}\sum_{m=0}^{\infty}\int_{-\pi}^{\pi} F'_m \sin(mt)\sin(m't)\,dt$$

But:

$$\int_{-\pi}^{\pi} \sin(mt)\sin(m't)\,dt = \begin{cases}\pi & if\ m = m' \\ 0 & if\ m \neq m'\end{cases} \equiv \pi\,\delta_{m,m'}$$

So: $$\int_{-\pi}^{\pi} f(t)\sin(m't)\,dt = \frac{1}{\pi}\sum_{m=0}^{\infty} F'_m\,\pi\,\delta_{m,m'}$$ ← only the $m' = m$ term contributes

Dropping the ' from the m: $$F'_m = \int_{-\pi}^{\pi} f(t)\sin(mt)\,dt$$ ← yields the coefficients for any $f(t)$!

Fourier Series

So if $f(t)$ is a general function, neither even nor odd, it can be written:

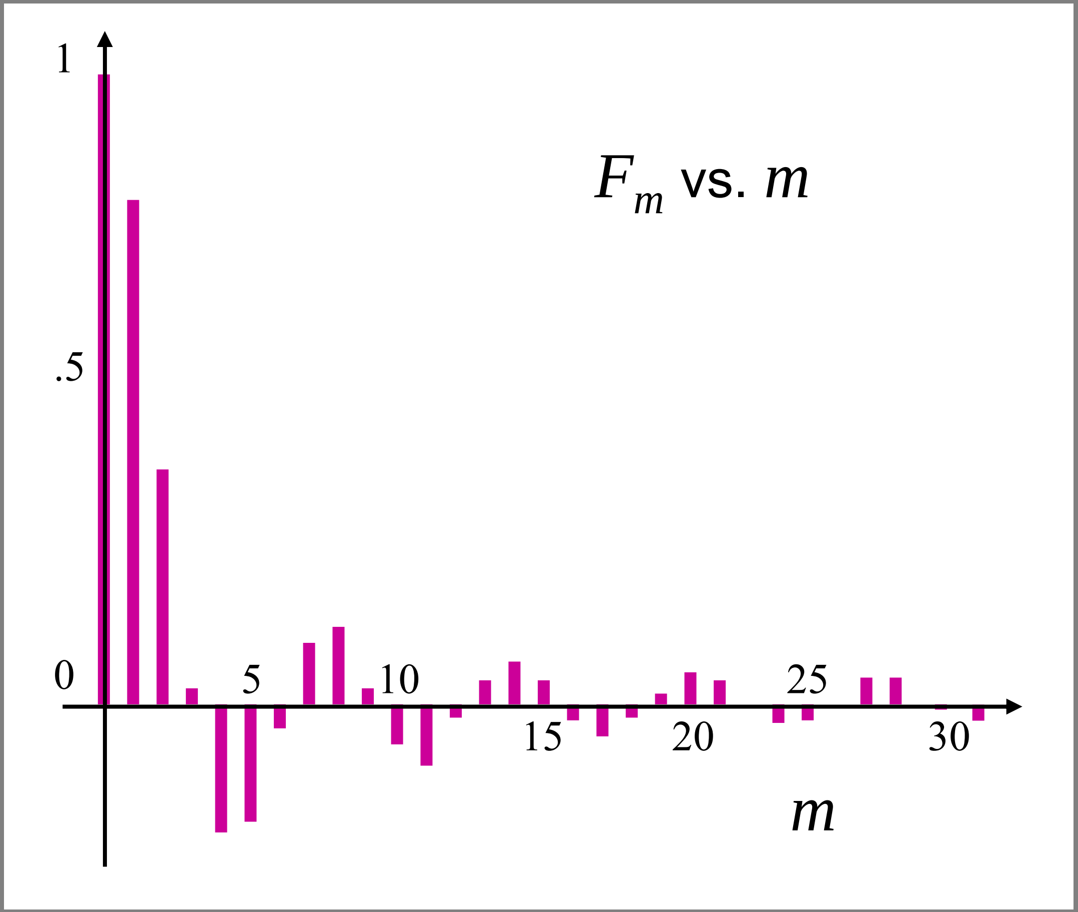
$$f(t) = \frac{1}{\pi}\sum_{m=0}^{\infty} F_m \cos(mt) + \frac{1}{\pi}\sum_{m=0}^{\infty} F'_m \sin(mt)$$

even component   odd component

where

$$F_m = \int f(t)\cos(mt)\,dt \quad \text{and} \quad F'_m = \int f(t)\sin(mt)\,dt$$

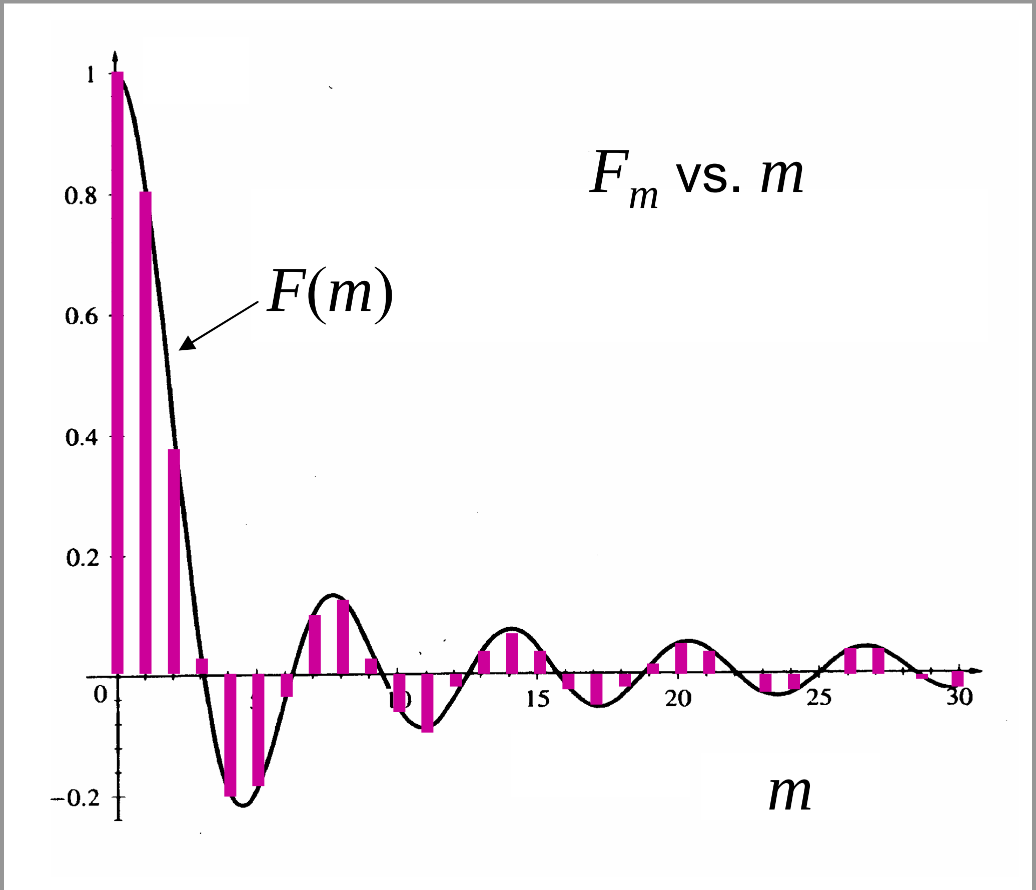
We can plot the coefficients of a Fourier Series



We really need two such plots, one for the cosine series and another for the sine series.

Discrete Fourier Series vs. Continuous Fourier Transform

Let the integer m become a real number and let the coefficients, F_m, become a function $F(m)$.



Again, we really need two such plots, one for the cosine series and another for the sine series.

The Fourier Transform

Consider the Fourier coefficients. Let's define a function $F(m)$ that incorporates both cosine and sine series coefficients, with the sine series distinguished by making it the imaginary component:

$$F(m) \equiv F_m - i\,F'_m = \int f(t)\cos(mt)\,dt - i\int f(t)\sin(mt)\,dt$$

Let's now allow $f(t)$ to range from $-\infty$ to ∞, so we'll have to integrate from $-\infty$ to ∞, and let's redefine m to be the "frequency," which we'll now call ω:

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\exp(-i\omega t)\,dt$$

The Fourier Transform

$F(\omega)$ is called the Fourier Transform of $f(t)$. It contains equivalent information to that in $f(t)$. We say that $f(t)$ lives in the "time domain," and $F(\omega)$ lives in the "frequency domain." $F(\omega)$ is just another way of looking at a function or wave.

The Inverse Fourier Transform

The Fourier Transform takes us from $f(t)$ to $F(\omega)$.
How about going back?

Recall our formula for the Fourier Series of $f(t)$:

$$f(t) = \frac{1}{\pi}\sum_{m=0}^{\infty} F_m \cos(mt) + \frac{1}{\pi}\sum_{m=0}^{\infty} F_m' \sin(mt)$$

Now transform the sums to integrals from –∞ to ∞, and again replace F_m with $F(\omega)$. Remembering the fact that we introduced a factor of i (and including a factor of 2 that just crops up), we have:

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)\exp(i\omega t)\,d\omega$$

Inverse Fourier Transform

The Fourier Transform and its Inverse

The Fourier Transform and its Inverse:

$$F(\omega) = \int_{-\infty}^{\infty} f(t) \exp(-i\omega t)\, dt$$

FourierTransform

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) \exp(i\omega t)\, d\omega$$

Inverse Fourier Transform

So we can transform to the frequency domain and back. Interestingly, these functions are very similar.

There are different definitions of these transforms. The 2π can occur in several places, but the idea is generally the same.

Fourier Transform Notation

There are several ways to denote the Fourier transform of a function.

If the function is labeled by a lower-case letter, such as f, we can write:

$$f(t) \rightarrow F(\omega)$$

If the function is labeled by an upper-case letter, such as E, we can write:

$$E(t) \rightarrow \mathscr{F}\{E(t)\} \quad \text{or:} \quad E(t) \rightarrow \tilde{E}(\omega)$$

Sometimes, this symbol is used instead of the arrow: $\supset$

The Spectrum

We define the spectrum of a wave $E(t)$ to be:

$$\left| \mathscr{F}\left\{ E(t) \right\} \right|^2$$

This is our measure of the frequencies present in a light wave.

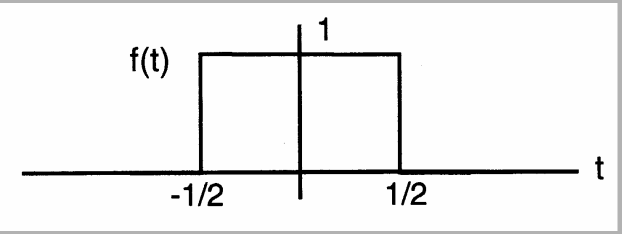
Example: the Fourier Transform of a rectangle function: rect(t)

$$F(\omega) = \int_{-1/2}^{1/2} \exp(-i\omega t)\,dt = \frac{1}{-i\omega}\left[\exp(-i\omega t)\right]_{-1/2}^{1/2}$$

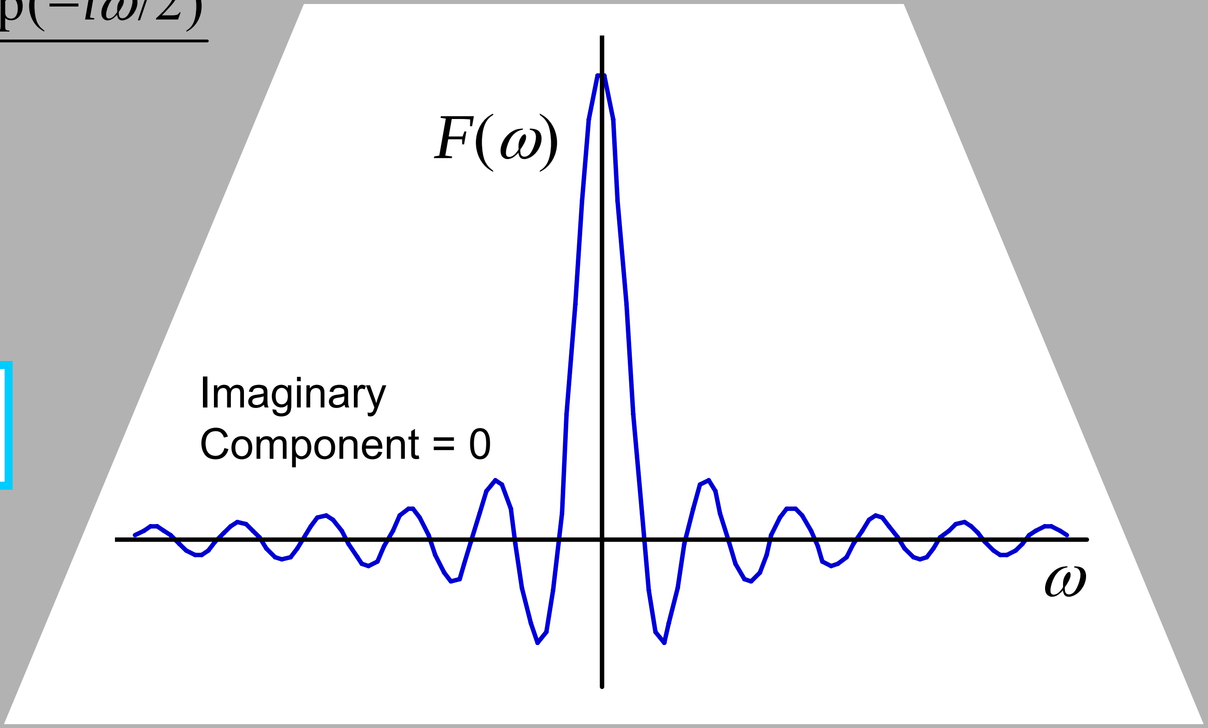
$$= \frac{1}{-i\omega}\left[\exp(-i\omega/2) - \exp(i\omega/2)\right]$$

$$= \frac{1}{(\omega/2)}\,\frac{\exp(i\omega/2) - \exp(-i\omega/2)}{2i}$$

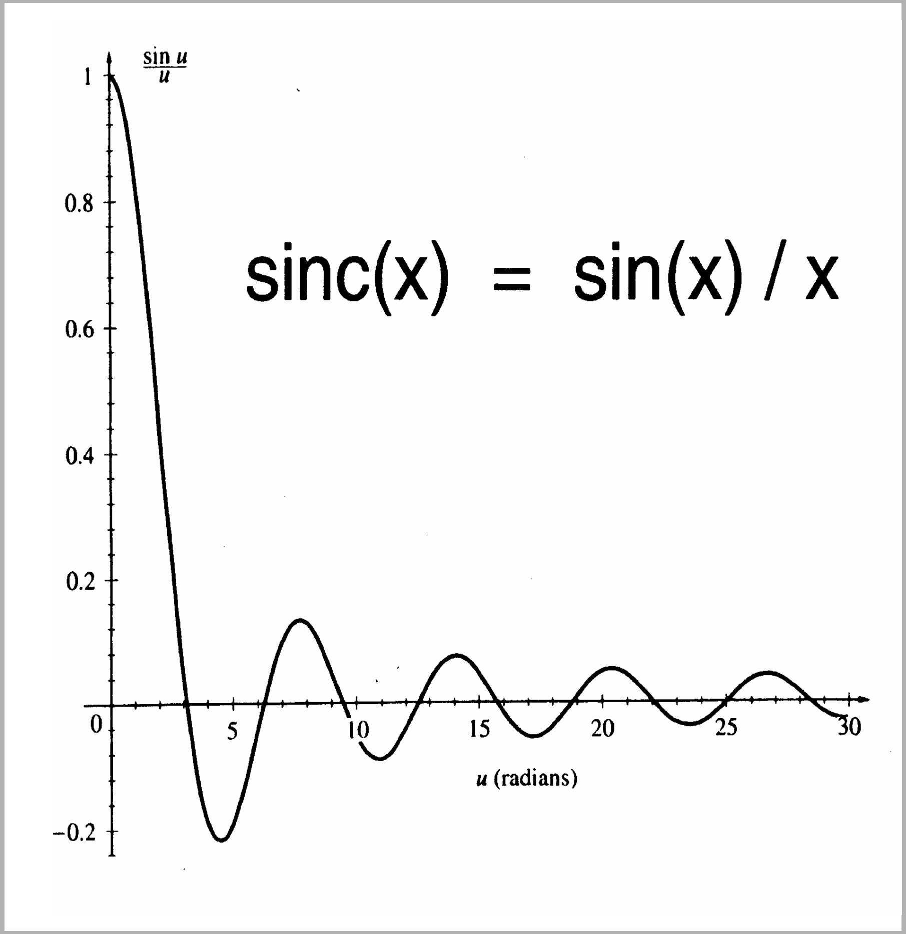
$$= \frac{\sin(\omega/2)}{(\omega/2)}$$



$$\boxed{F(\omega) = \mathrm{sinc}(\omega/2)}$$



Sinc(x) and why it's important



Sinc(x/2) is the Fourier transform of a rectangle function.

Sinc^2(x/2) is the Fourier transform of a triangle function.

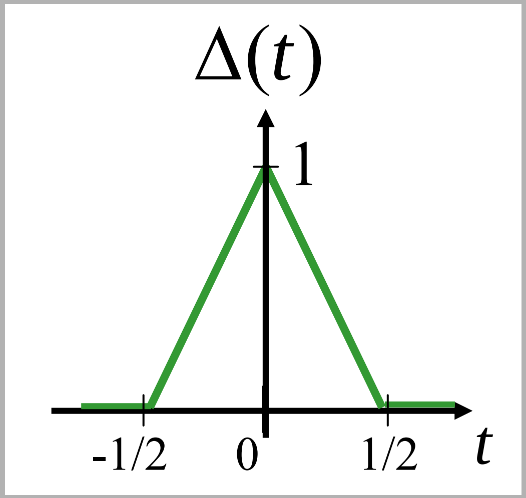
Sinc^2(ax) is the diffraction pattern from a slit.

It just crops up everywhere...

The Fourier Transform of the triangle function, Δ(t), is $\text{sinc}^2(\omega/2)$

The triangle function is just what it sounds like.

Sometimes people use $\Lambda(t)$, too, for the triangle function.



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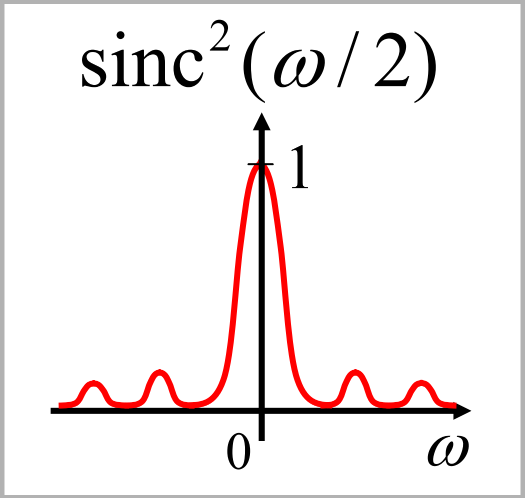


We'll prove this when we learn about convolution.

Example: the Fourier Transform of a decaying exponential: exp(-*at*) (*t* > 0)

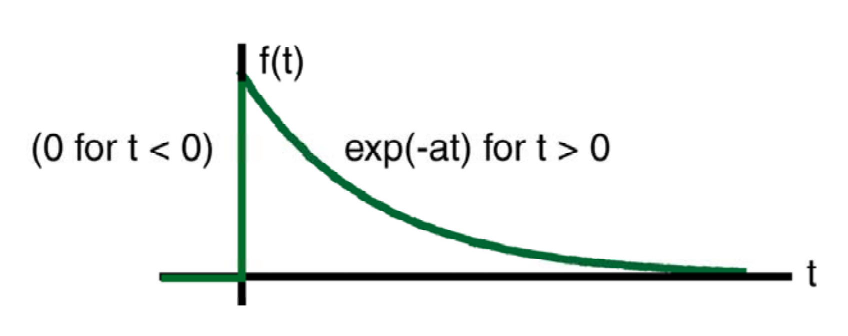
$$F(\omega) = \int_0^\infty \exp(-at)\exp(-i\omega t)\,dt$$

$$= \int_0^\infty \exp(-at - i\omega t)\,dt = \int_0^\infty \exp(-[a+i\omega]t)\,dt$$

$$= \frac{-1}{a+i\omega}\exp(-[a+i\omega]t)\Big|_0^{+\infty} = \frac{-1}{a+i\omega}[\exp(-\infty) - \exp(0)]$$

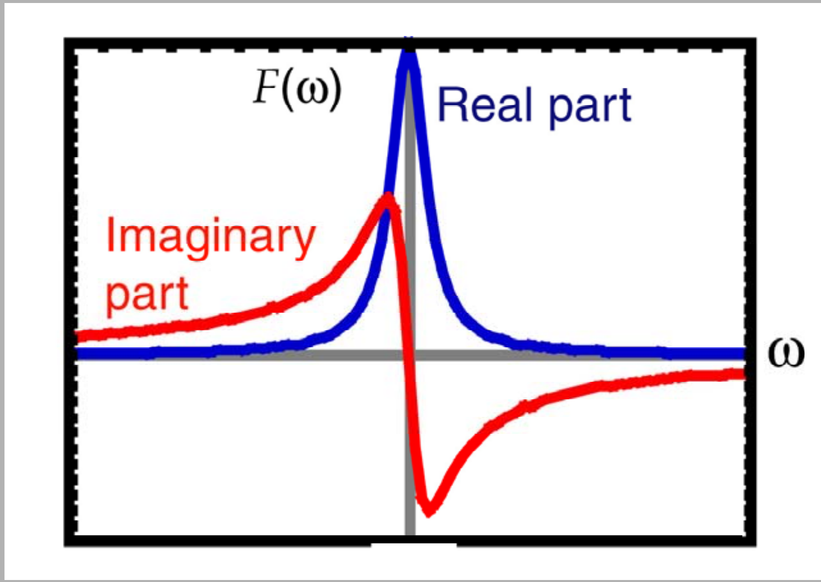
$$= \frac{-1}{a+i\omega}[0-1]$$

$$= \frac{1}{a+i\omega}$$



$$F(\omega) = -i\,\frac{1}{\omega - ia}$$

A complex Lorentzian!

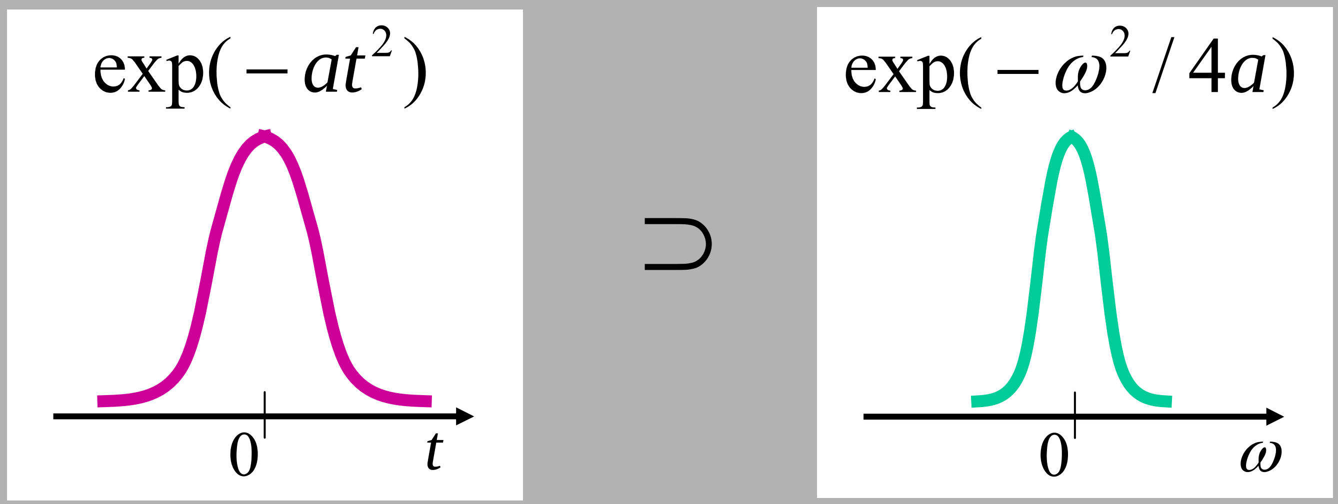


Example: the Fourier Transform of a Gaussian, $\exp(-at^2)$, is itself!

$$\mathcal{F}\{\exp(-at^2)\} = \int_{-\infty}^{\infty} \exp(-at^2)\exp(-i\omega t)\,dt$$

$$\propto \exp(-\omega^2/4a)$$

The details are a HW problem!



Some functions don't have Fourier transforms.

The condition for the existence of a given $F(\omega)$ is:

$$\int_{-\infty}^{\infty} \left| f(t) \right| \, dt \; < \; \infty$$

Functions that do not asymptote to zero in both the $+\infty$ and $-\infty$ directions generally do not have Fourier transforms.

So we'll assume that all functions of interest go to zero at $\pm\infty$.

Fourier Transform Symmetry Properties

Expanding the Fourier transform of a function, *f(t)*:

$$F(\omega) = \int_{-\infty}^{\infty} [\mathrm{Re}\{f(t)\} + i\,\mathrm{Im}\{f(t)\}]\ [\cos(\omega t) - i\sin(\omega t)]\,dt$$

Expanding further:

= 0 if Re or Im{*f*(*t*)} is odd ↓

= 0 if Re or Im{*f*(*t*)} is even ↓

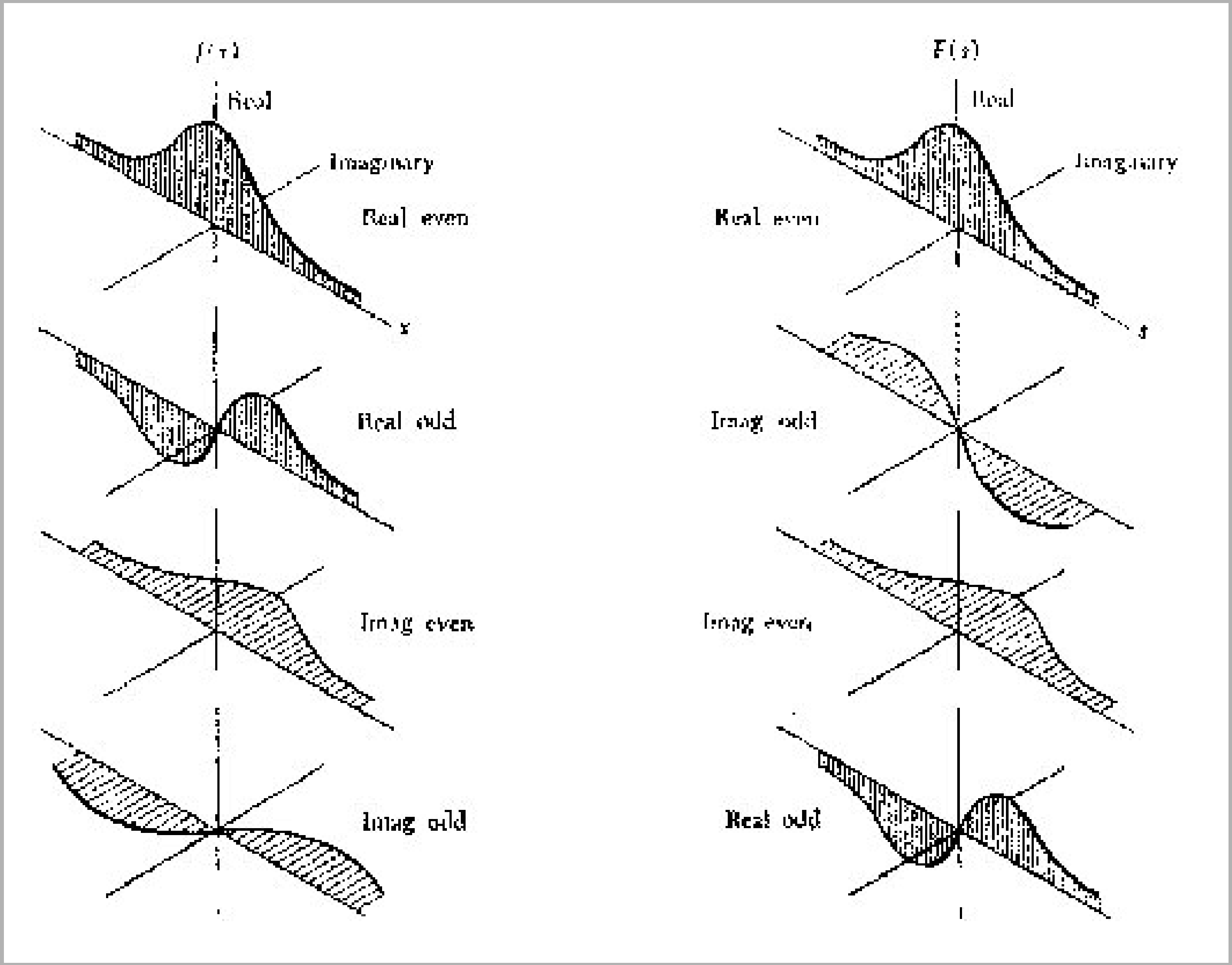
$$F(\omega) = \int_{-\infty}^{\infty} \mathrm{Re}\{f(t)\}\cos(\omega t)\,dt + \int_{-\infty}^{\infty} \mathrm{Im}\{f(t)\}\sin(\omega t)\,dt \quad \leftarrow \mathrm{Re}\{F(\omega)\}$$

$$+\ i\int_{-\infty}^{\infty} \mathrm{Im}\{f(t)\}\cos(\omega t)\,dt - i\int_{-\infty}^{\infty} \mathrm{Re}\{f(t)\}\sin(\omega t)\,dt \quad \leftarrow \mathrm{Im}\{F(\omega)\}$$

↑ Even functions of ω

↑ Odd functions of ω

Fourier Transform Symmetry Examples I



Fourier Transform Symmetry Examples II