Today

- Transfer functions and convolution.
- Method of Undetermined Coefficients for any periodic function.
- Fourier Series and method of undetermined coefficients

Convolution

- We often end up with transforms to invert that are the product of two known transforms. For example,

$$Y(s) = \frac{2}{s^2(s^2+4)} = \frac{1}{s^2} \cdot \frac{2}{s^2+4}$$

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- Can we express the inverse of a product in terms of the known pieces?

$$F(s)G(s) = \mathcal{L}\{??\}$$

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$$F(s) = \int_0^\infty e^{-st} f(t)\ dt \quad \longrightarrow \quad F(s) = \int_0^\infty e^{-s\tau} f(\tau)\ d\tau$$

$$G(s) = \int_0^\infty e^{-st} g(t)\ dt$$

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Convolution

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$$= \int_0^\infty e^{-sw} g(w) \int_0^\infty e^{-s\tau} f(\tau)\ d\tau\ dw$$

$$= \int_0^\infty g(w) \int_0^\infty e^{-s(\tau+w)} f(\tau)\ d\tau\ dw$$

Replace τ using $u = \tau + w$ where w is constant in the inner integral.

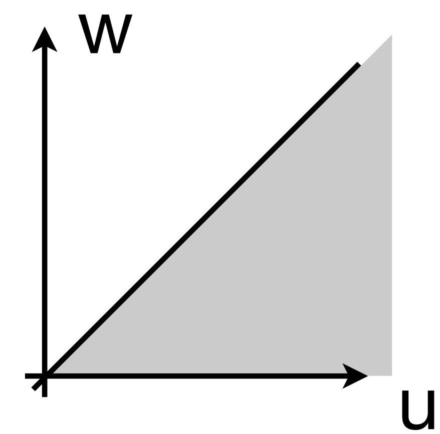
$$= \int_0^\infty g(w) \int_w^\infty e^{-s(u)} f(u-w)\ du\ dw$$

$$= \int_0^\infty \int_w^\infty e^{-su} g(w) f(u-w)\ du\ dw$$

$$= \int_a^b \int_c^d e^{-su} g(w) f(u-w)\ dw\ du$$

Convolution

- What are the correct values for a, b, c and d?



$$\int_0^\infty \int_w^\infty e^{-su} g(w) f(u-w)\ du\ dw$$

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Convolution

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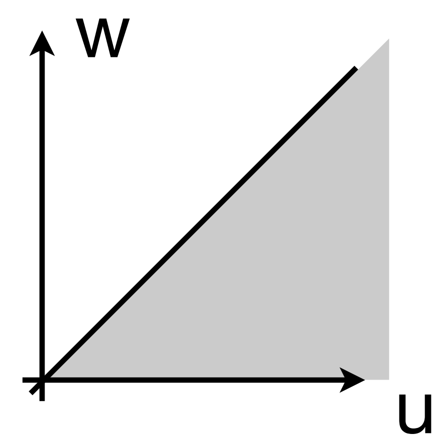
$$\int_0^\infty \int_w^\infty e^{-su} g(w) f(u-w)\ du\ dw$$

w=constant



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Convolution

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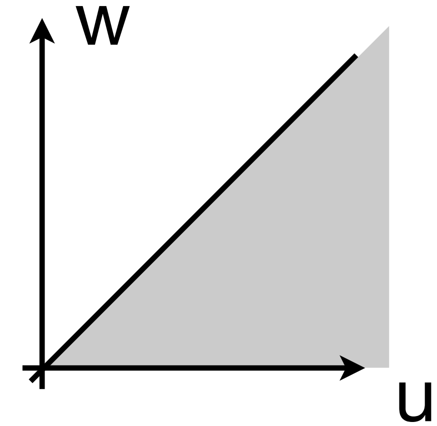

$$\int_0^{\infty} \int_w^{\infty} e^{-su} g(w) f(u-w)\ du\ dw$$

u= u= w=constant

$$= \int_a^b \int_c^d e^{-su} g(w) f(u-w)\ dw\ du$$

Convolution

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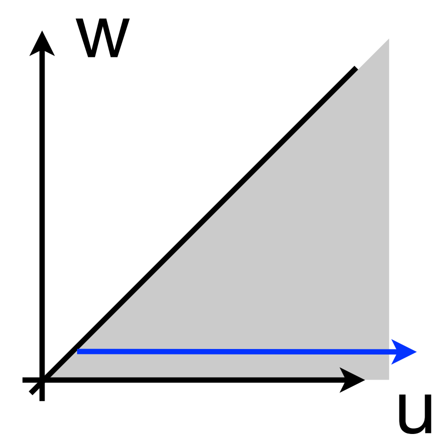


$$\int_0^\infty \int_{u=w}^{u=\infty} e^{-su} g(w) f(u-w)\ du\ dw$$

w=constant

$$= \int_a^b \int_c^d e^{-su} g(w) f(u-w)\ dw\ du$$

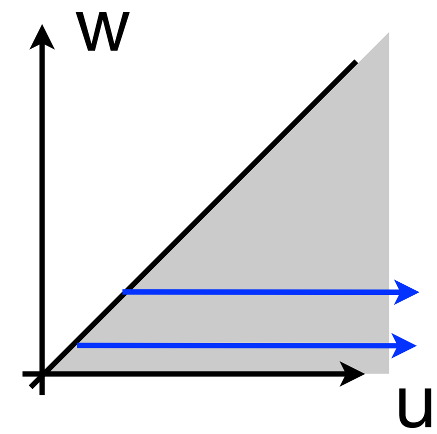
Convolution

- What are the correct values for a, b, c and d?

$$\int_{0}^{\infty} \int_{w}^{\infty} e^{-su} g(w) f(u-w)\; du\; dw$$

u= (upper limit), u= (lower limit)

w=constant



$$= \int_{a}^{b} \int_{c}^{d} e^{-su} g(w) f(u-w)\; dw\; du$$

Convolution

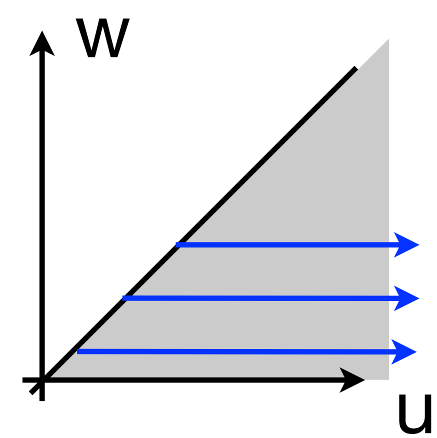
- What are the correct values for a, b, c and d?

$$\int_0^\infty \int_w^\infty e^{-su} g(w) f(u-w)\, du\, dw$$

u=

u=

w=constant



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Convolution

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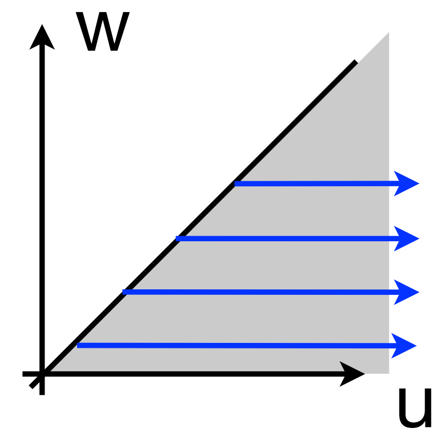

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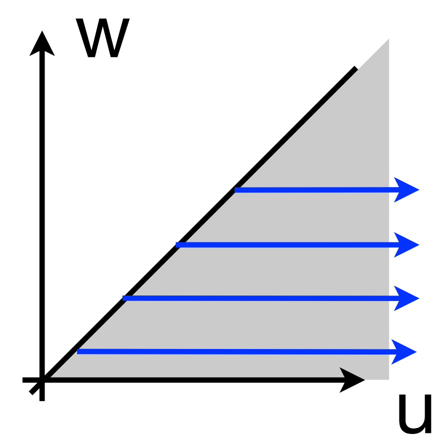

$$\int_0^\infty \int_w^\infty e^{-su} g(w) f(u-w)\; du\; dw$$

u= (upper limit), u= (lower limit), w=constant

$$= \int_a^b \int_c^d e^{-su} g(w) f(u-w)\; dw\; du$$

(A) Integrate in u from a=0 to b=∞ and in w from c=u, d=∞.

(B) Integrate in u from a=0 to b=w and in w from c=0 to d=∞.

(C) Integrate in u from a=0 to b=∞ and in w from c=0 to d=u.

(D) Integrate in u from a=0 to b=∞ and in w from c=w to d=∞.

(E) Huh?

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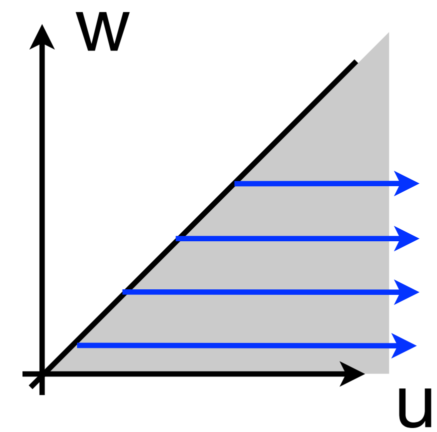

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(A) Integrate in u from a=0 to b=∞ and in w from c=u, d=∞.

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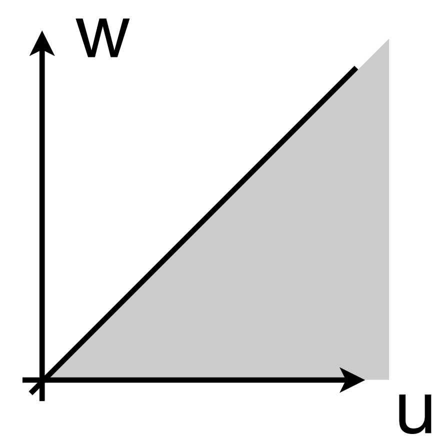

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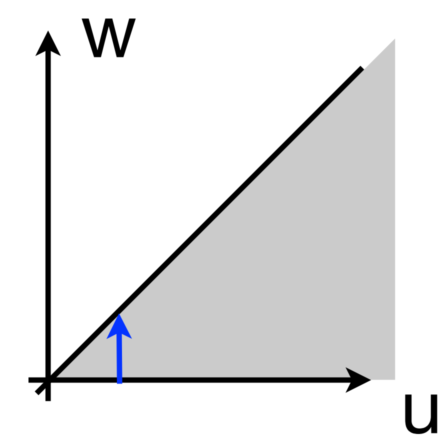

$$= \int_a^b \int_c^d e^{-su} g(w) f(u-w)\ dw\ du$$

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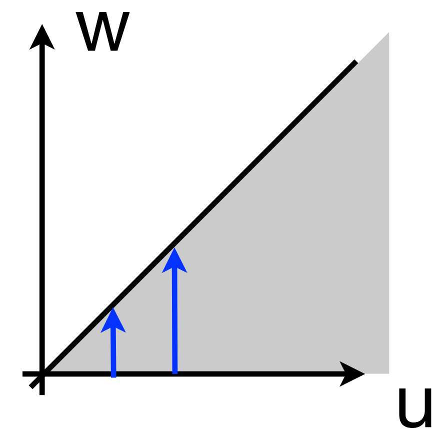

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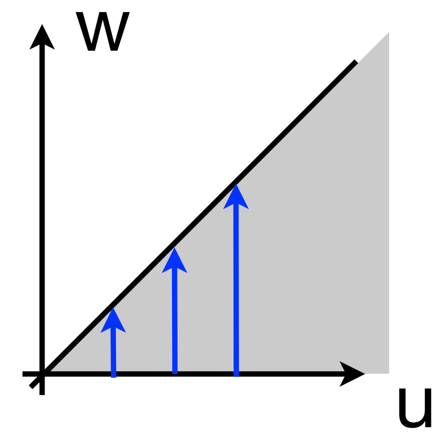

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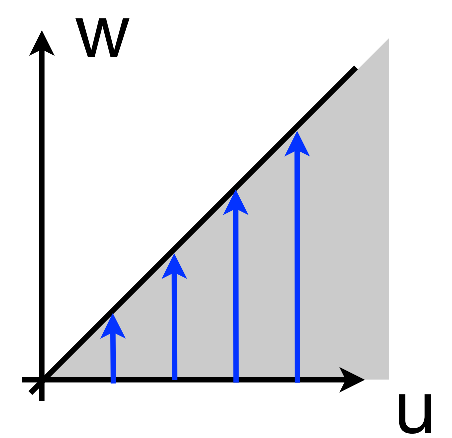

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$$F(s)G(s) = \int_0^\infty e^{-s\tau} f(\tau)\ d\tau \int_0^\infty e^{-sw} g(w)\ dw$$

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$$= \int_0^\infty \int_0^u e^{-su} g(w) f(u-w)\ dw\ du$$

$$= \int_0^\infty e^{-su} \int_0^u g(w) f(u-w)\ dw\ du$$

$$= \int_0^\infty e^{-su} h(u)\ du\ = H(s)$$

where $h(u) = \int_0^u g(w) f(u-w)\ dw$

This is called the convolution of f and g.
Denoted $f * g$.

Convolution

$$F(s)G(s) = \int_0^\infty e^{-s\tau} f(\tau)\ d\tau \int_0^\infty e^{-sw} g(w)\ dw$$

$$= \int_0^\infty \int_0^u e^{-su} g(w) f(u-w)\ dw\ du$$

$$= \int_0^\infty e^{-su} \int_0^u g(w) f(u-w)\ dw\ du$$

$$= \int_0^\infty e^{-su} h(u)\ du\ = H(s)$$

The transform of a convolution is the product of the transforms.

$$h(t) = f * g(t) = \int_0^u g(w) f(t-w)\ dw$$

$$\Rightarrow H(s) = F(s)G(s)$$

where $h(u) = \int_0^u g(w) f(u-w)\ dw$

This is called the convolution of f and g.
Denoted $f * g$.

Convolution

- To invert $Y(s) = \dfrac{1}{s^2} \cdot \dfrac{2}{s^2+4}$, we can use the fact that the inverse is the convolution of the inverses of the two pieces (instead of PFD...).

$$\mathcal{L}^{-1}\left\{\frac{1}{s^2}\right\} =$$

$$\mathcal{L}^{-1}\left\{\frac{2}{s^2+4}\right\} =$$

Convolution

- To invert $Y(s) = \frac{1}{s^2} \cdot \frac{2}{s^2+4}$, we can use the fact that the inverse is the convolution of the inverses of the two pieces (instead of PFD...).

$$\mathcal{L}^{-1}\left\{\frac{1}{s^2}\right\} = t$$

$$\mathcal{L}^{-1}\left\{\frac{2}{s^2+4}\right\} =$$

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$$\mathcal{L}^{-1}\left\{\frac{2}{s^2+4}\right\} = \sin(2t)$$

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$$\mathcal{L}^{-1}\left\{\frac{1}{s^2}\right\} = t$$

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$$f * g(t) = \int_0^u g(w) f(t-w)\ dw$$

$y(t) =$

(A) $\int_0^t (t-w)\sin(2w)\ dw$

(B) $\int_0^t (t-w)\sin(2t)\ dw$

(C) $\int_0^t w\sin(2(t-w))\ dw$

(D) $\int_0^t w\sin(2(w-t))\ dw$

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$$\mathcal{L}^{-1}\left\{\frac{1}{s^2}\right\} = \quad t$$

$$\mathcal{L}^{-1}\left\{\frac{2}{s^2+4}\right\} = \quad \sin(2t)$$

$$f * g(t) = \int_0^u g(w) f(t-w)\ dw$$

$y(t) =$

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$$\mathcal{L}^{-1}\left\{\frac{1}{s^2}\right\} = \ t$$

$$\mathcal{L}^{-1}\left\{\frac{2}{s^2+4}\right\} = \ \sin(2t)$$

$$f * g(t) = \int_0^u g(w) f(t-w)\ dw$$

$$f * g = g * f$$

$$\int_0^t f(t-w) g(w)\ dw = \int_0^t f(t) g(t-w)\ dw$$

$y(t) =$

☆ (A) $\int_0^t (t-w)\sin(2w)\ dw$

☆ (C) $\int_0^t w\sin(2(t-w))\ dw$

(B) $\int_0^t (t-w)\sin(2t)\ dw$

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Convolution

- Transfer functions

$$ay'' + by' + cy = g(t), \quad y(0) = 0, \; y'(0) = 0$$

Convolution

- Transfer functions

$$ay'' + by' + cy = g(t), \quad y(0) = 0,\ y'(0) = 0$$

$$Y(s) = \frac{1}{as^2 + bs + c} G(s)$$

Convolution

- Transfer functions

$$ay'' + by' + cy = g(t), \quad y(0) = 0, \; y'(0) = 0$$

$$Y(s) = \frac{1}{as^2 + bs + c} G(s)$$

- Define the transfer function for the ODE:

Convolution

- Transfer functions

$$ay'' + by' + cy = g(t), \quad y(0) = 0,\ y'(0) = 0$$

$$Y(s) = \frac{1}{as^2 + bs + c} G(s)$$

- Define the transfer function for the ODE:

$$H(s) = \frac{1}{as^2 + bs + c}$$

Convolution

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- Define the transfer function for the ODE:

$$H(s) = \frac{1}{as^2 + bs + c}$$

Independent of g(t)!

Convolution

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- Define the transfer function for the ODE:

$$H(s) = \frac{1}{as^2 + bs + c}$$

Independent of g(t)!

$$y(t) = (h * g)(t)$$

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$$Y(s) = \frac{1}{as^2 + bs + c} G(s)$$

- Define the transfer function for the ODE:

$$H(s) = \frac{1}{as^2 + bs + c}$$ Independent of g(t)!

$$y(t) = (h * g)(t)$$

- h(t) is called the impulse response because it solves (1) when g(t)=δ(t).

Convolution

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$$g(t) = \delta(t)$$

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$$G(s) = e^{-0s} = 1$$

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$$H(s) = \frac{1}{as^2 + bs + c}$$ Independent of g(t)!

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$$g(t) = \delta(t)$$
$$G(s) = e^{-0s} = 1$$
$$Y(s) = \frac{1}{as^2 + bs + c}$$

$$y_{IR}(t) = h(t) = \mathcal{L}^{-1}\left\{\frac{1}{as^2 + bs + c}\right\}$$

Convolution

- Transfer functions

$$ay'' + by' + cy = g(t), \quad y(0) = 0, \; y'(0) = 0$$

$$Y(s) = \frac{1}{as^2 + bs + c} G(s)$$

- Define the transfer function for the ODE:

$$H(s) = \frac{1}{as^2 + bs + c}$$ Independent of g(t)!

$$y(t) = (h * g)(t)$$

- h(t) is called the impulse response because it solves (1) when g(t)=δ(t).

$$g(t) = \delta(t)$$

$$G(s) = e^{-0s} = 1$$

$$Y(s) = \frac{1}{as^2 + bs + c}$$

$$y_{IR}(t) = h(t) = \mathcal{L}^{-1}\left\{\frac{1}{as^2 + bs + c}\right\}$$

Convolution

- Interpreting the transfer function in a model of memory.
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- Equation:
- Transform of n(t):
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$$n(t) = \int_0^t h(t-w)g(w)\ dw\ = \int_0^t e^{-k(t-w)}g(w)\ dw$$

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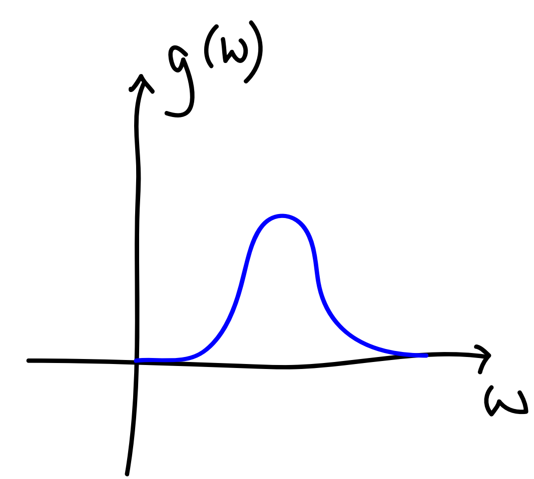

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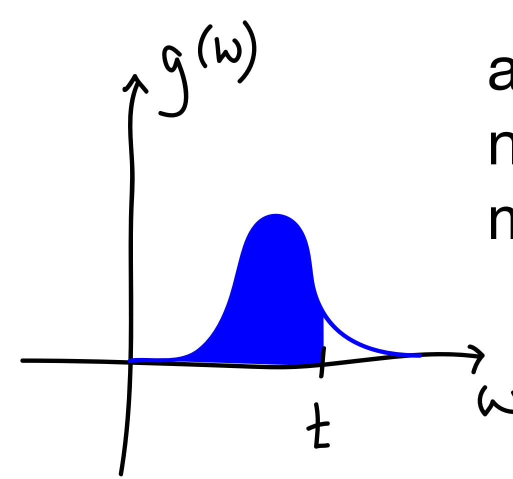

all phone numbers ever memorized

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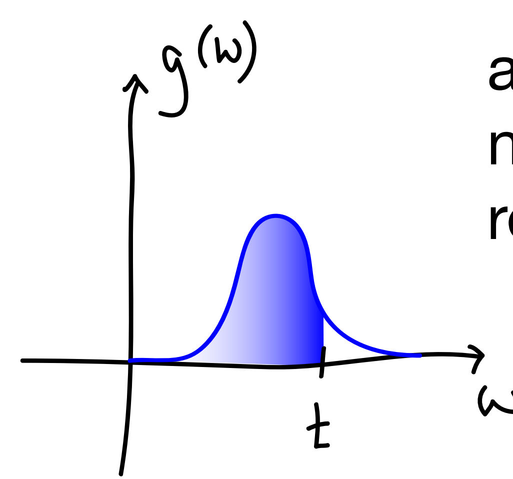

all phone numbers still remembered

Fourier series

- Recall Method of Undetermined Coefficients for equations of the form

$$ay'' + by' + cy = f(t)$$

https://www.desmos.com/calculator/tqaia8bt7n

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- Applicable for functions f(t) that are polynomials, exponentials, sin, cos and products of those.

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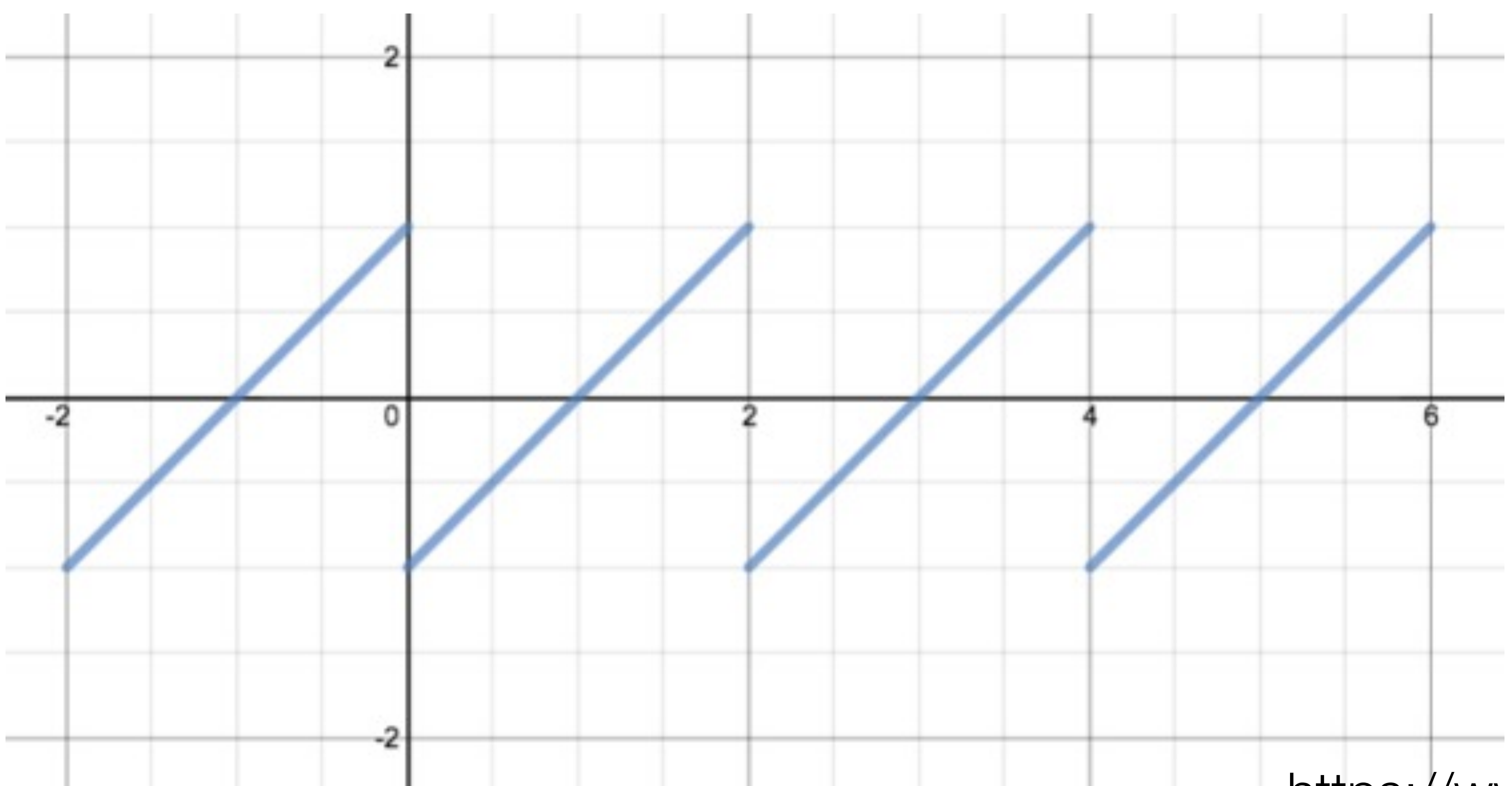

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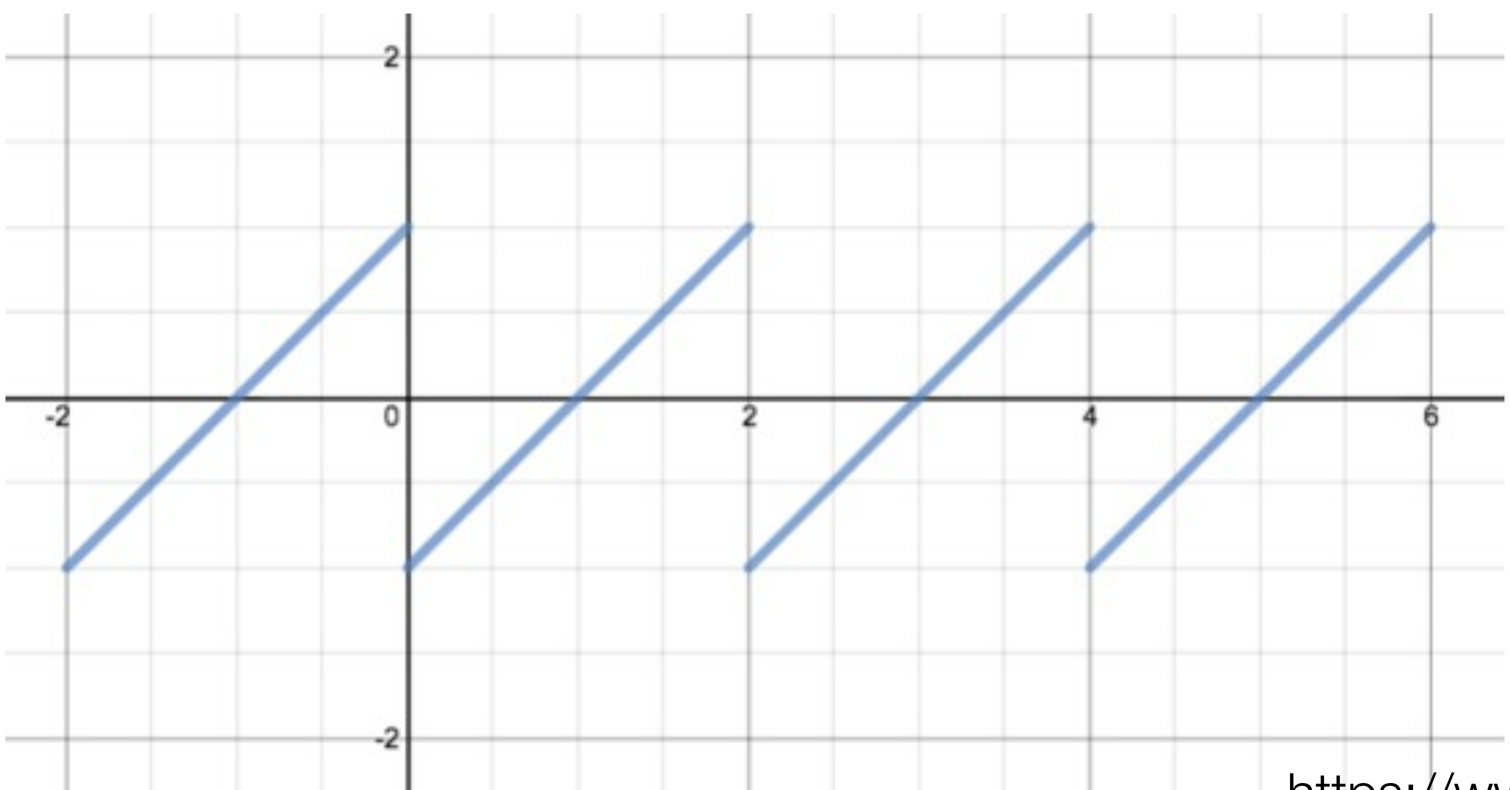

- What if we could construct such functions using only sine and cosine functions?

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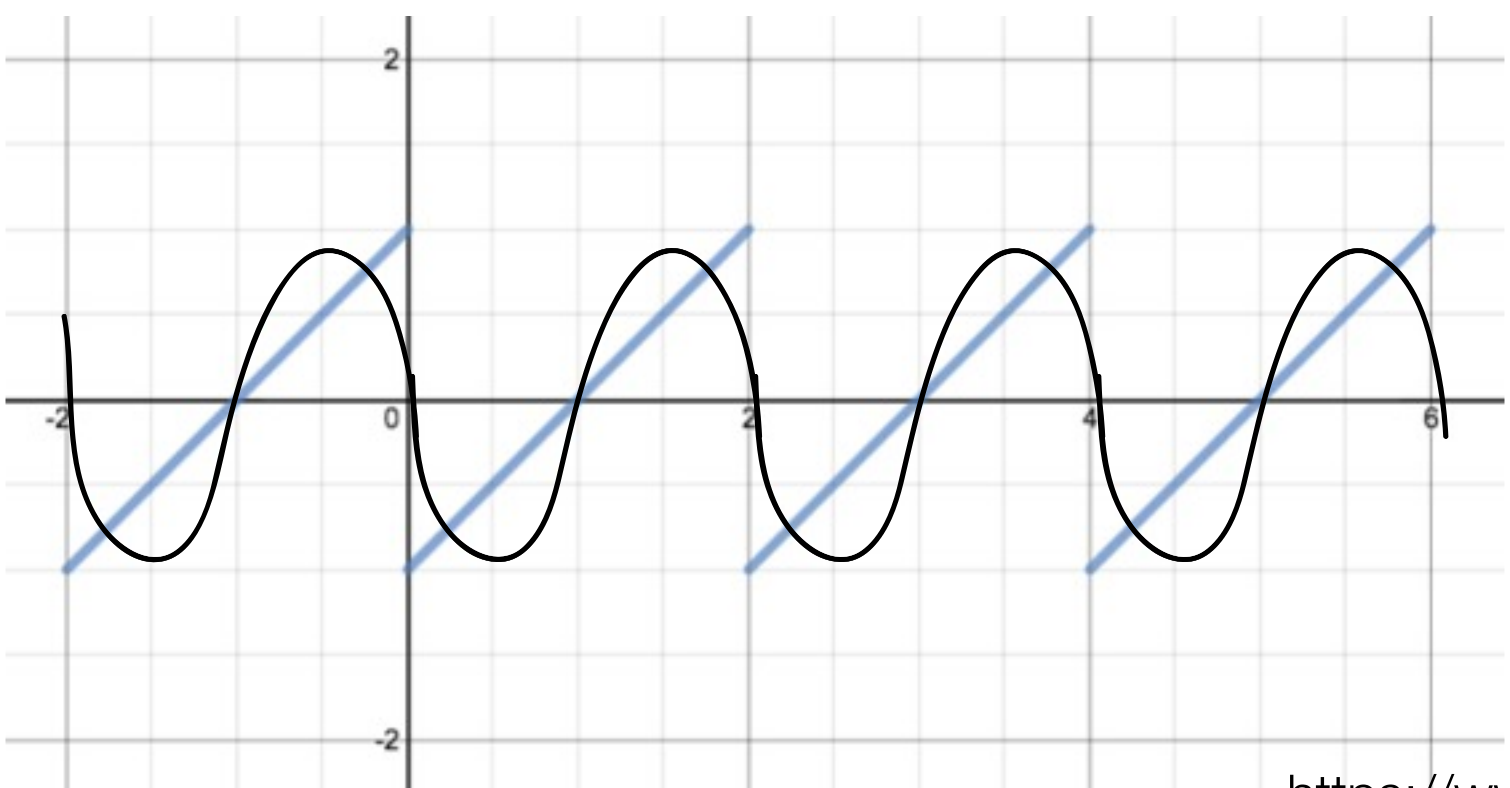

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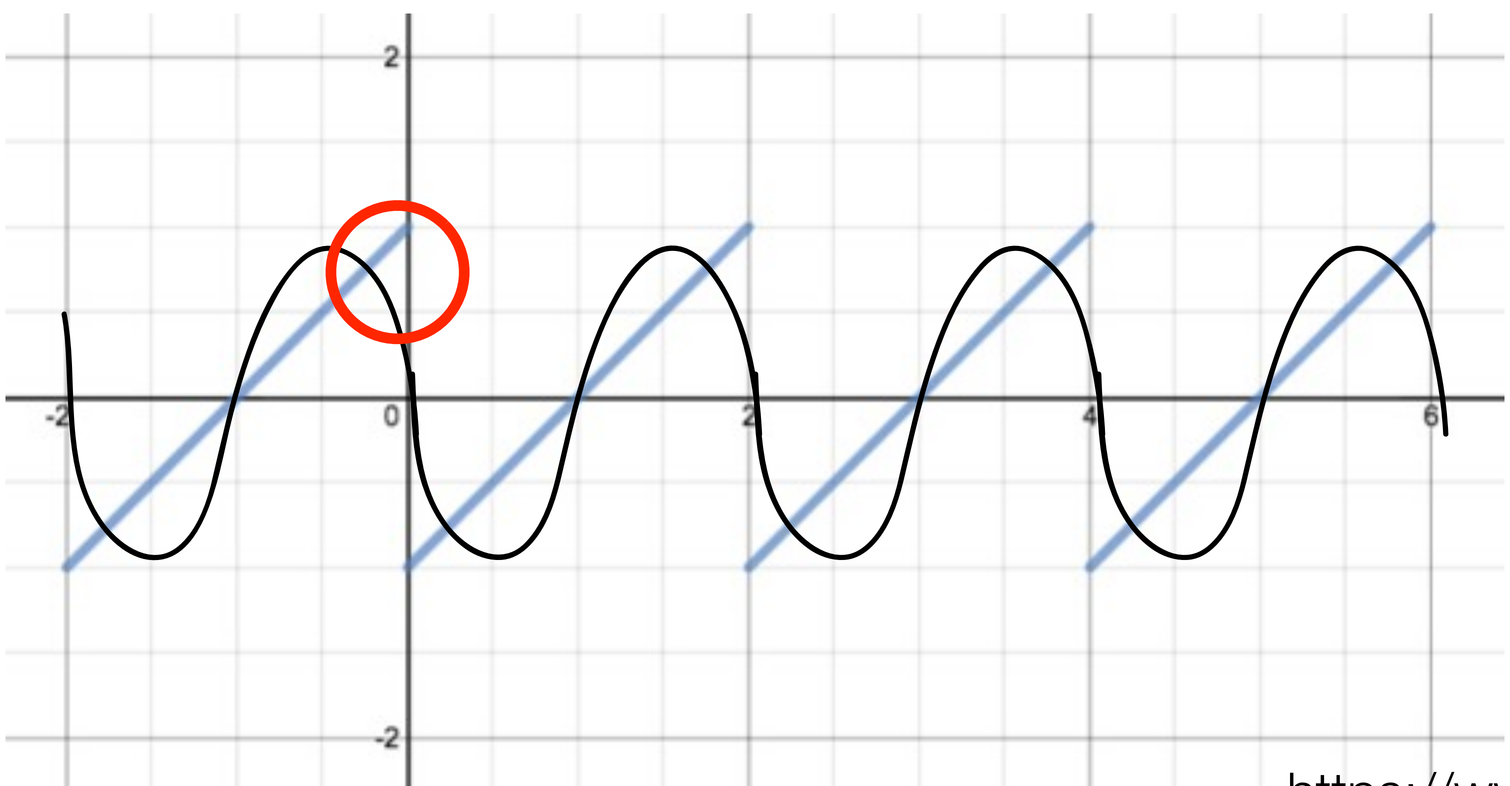

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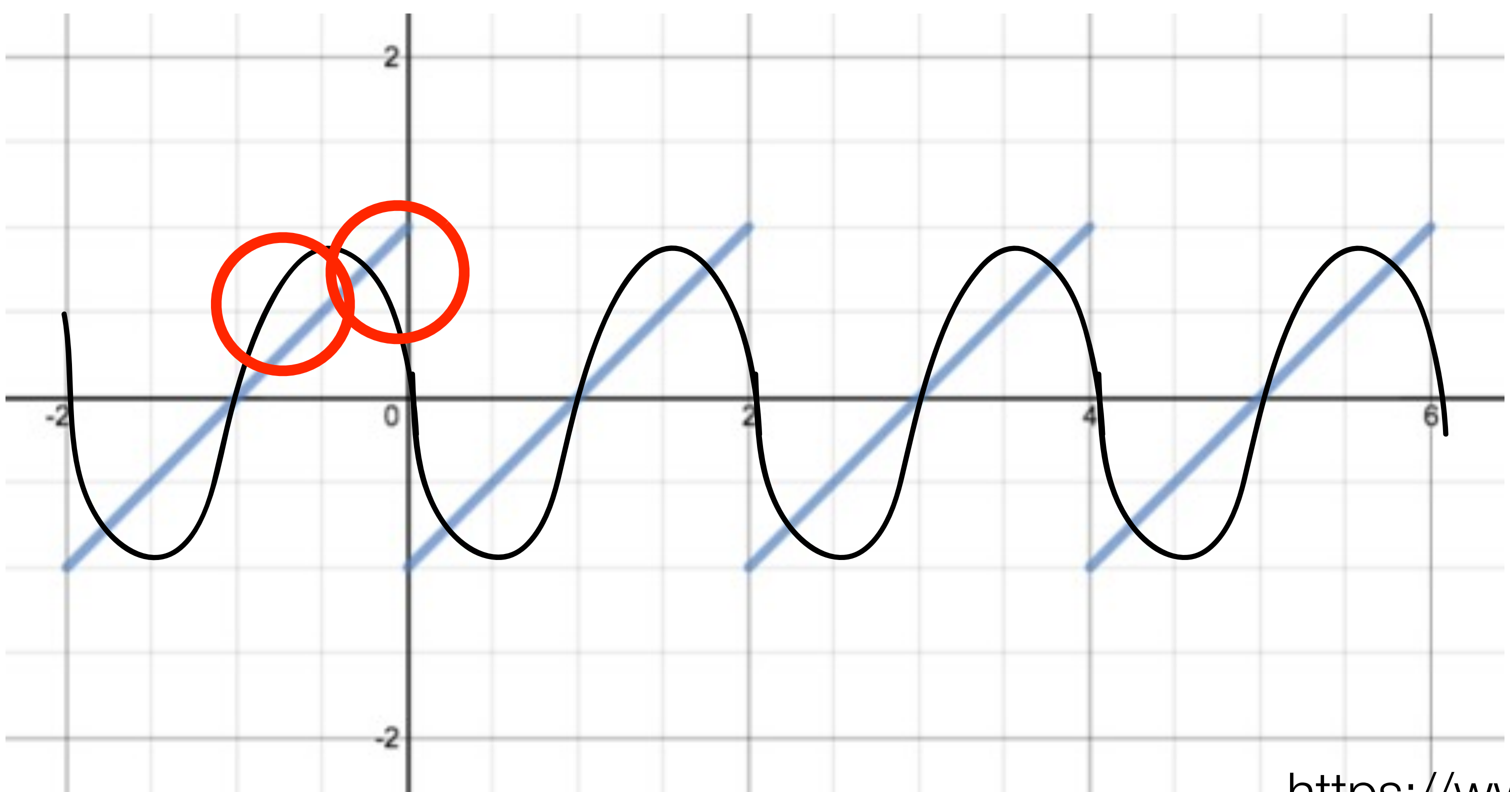

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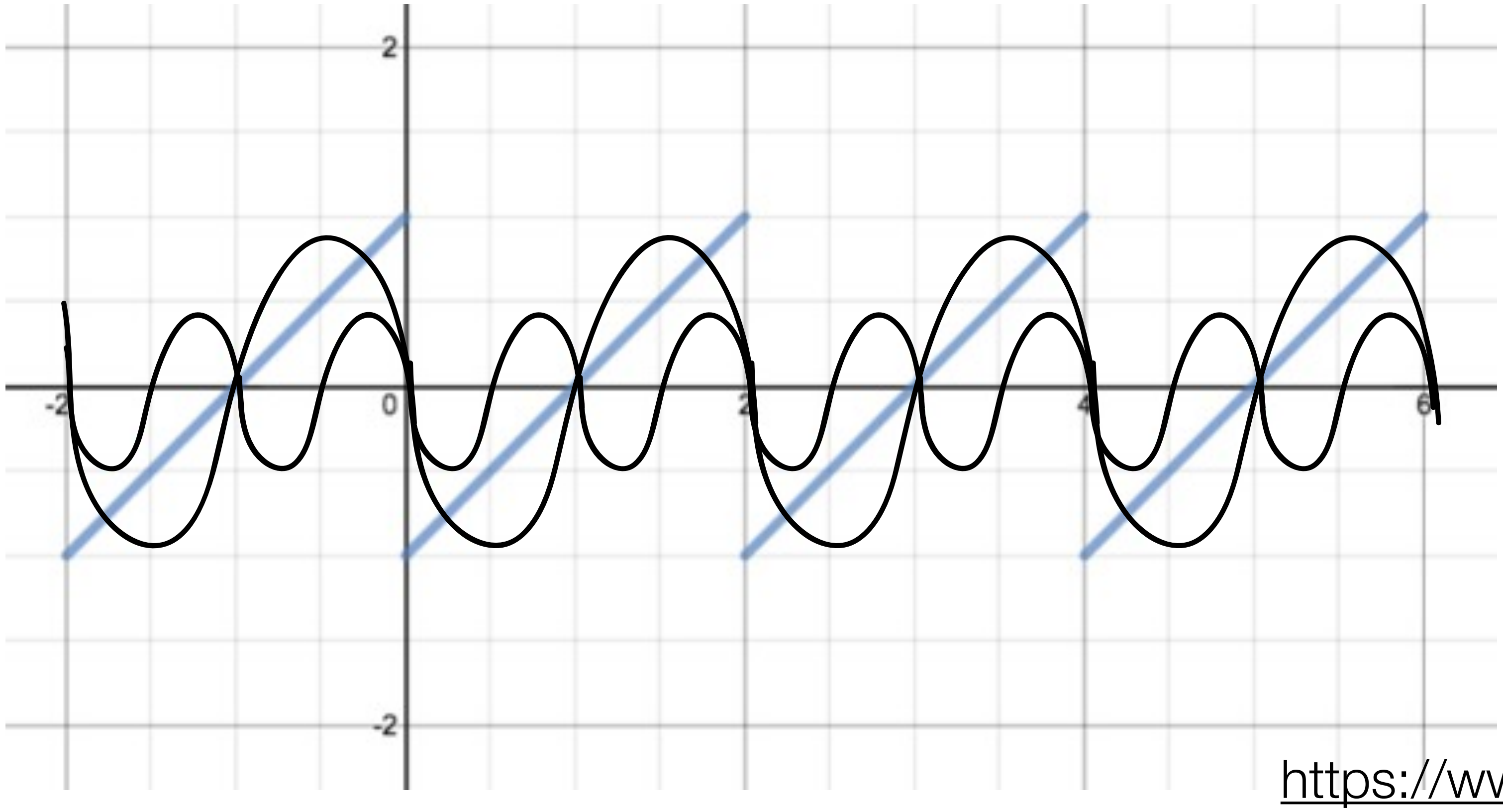

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Fourier series

- For the equation

$$y'' + 10y = \cos(t) + \frac{1}{2}\cos(2t) + \frac{1}{3}\cos(3t) + \frac{1}{4}\cos(4t) + \cdots$$

- what will be the dominant frequency (largest coefficient) in the solution?

(A) w = 1

(B) w = 2

(C) w = 3

(D) w = 4

(E) Don't know. Explain please.

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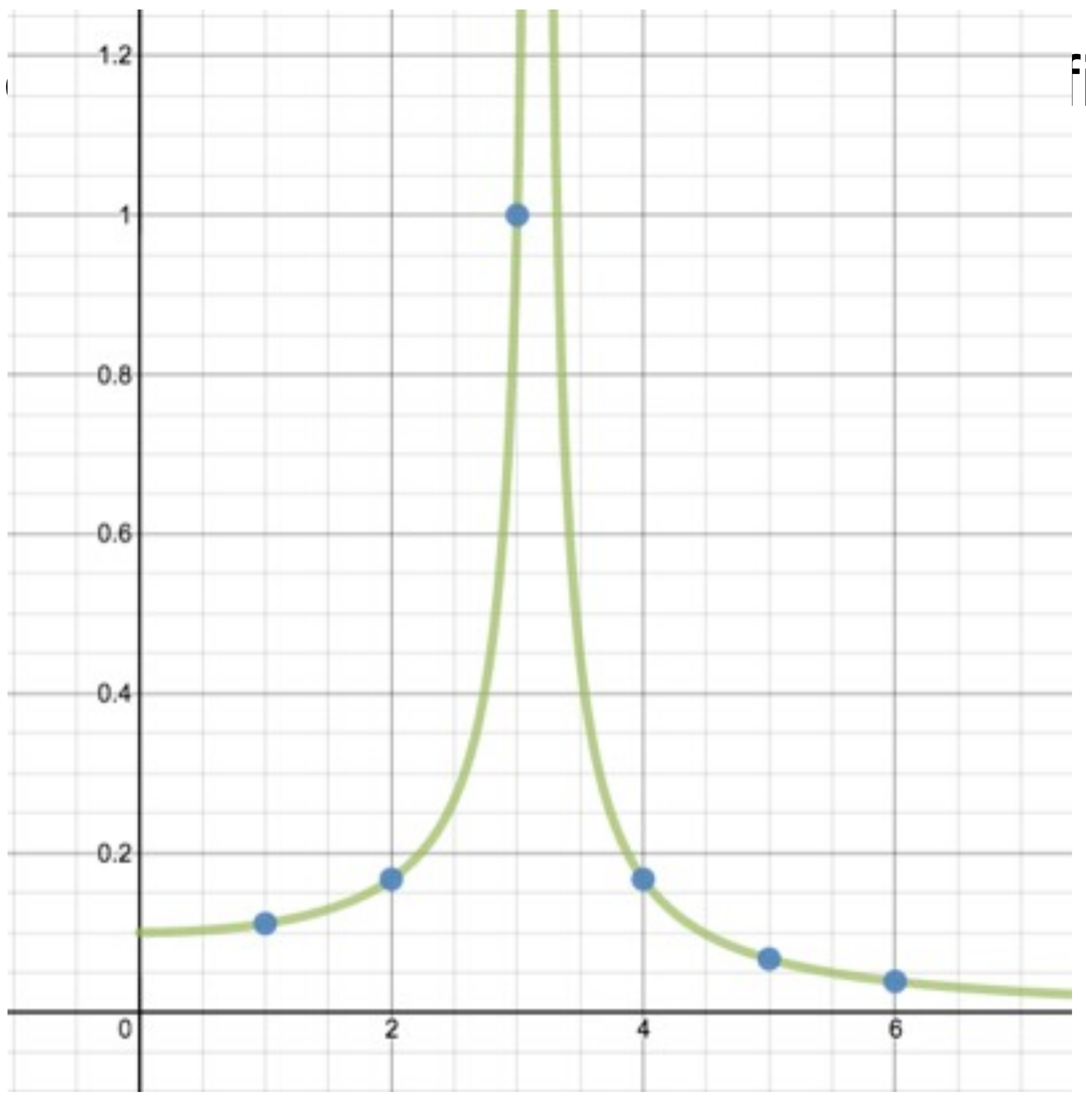

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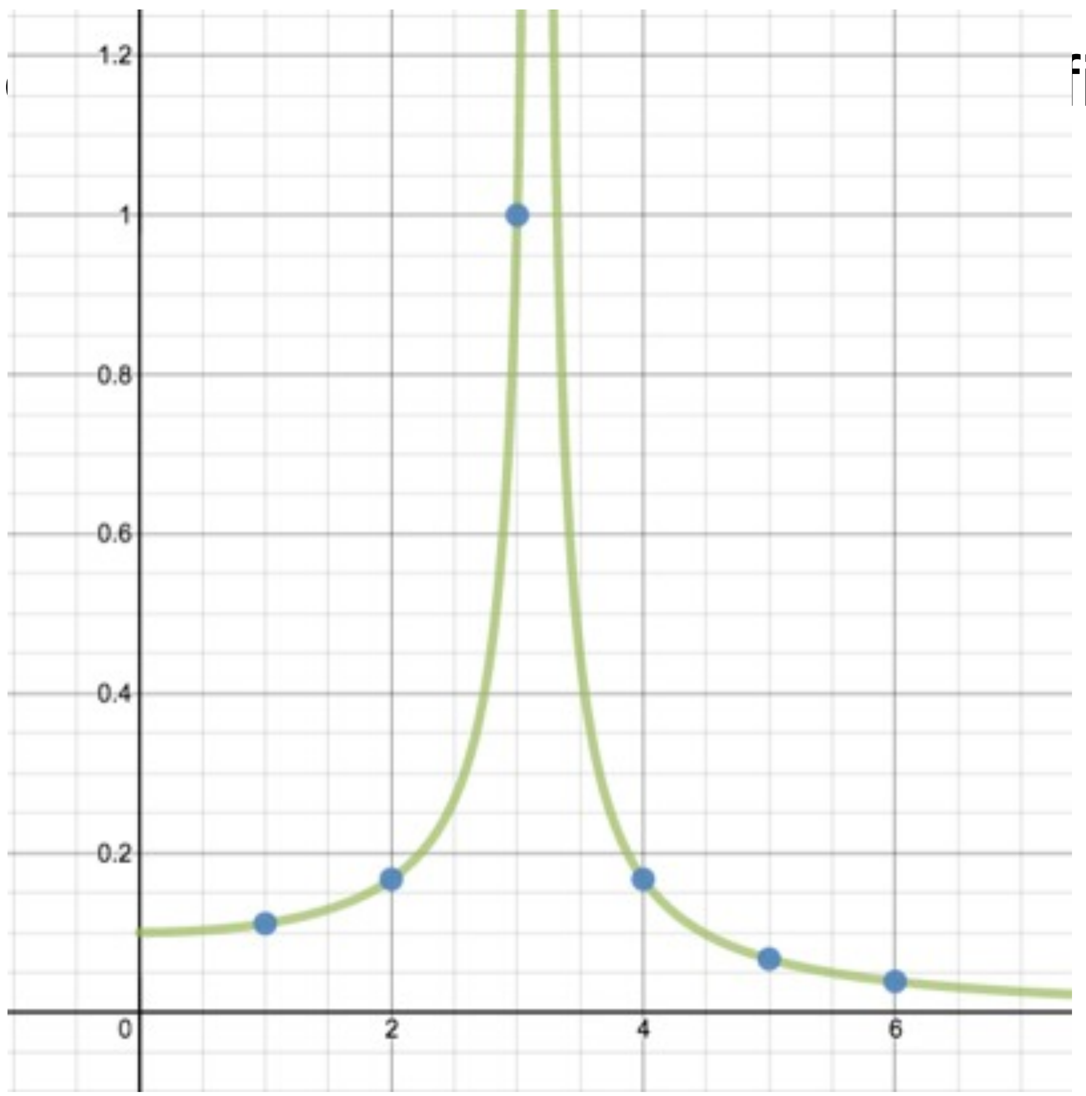

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