

Data X

LTI and Spectral Information

Data X: A Course on Data, Signals, and Systems

Ikhlaq Sidhu
Chief Scientist & Founding Director,
Sutardja Center for Entrepreneurship & Technology
IEOR Emerging Area Professor Award, UC Berkeley

Jean Baptiste Joseph Fourier (1768-1830)

- Had crazy idea (1807):
- **Any** periodic function can be rewritten as a weighted sum of **Sines** and **Cosines** of different frequencies.
- Don't believe it?
 - Neither did Lagrange, Laplace, Poisson and other big wigs
 - Not translated into English until 1878!
- But it's true!
 - called **Fourier Series**
 - Possibly the greatest tool used in Engineering

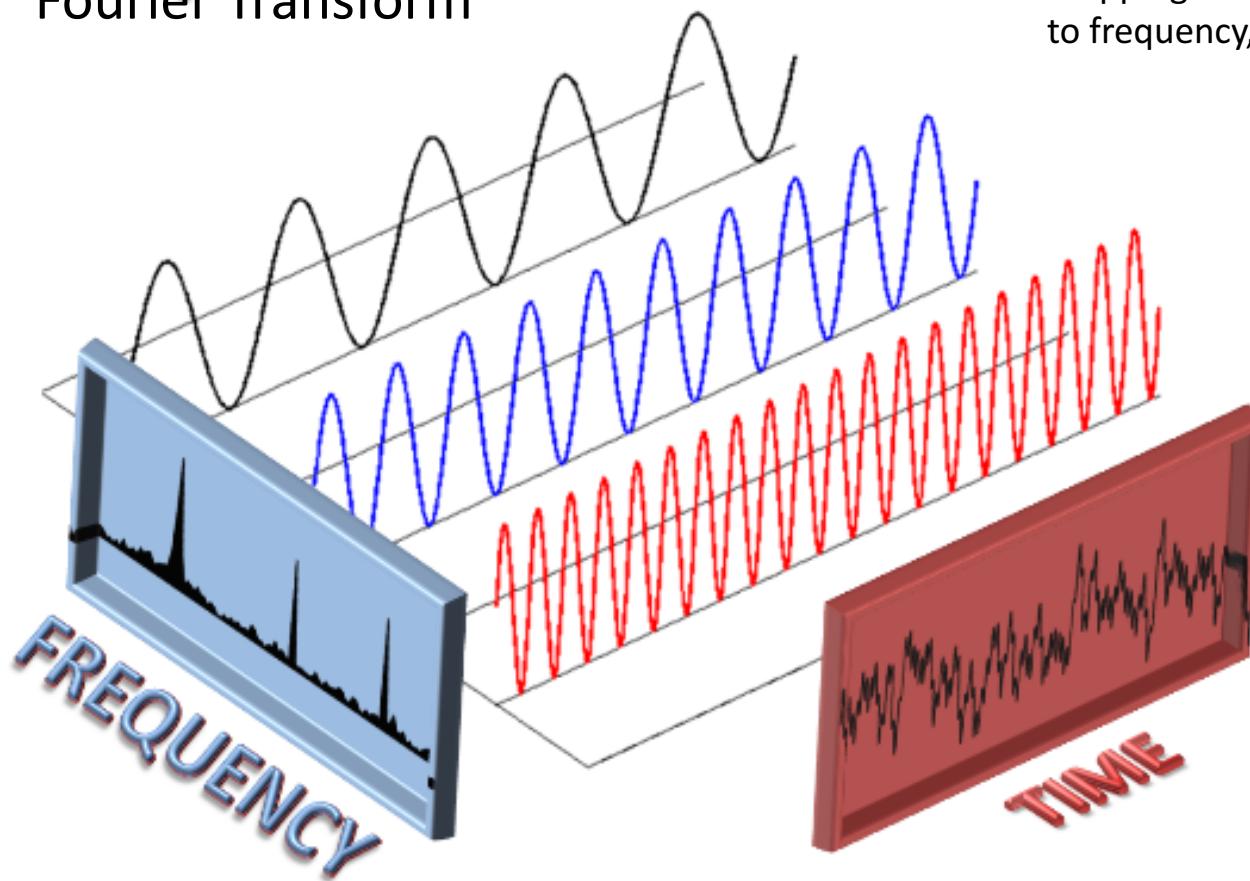


S. Narasimhan, Computer Vision



Fourier Transform

Mapping from a time
to frequency, and back.

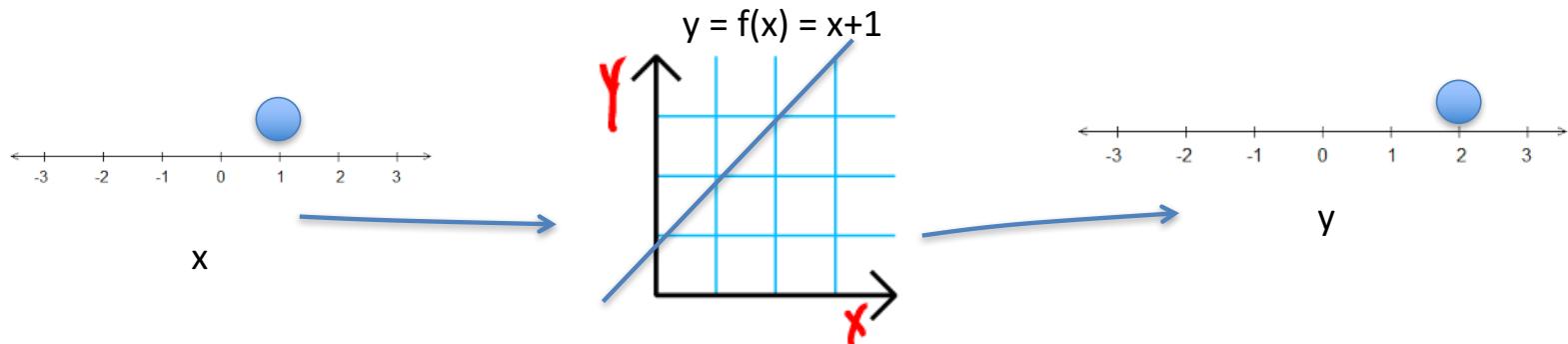


groups.csail.mit.edu/netmit/wordpress/projects/sparse-fourier-transform/

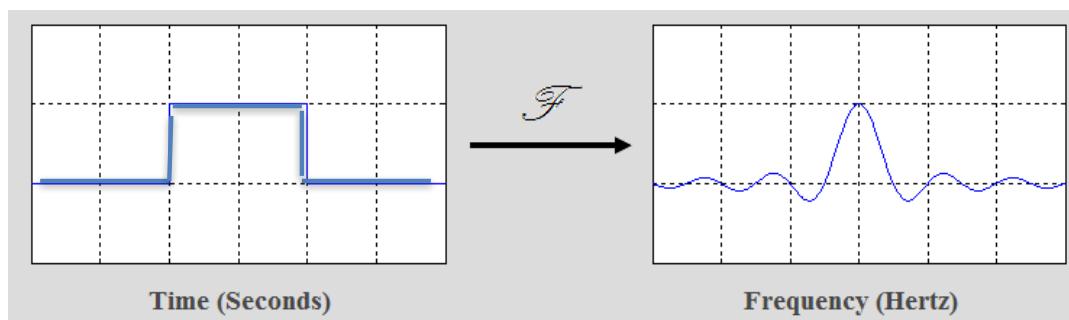


Fourier Transform

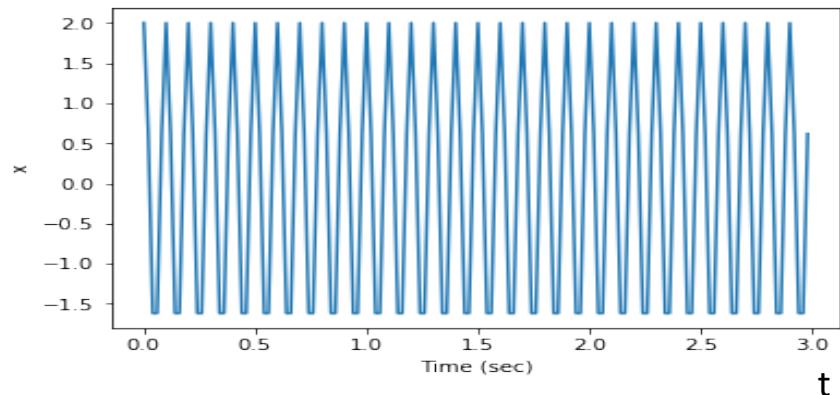
The most famous of mathematical transforms



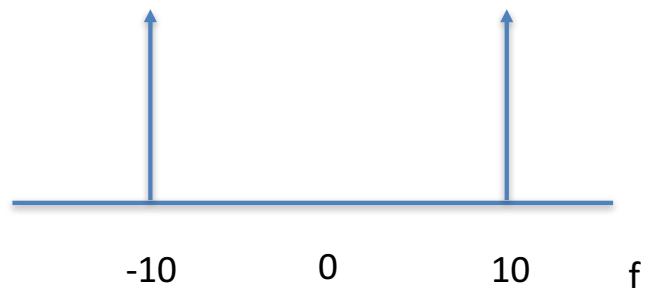
A Transform maps a function to another function



Intuition



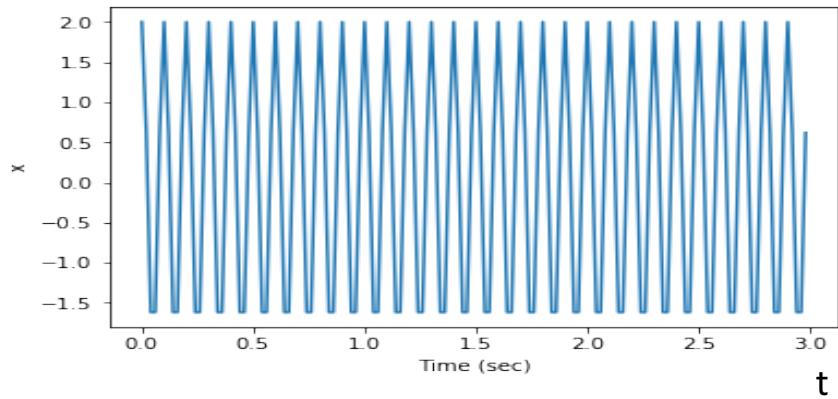
$$x(t) = 2 \cos(2 \pi 10 t)$$



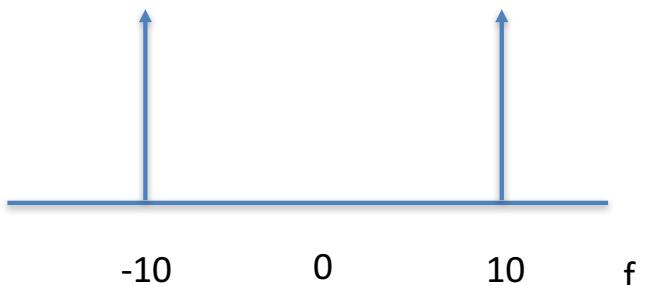
$$X(f) = \delta(f+10) + \delta(f-10)$$



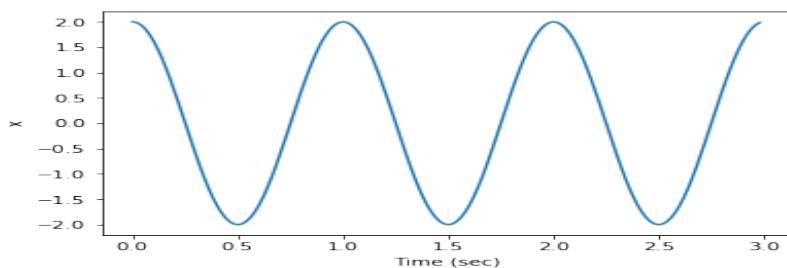
Intuition



$$x(t) = 2 \cos(2 \pi 10 t)$$



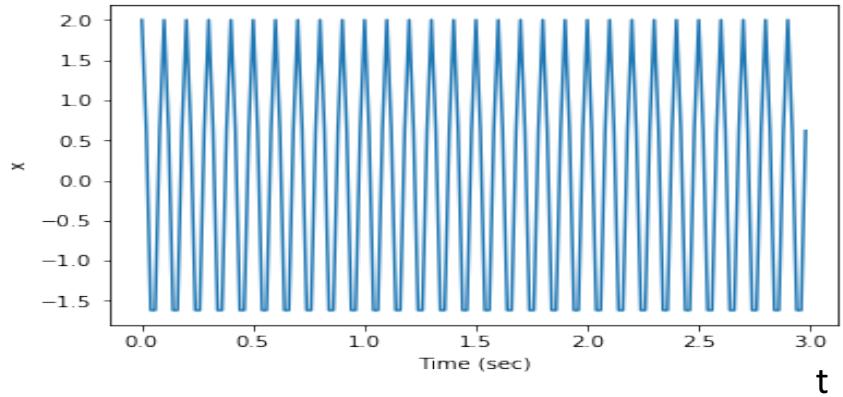
$$X(f) = \delta(f+10) + \delta(f-10)$$



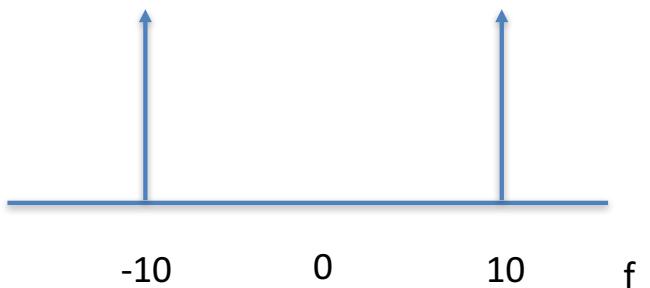
$$x(t) = 2 \cos(2 \pi 1 t)$$



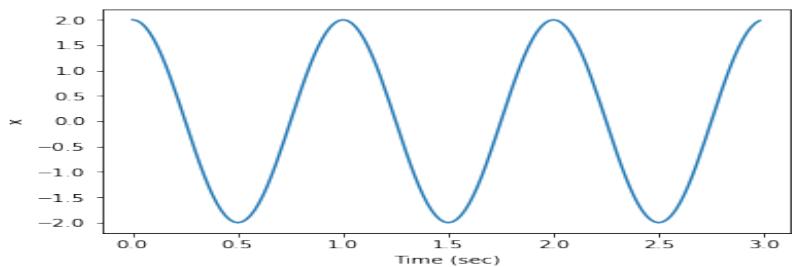
Intuition



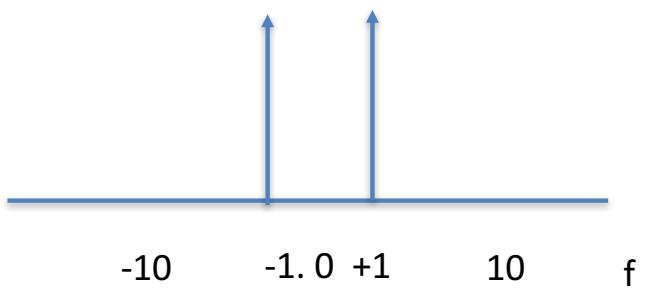
$$x(t) = 2 \cos(2 \pi 10 t)$$



$$X(f) = \delta(f+10) + \delta(f-10)$$



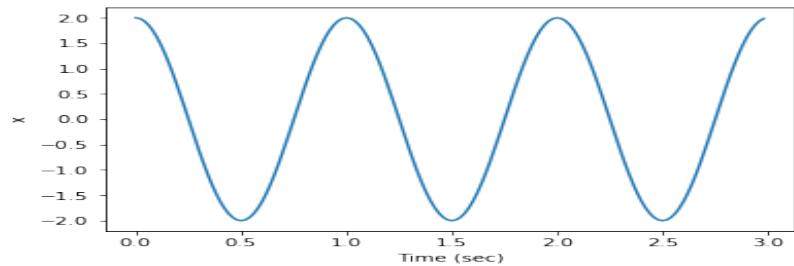
$$x(t) = 2 \cos(2 \pi 1 t)$$



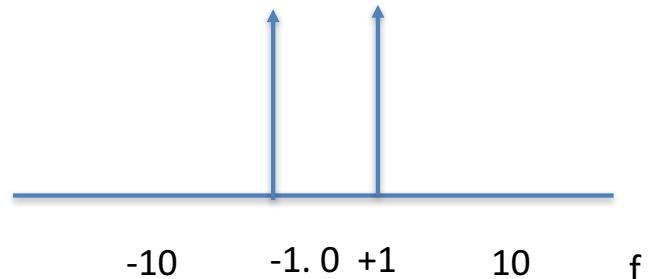
$$X(f) = \delta(f+1) + \delta(f-1)$$



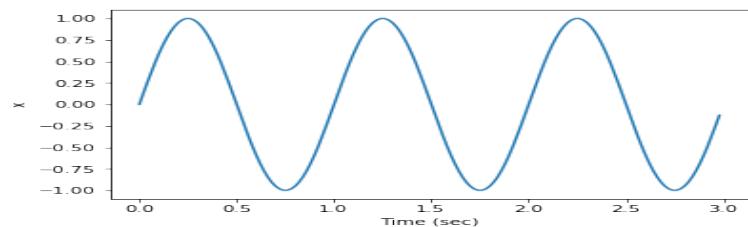
Intuition



$$x(t) = 2 \cos(2 \pi 1 t)$$



$$X(f) = \delta(f+1) + \delta(f-1)$$

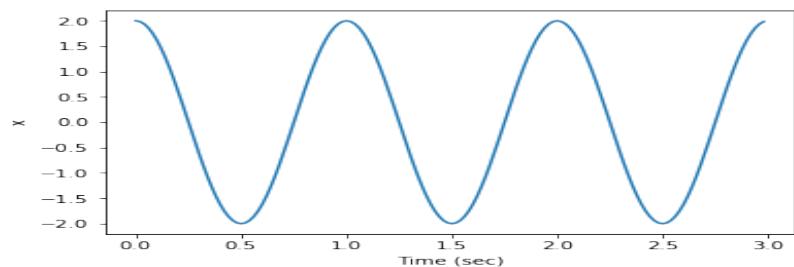


$$x(t) = \sin(2 \pi 1 t)$$

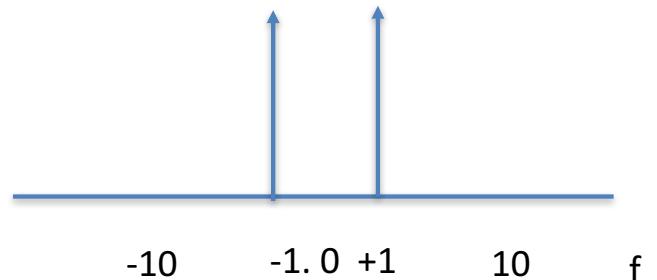


Intuition

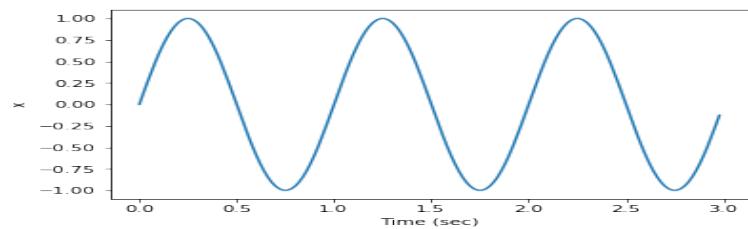
Magnitude is same
Phase is different



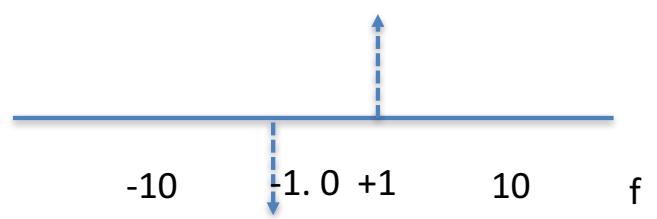
$$x(t) = 2 \cos(2 \pi 1 t)$$



$$X(f) = \delta(f+1) + \delta(f-1)$$



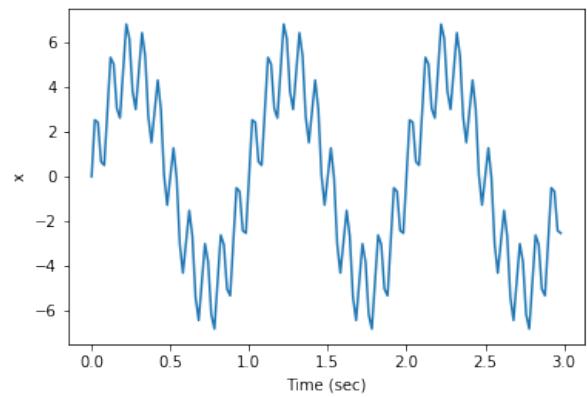
$$x(t) = \sin(2 \pi 1 t)$$



$$X(f) = -j/2 \delta(f+1) + j/2 \delta(f-1)$$



Intuition

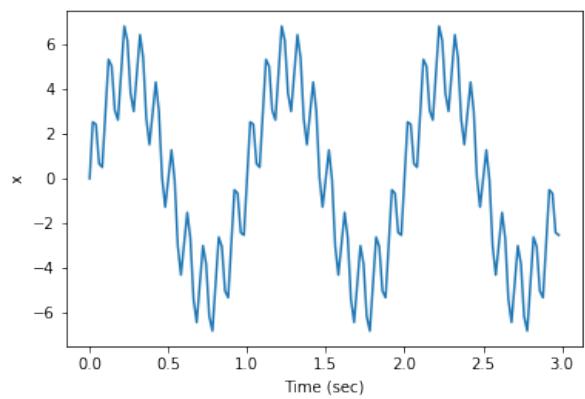


$$x(t) = 5 \cos(2 \pi 10 t) + 2 \cos(2 \pi 1 t)$$

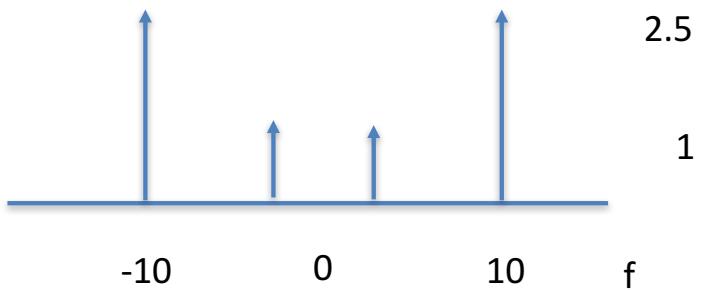
Data X

A blurred image of a data matrix with binary values (0s and 1s) representing the signal $x(t)$ over time. The word "Data" is visible on the left side of the matrix.

Intuition



$$x(t) = 5 \cos(2 \pi 10 t) + 2 \cos(2 \pi 1 t)$$



$$X(f) = 2.5[\delta(f+10) + \delta(f-10)] + 1[\delta(f+1) + \delta(f-1)]$$



How do we get these transformations?

$$X(f) = \int_{-\infty}^{\infty} x(t) \times e^{-i2\pi ft} dt$$

- x or t = time, f(x) or x(t) is a function of time
- i or j are for imaginary numbers. Note X and x are both complex.
- f or s is often used for frequency, so F(s) is a function in frequency
- Integrate (average) over all time (for every given frequency)

$$f(x) = \int_{-\infty}^{\infty} F(s) e^{i2\pi sx} ds$$

Remember that

$$\cos(\theta) + i \times \sin(\theta) = e^{i\theta}$$

$$\cos(2\pi ft) + i \times \sin(2\pi ft) = e^{i2\pi ft}$$

And this is the unit circle

$$e^{-j2\pi ft} = \cos(2\pi fx) - j\sin(2\pi fx)$$

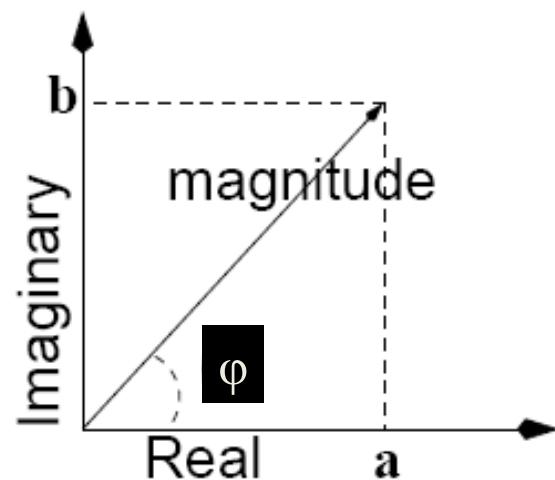


Mathematical Background: Complex Numbers

- Magnitude-Phase (i.e., vector) representation
- Any sinusoid, like $x(t) = A \cos(2 \pi f_0 t + \varphi)$
- Can be represented as a phasor in magnitude and phase notation:

$$x(t) = A e^{j\varphi}$$

$$A = |x(t)|$$



Reminder, this is also the unit circle

$$x(t) = A e^{j\varphi} = A \cos(\varphi) + j A \sin(\varphi)$$

Note:

$$x = a + jb, \text{ where } j = \sqrt{-1}$$

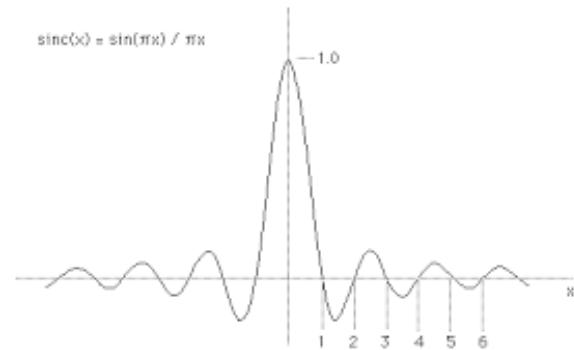
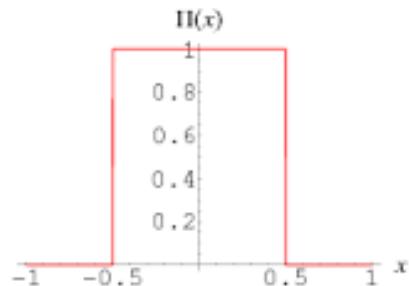
$$|x| = \sqrt{a^2 + b^2}$$

$$\phi(x) = \tan^{-1}(b/a)$$



A Pulse In Time

This example is the famous $\text{rect}(x)$
which transforms to $\text{sinc}(f)$



$$\text{rect}(t) = \Pi(t) := \begin{cases} 0 & \text{if } |t| > \frac{1}{2} \\ \frac{1}{2} & \text{if } |t| = \frac{1}{2} \\ 1 & \text{if } |t| < \frac{1}{2}. \end{cases}$$

Which is right?

$$\text{sinc}(x) = \frac{\sin(x)}{x}.$$

$$\text{sinc}(x) = \frac{\sin(\pi x)}{\pi x}.$$

Zero crossing

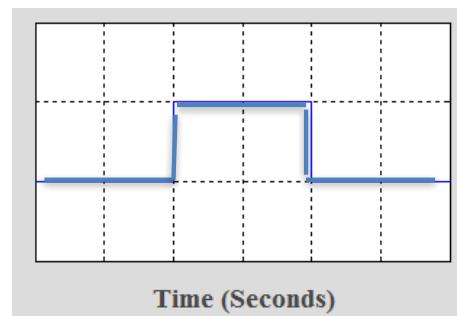
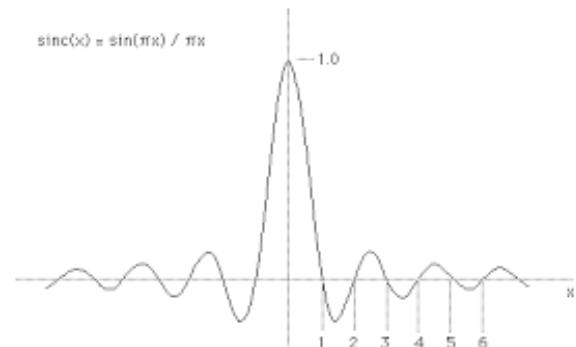
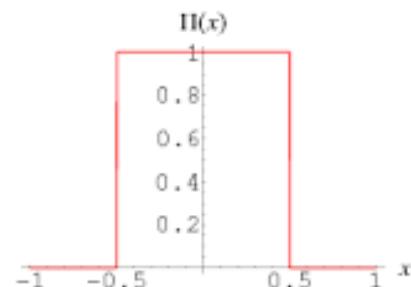
Pi radians

integers

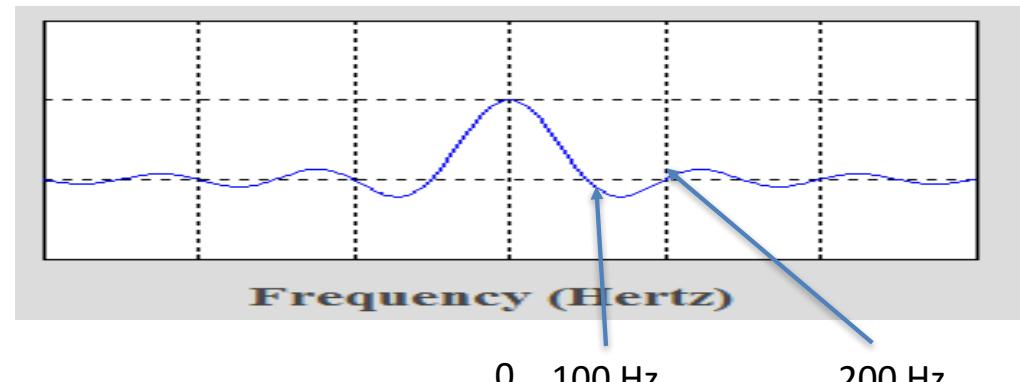


A Pulse In Time

This example is the famous $\text{rect}(x)$
which transforms to $\text{Sinc}(f)$



Width = 0.01 seconds

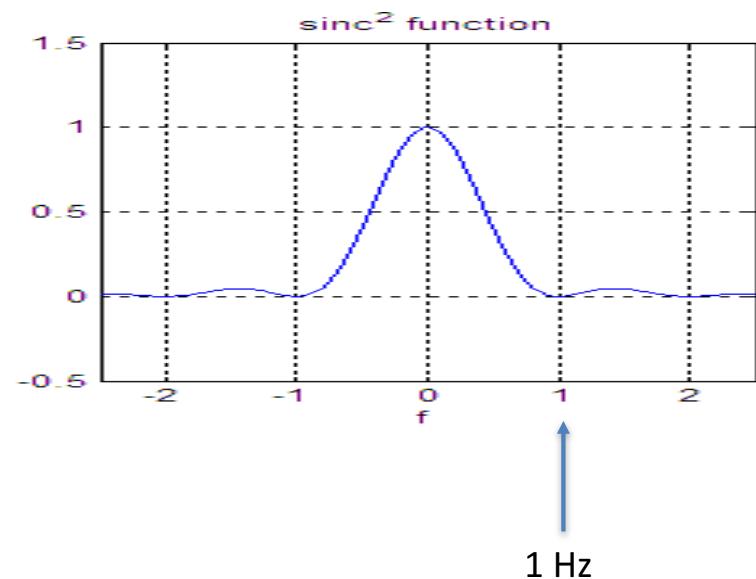
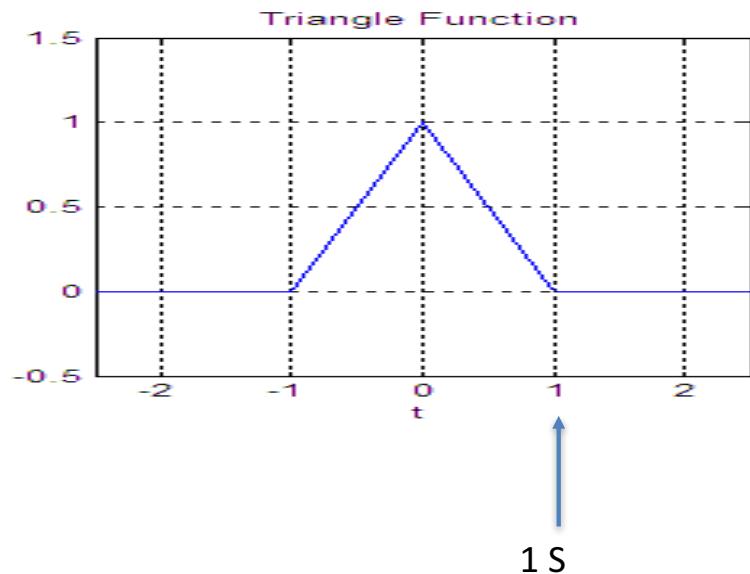


0 100 Hz 200 Hz



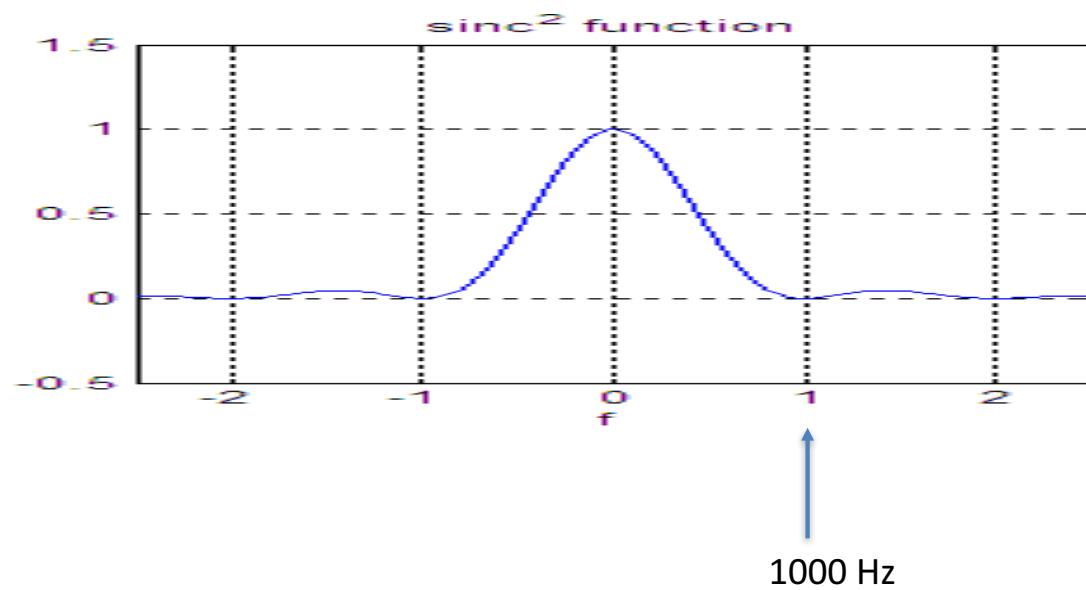
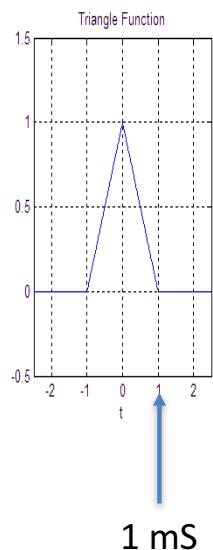
Another Common Example

Fourier of $\triangle(t)$



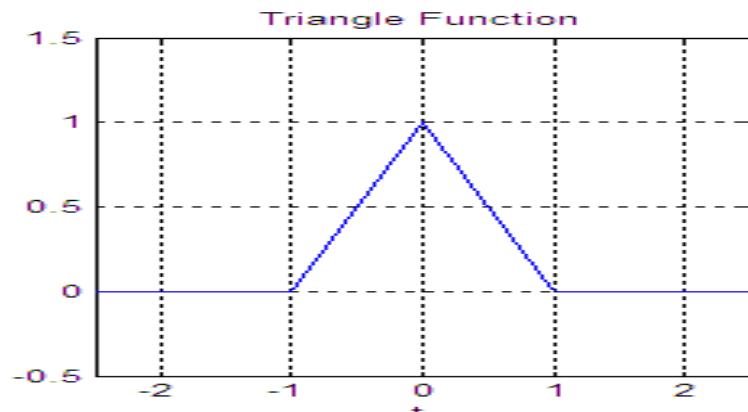
Another Common Example

What is Fourier of $\triangle(t)$

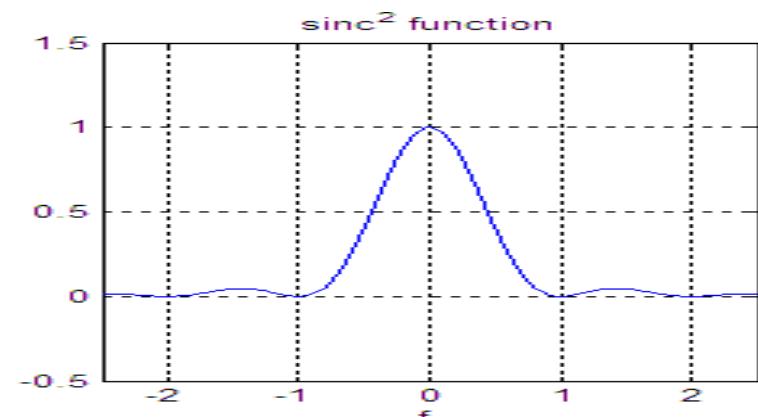


Another Common Example

Fourier of $\triangle(t)$



1 mS



1000 Hz

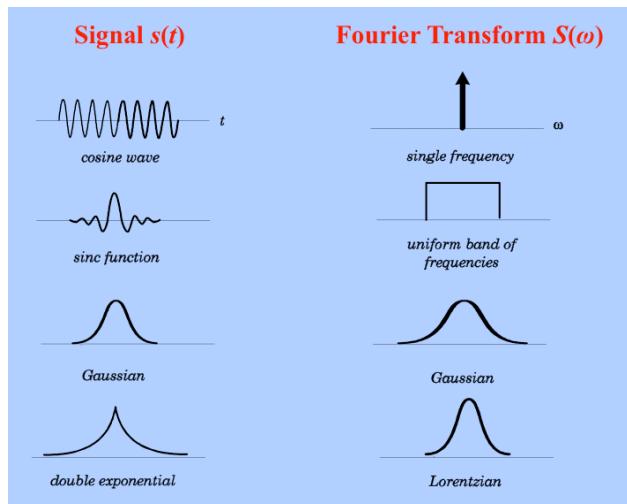
Scaling $f(ax)$

$$\frac{1}{|a|} F\left(\frac{u}{a}\right)$$



Properties of Fourier Transform

Common Closed Form Transforms and Properties



S. Narasimhan, Computer Vision

Spatial Domain (x)

Frequency Domain (u)

Linearity

$$c_1 f(x) + c_2 g(x)$$

$$c_1 F(u) + c_2 G(u)$$

Scaling

$$f(ax)$$

$$\frac{1}{|a|} F\left(\frac{u}{a}\right)$$

Shifting

$$f(x - x_0)$$

$$e^{-i2\pi u x_0} F(u)$$

Symmetry

$$F(x)$$

$$f(-u)$$

Conjugation

$$f^*(x)$$

$$F^*(-u)$$

Convolution

$$f(x) * g(x)$$

$$F(u)G(u)$$

Differentiation

$$\frac{d^n f(x)}{dx^n}$$

$$(i2\pi u)^n F(u)$$



Common Closed Form Transforms and More Properties

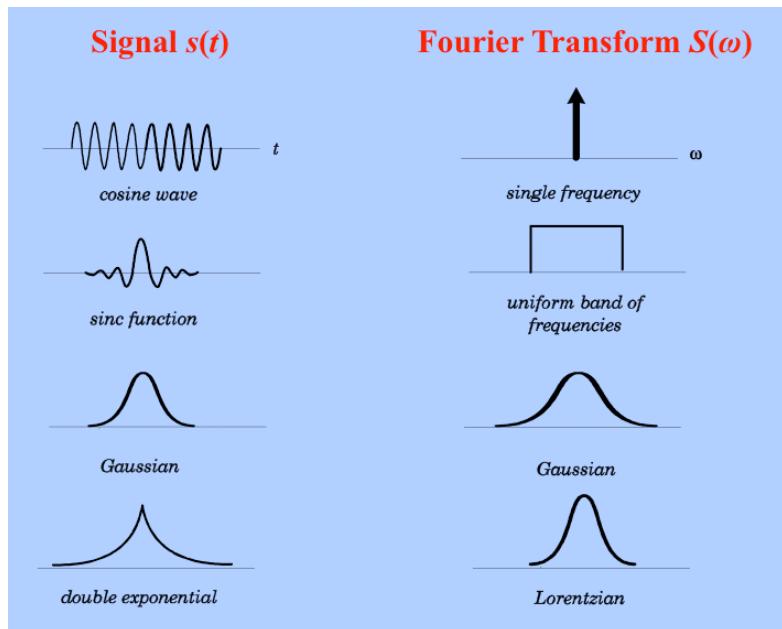


TABLE 4-1
Fourier Transform Theorems^a

Name of Theorem

1. Superposition (a_1 and a_2 arbitrary constants)	$a_1x_1(t) + a_2x_2(t)$	$a_1X_1(f) + a_2X_2(f)$
2. Time delay	$x(t - t_0)$	$X(f)e^{-j2\pi f t_0}$
3a. Scale change	$x(at)$	$ a ^{-1}X\left(\frac{f}{a}\right)$
b. Time reversal	$x(-t)$	$X(-f) = X * (f)$
4. Duality	$X(t)$	$x(-f)$
5a. Frequency translation	$x(t)e^{j\omega_0 t}$	$X(f - f_0)$
b. Modulation	$x(t) \cos \omega_0 t$	$\frac{1}{2}X(f - f_0) + \frac{1}{2}X(f + f_0)$
6. Differentiation	$\frac{d^n x(t)}{dt^n}$	$(j2\pi f)^n X(f)$
7. Integration	$\int_{-\infty}^t x(t') dt'$	$(j2\pi f)^{-1}X(f) + \frac{1}{2}X(0)\delta(f)$
8. Convolution	$\int_{-\infty}^{\infty} x_1(t - t') x_2(t') dt'$	$X_1(f)X_2(f)$
	$= \int_{-\infty}^{\infty} x_1(t') x_2(t - t') dt'$	
9. Multiplication	$x_1(t)x_2(t)$	$\int_{-\infty}^{\infty} X_1(f - f')X_2(f') df'$
		$= \int_{-\infty}^{\infty} X_1(f')X_2(f - f') df'$

^a $\omega_0 = 2\pi f_0$; $x(t)$ is assumed to be real in 3b.



So that's all great, but what about data?

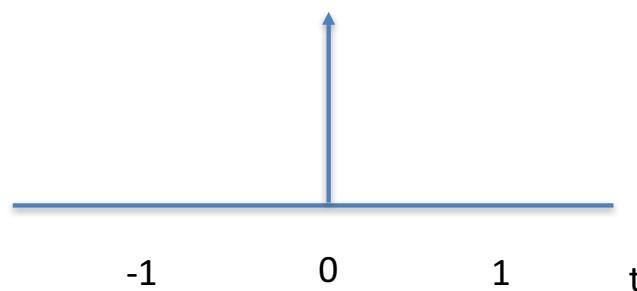
```
>>> np.fft.fft(np.exp(2j * np.pi * np.arange(8) / 8))
array([-3.44505240e-16 +1.14383329e-17j,
       8.00000000e+00 -5.71092652e-15j,
       2.33482938e-16 +1.22460635e-16j,
       1.64863782e-15 +1.77635684e-15j,
       9.95839695e-17 +2.33482938e-16j,
       0.00000000e+00 +1.66837030e-15j,
       1.14383329e-17 +1.22460635e-16j,
      -1.64863782e-15 +1.77635684e-15j])
```



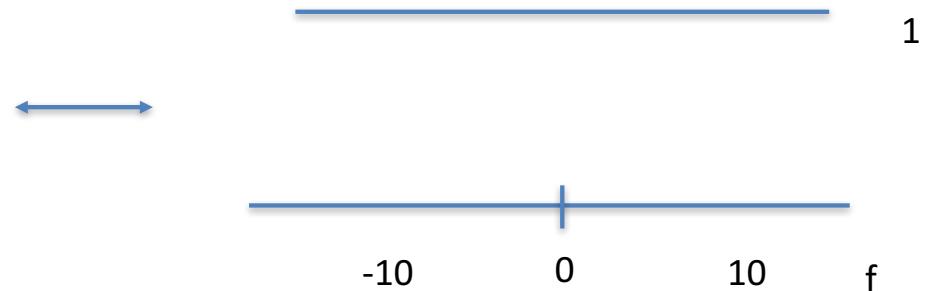
Example: impulse or “delta” function

- FT of delta function:

$$F(\delta(x)) = \int_{-\infty}^{\infty} \delta(x) e^{-j2\pi fx} dx = e^0 = 1$$



Like a very narrow pulse



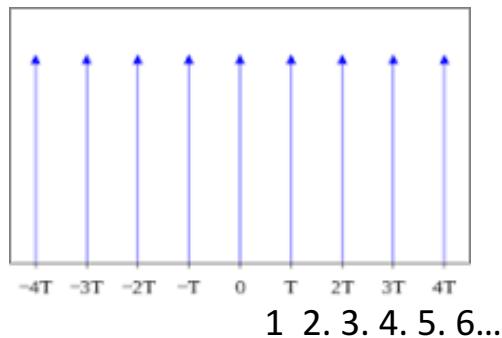
Results in a ‘very’ broad spectrum sinc



Data

But wait, data is discrete, but Fourier continuous

This is the
comb
function:



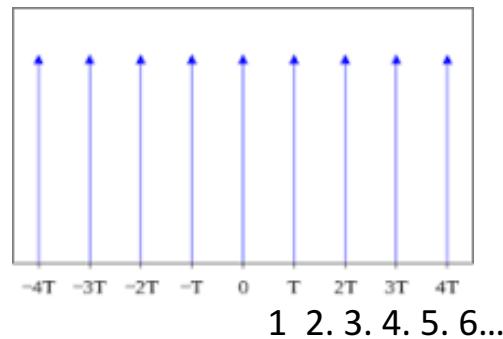
What would this be?
 $\text{III}(t/T) =$

$$\text{III}(t) = \sum_{k=-\infty}^{\infty} \delta(t-k)$$



But wait, data is discrete, but Fourier continuous

This is the
comb
function:



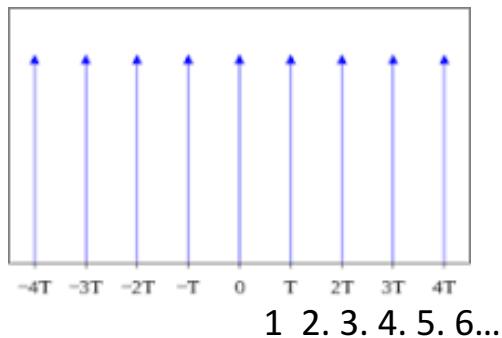
$$\text{III}(t) = \sum_{k=-\infty}^{\infty} \delta(t-k)$$

Answer: Fourier of $\text{Comb}(t) = \text{Comb}(f)$



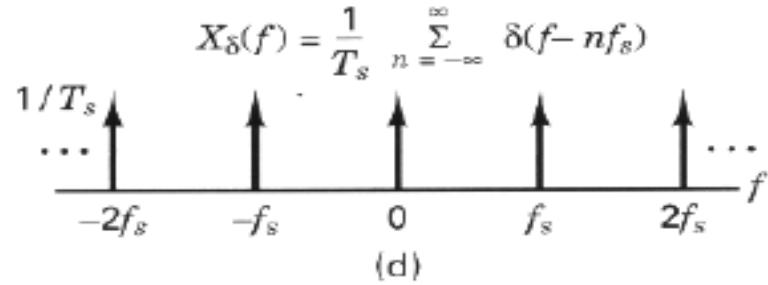
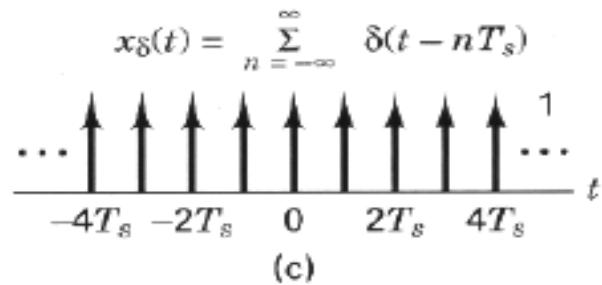
But wait, that was discrete, and Fourier was continuous

This is the
comb
function:



Answer: Fourier of Comb(t) = Comb(f)

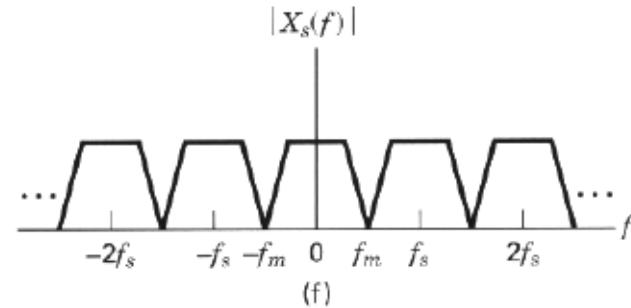
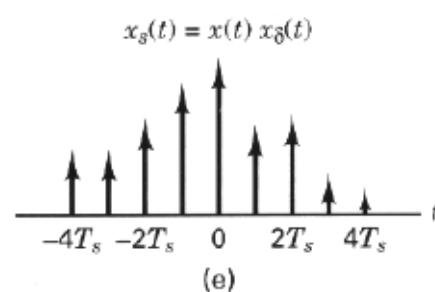
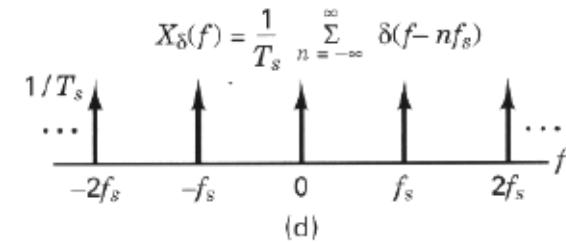
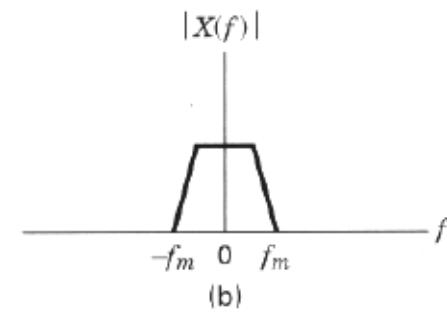
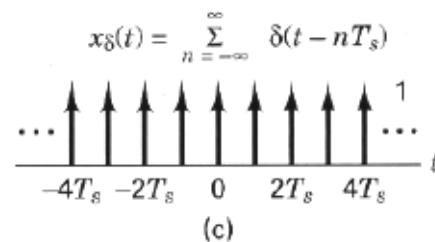
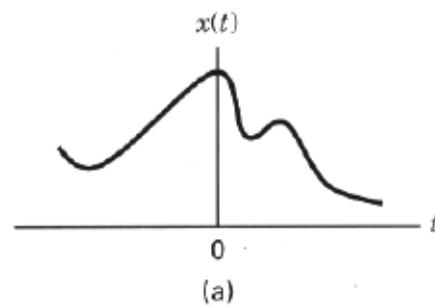
$$\text{III}_T(t) \stackrel{\text{def}}{=} \sum_{k=-\infty}^{\infty} \delta(t - kT) = \frac{1}{T} \text{III}\left(\frac{t}{T}\right)$$



By understanding the properties of the Comb, we can map between the time signal and the frequency samples

Sampled with time T_s , and with N samples means:

Each frequency bin in the FFT = F_s/N



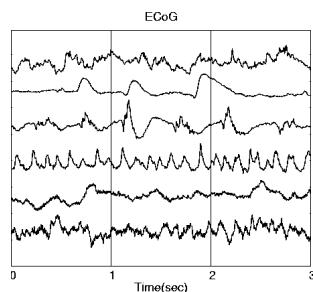
<http://docs.exdat.com/docs/index-44055.html>



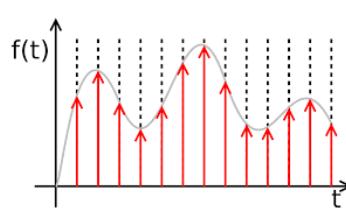
So that's all great, but what about data?

With data, we need to know 2 things:

1. What is the list of numbers (data) that was taken from the reading? Call is $x[n]$
2. What was the sampling frequency (f_s) or sampling period (T_s) from the original source?



Continuous signals
 $x(t)$



Sampled signals (data)
 $x(nT_s)$

Rec	Observed
1	60.323
2	61.122
3	60.171
4	61.187
5	63.221
6	63.639
7	64.999
8	63.761
9	66.019
10	67.857
11	68.169
12	66.513
13	68.655
14	69.564
15	69.331
16	70.551



Discrete data
 $x_n = x_1, x_2, x_3, \dots$

(might lose time reference)



Working with Numpy FFT Results: Scaling and Folding

Imports

```
In [1]: %matplotlib inline
import numpy as np
import matplotlib.pyplot as plt
```

NumPy FFT Example 1

For an FFT to make sense,
we need to know:

1. The data (list) = x
2. The sample rate = 50 Hz

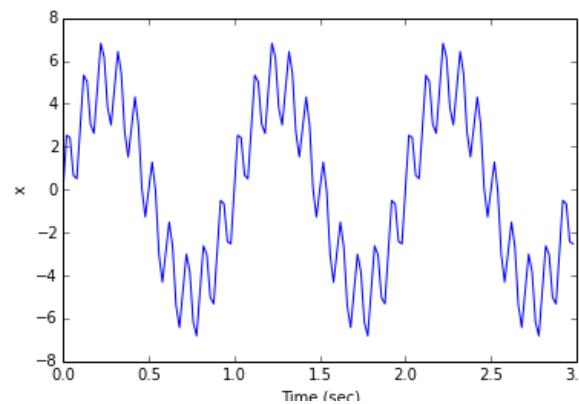
Create a Test Signal

f_s is the sampling frequency, while f is a base frequency for the signal content. We create a signal that contains components at a couple of multiples of this base frequency. Note the amplitudes here since we will be trying to extract those correctly from the FFT later.

```
In [2]: f_s = 50.0 # Hz
f = 1.0 # Hz
time = np.arange(0.0, 3.0, 1/f_s)
x = 5 * np.sin(2 * np.pi * f * time) + 2 * np.sin(10 * 2 * np.pi * f * time)
```

```
In [3]: plt.plot(time, x)
plt.xlabel("Time (sec)")
plt.ylabel("x")
```

```
Out[3]: <matplotlib.text.Text at 0x6e22b10>
```



 jedludlow / ipython_fft_example.ipynb
<https://gist.github.com/jedludlow/3919130>



NumPy FFT Example 1

Compute the FFT

The FFT and a matching vector of frequencies

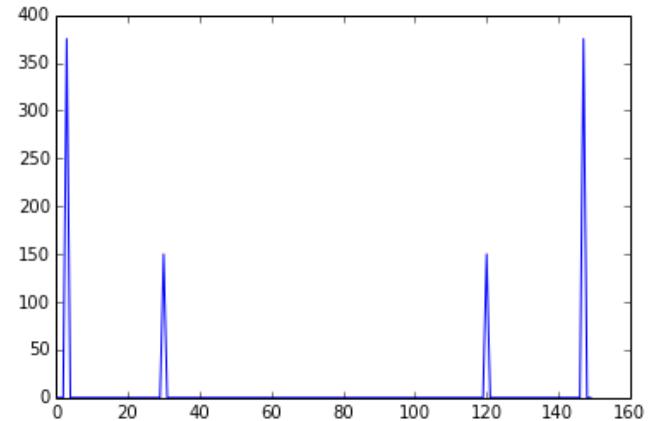
```
In [4]: fft_x = np.fft.fft(x)
n = len(fft_x)
freq = np.fft.fftfreq(n, 1/f_s)
print n
print freq
```

```
150
[ 0.      0.33333333  0.66666667  1.        1.33333333
  1.66666667  2.      2.33333333  2.66666667  3.        3.33333333
  3.66666667  4.      4.33333333  4.66666667  5.        5.33333333
  5.66666667  6.      6.33333333  6.66666667  7.        7.33333333
  7.66666667  8.      8.33333333  8.66666667  9.        9.33333333
  9.66666667  10.     10.33333333 10.66666667 11.       11.33333333
 11.66666667  12.     12.33333333 12.66666667 13.       13.33333333
 13.66666667  14.     14.33333333 14.66666667 15.       15.33333333
 15.66666667  16.     16.33333333 16.66666667 17.       17.33333333
 17.66666667  18.     18.33333333 18.66666667 19.       19.33333333
 19.66666667  20.     20.33333333 20.66666667 21.       21.33333333
 21.66666667  22.     22.33333333 22.66666667 23.       23.33333333
 23.66666667  24.     24.33333333 24.66666667 -25.      -24.66666667
 -24.33333333 -24.    -23.66666667 -23.33333333 -23.      -22.66666667
 -22.33333333 -22.    -21.66666667 -21.33333333 -21.      -20.66666667
 -20.33333333 -20.    -19.66666667 -19.33333333 -19.      -18.66666667
 -18.33333333 -18.    -17.66666667 -17.33333333 -17.      -16.66666667
 -16.33333333 -16.    -15.66666667 -15.33333333 -15.      -14.66666667
 ...         ...      ...         ...         ...      ...
 017
-14.33333333 -14.    -13.66666667 -13.33333333 -13.      -12.66666667
-12.33333333 -12.    -11.66666667 -11.33333333 -11.      -10.66666667
-10.33333333 -10.    -9.66666667 -9.33333333 -9.       -8.66666667
-8.33333333 -8.     -7.66666667 -7.33333333 -7.       -6.66666667
-6.33333333 -6.     -5.66666667 -5.33333333 -5.       -4.66666667
-4.33333333 -4.     -3.66666667 -3.33333333 -3.       -2.66666667
-2.33333333 -2.     -1.66666667 -1.33333333 -1.       -0.66666667
-0.33333333]
```

$$\begin{aligned} fs &= 50 \\ n &= 3 * 50 \\ fs/n &= 1/3 \end{aligned}$$

```
In [5]: plt.plot(np.abs(fft_x))
```

```
Out[5]: [<matplotlib.lines.Line2D at 0x70986f0>]
```



150 points in the original data
150 points in the fft result



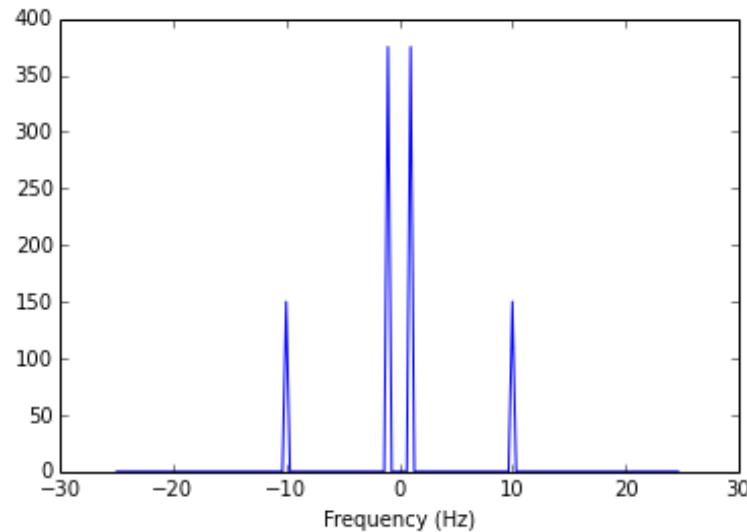
Swap Half Spaces

Note that frequencies in the FFT and the freq vector go from zero to some larger positive number then from a large negative number back toward zero. We can swap that so that the DC component is in the center of the vector while maintaining a two-sided spectrum.

```
In [6]: fft_x_shifted = np.fft.fftshift(fft_x)
freq_shifted = np.fft.fftshift(freq)
```

```
In [7]: plt.plot(freq_shifted, np.abs(fft_x_shifted))
plt.xlabel("Frequency (Hz)")
```

```
Out[7]: <matplotlib.text.Text at 0x70a2b50>
```



NumPy FFT Example 1



NumPy FFT Example 1

$$\begin{aligned}fs &= 50 \\n &= 3 * 50 \\fs/n &= 1/3\end{aligned}$$

Fold Negative Frequencies and Scale

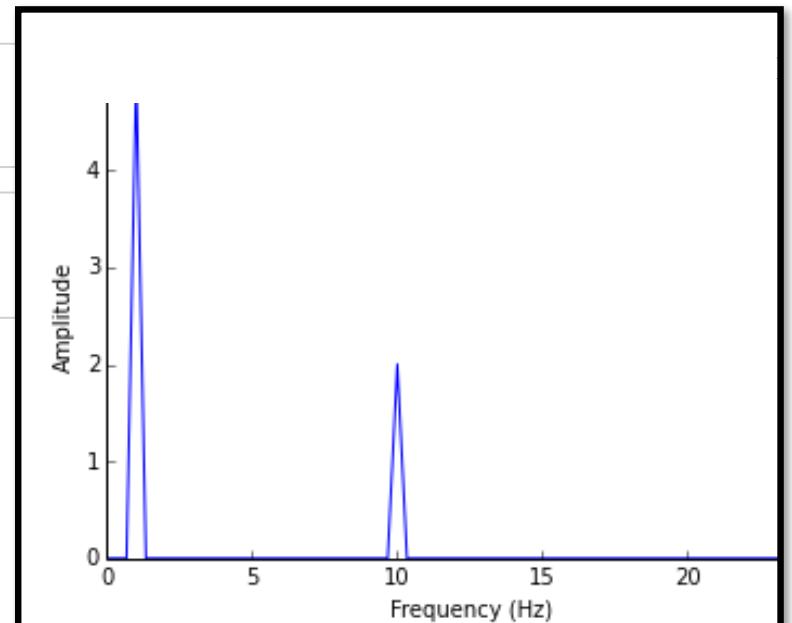
It's actually more common to look at just the first half of the unshifted FFT and frequency vectors and fold all the amplitude information into the positive frequencies. Furthermore, to get amplitude right, we must normalize by the length of the original FFT. Note the factor of $2 / n$ in the following which accomplishes both the folding and scaling.

```
In [8]: half_n = np.ceil(n/2.0)
        fft_x_half = (2.0 / n) * fft_x[:half_n]
        freq_half = freq[:half_n]
```

```
In [9]: plt.plot(freq_half, np.abs(fft_x_half))
plt.xlabel("Frequency (Hz)")
plt.ylabel("Amplitude")
```

Out[9]: <matplotlib.text.Text at 0x6edc150>

This is just slicing of the arrays.



Data X

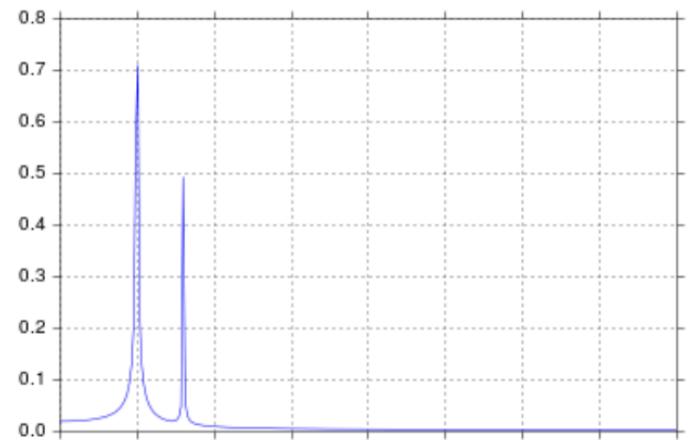
A SciPy Example

```
%matplotlib inline
import numpy as np
import matplotlib.pyplot as plt
import scipy.fftpack

# Number of samplepoints
N = 600
# sample spacing
T = 1.0 / 800.0
x = np.linspace(0.0, N*T, N)
y = np.sin(50.0 * 2.0*np.pi*x) + 0.5*np.sin(80.0 * 2.0*np.pi*x)
yf = scipy.fftpack.fft(y)
xf = np.linspace(0.0, 1.0/(2.0*T), N/2)

fig, ax = plt.subplots()
ax.plot(xf, 2.0/N * np.abs(yf[:N//2]))
plt.show()
```

I get what I believe to be very reasonable output.

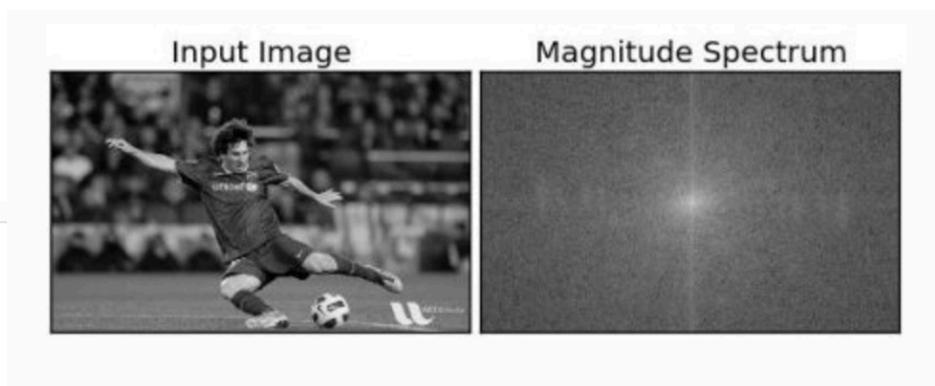


Getting image data and 2-d FFTs are possible with NumPy and Open CV

```
import cv2
import numpy as np
from matplotlib import pyplot as plt

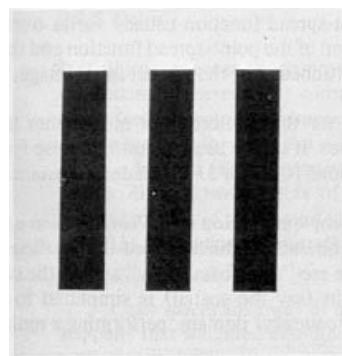
img = cv2.imread('messi5.jpg',0)
f = np.fft.fft2(img)
fshift = np.fft.fftshift(f)
magnitude_spectrum = 20*np.log(np.abs(fshift))

plt.subplot(121),plt.imshow(img, cmap = 'gray')
plt.title('Input Image'), plt.xticks([]), plt.yticks([])
plt.subplot(122),plt.imshow(magnitude_spectrum, cmap = 'gray')
plt.title('Magnitude Spectrum'), plt.xticks([]), plt.yticks([])
plt.show()
```

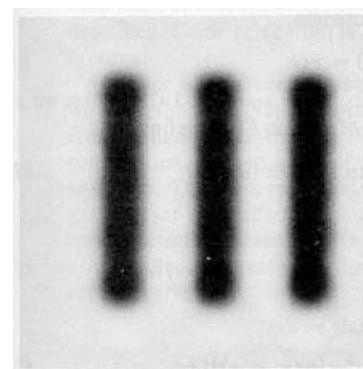


How do frequencies show up in an image?

- Low frequencies correspond to slowly varying information (e.g., continuous surface).
- High frequencies correspond to quickly varying information (e.g., edges)



Original Image

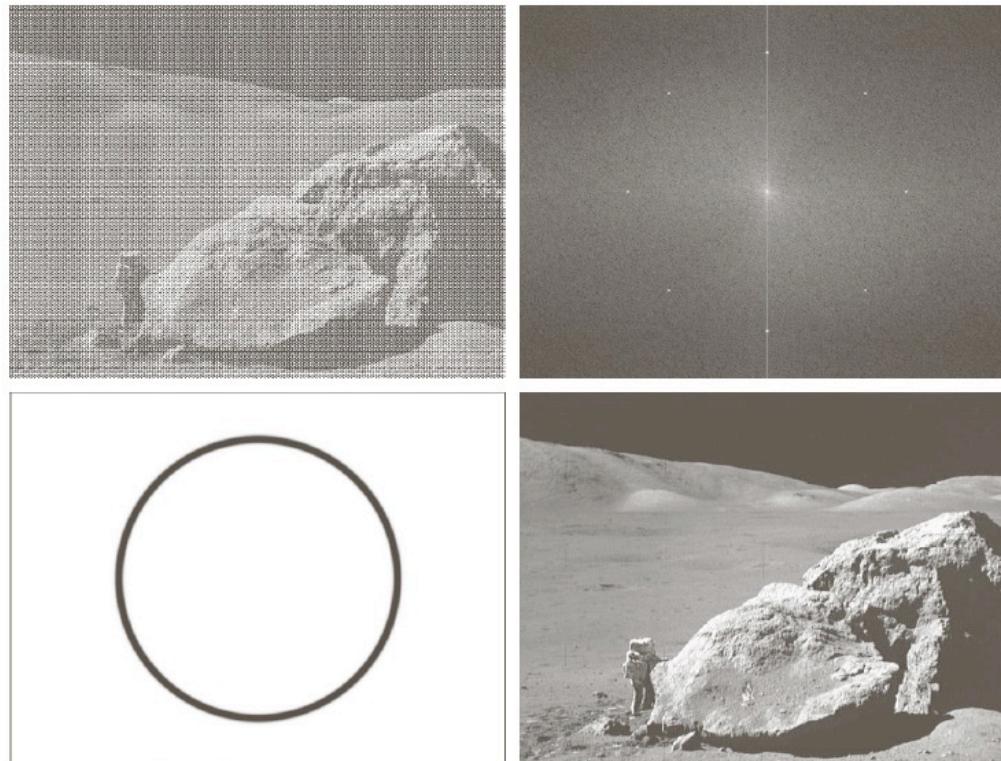


Low-passed

Naveen Sihag



Example of noise reduction using FT

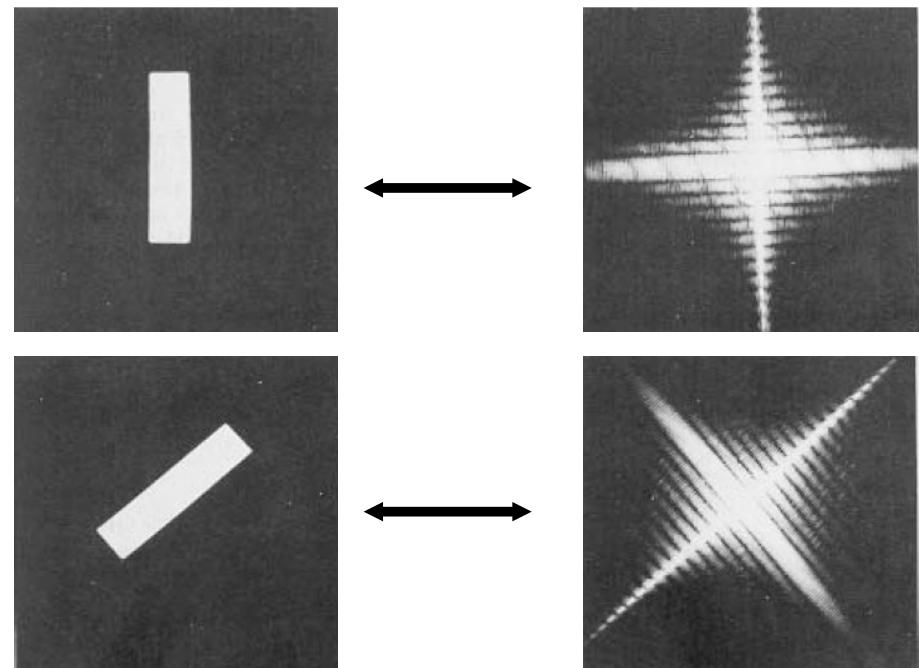


Naveen Sihag

Data X

DFT Properties: (5) Rotation

- Rotating $f(x,y)$ by θ rotates $F(u,v)$ by θ

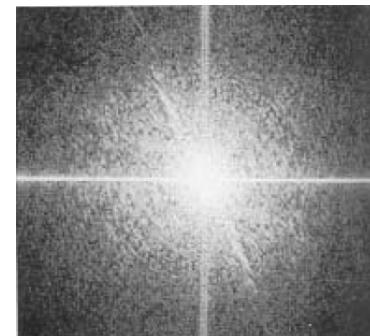


Naveen Sihag

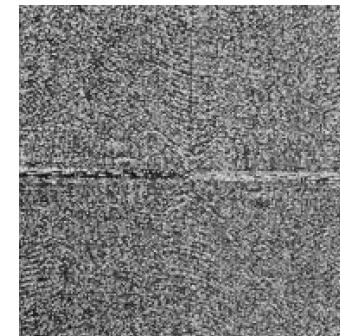


Magnitude and Phase of DFT

- What is more important?



magnitude



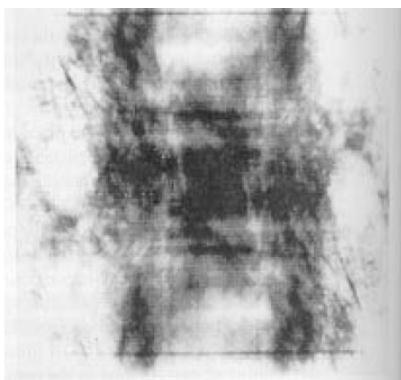
phase

- Hint: use inverse DFT to reconstruct the image using magnitude or phase only information

Naveen Sihag



Magnitude and Phase of DFT (cont'd)



Reconstructed image using
magnitude only
(i.e., magnitude determines the
contribution of each component!)

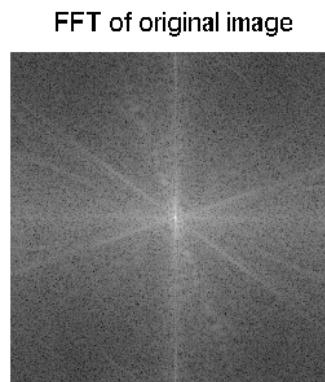
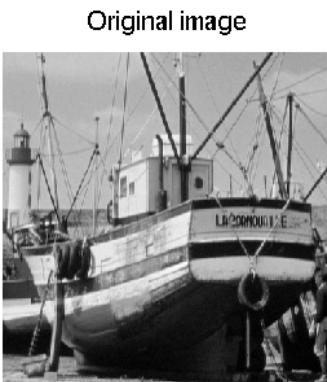


Reconstructed image using
phase only
(i.e., phase determines
which components are present!)

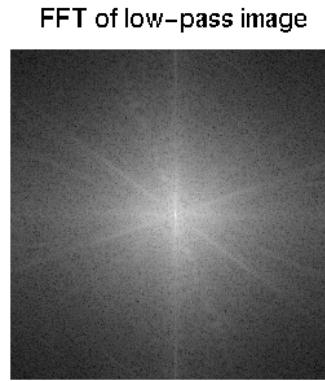
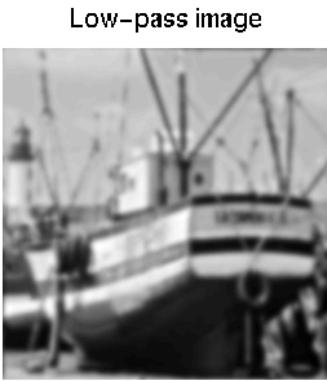
Naveen Sihag



Low-pass Filtering



Let the low frequencies pass and eliminating the high frequencies.



Generates image with overall shading, but not much detail

S. Narasimhan,
Computer Vision

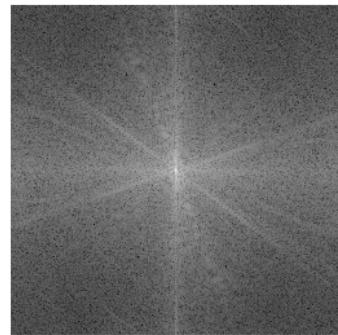


High-pass Filtering

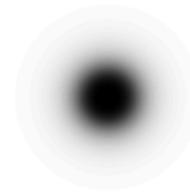
Original image



FFT of original image



High-pass filter

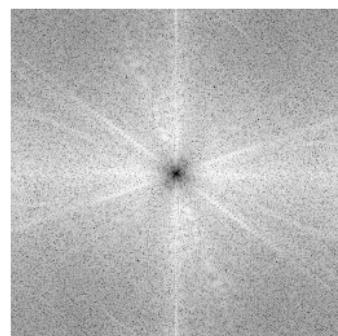


Lets through the high frequencies (the detail), but eliminates the low frequencies (the overall shape). It acts like an edge enhancer.

High-pass image



FFT of high-pass image



S. Narasimhan,
Computer Vision

Data X

End of Section

0 0 0 1 0 1 0 1 0 1 1 1 0 0 0 0 0 0 1 0 0 1 0 1 0 1 1 1 0 0
1 0 1 1 X 1 1 0 0 1 0 1 0 0 0 1 0 0 1 0 1 1 1 1 1 0 0 1 0 1 0 0
1 Data 0 0 1 0 1 0 1 0 1 0 0 0 1 0 0 1 0 1 1 1 1 1 0 0 1 0 1 0 0