

XII. Wavelet Transform

Main References

- [1] R. C. Gonzalez and R. E. Woods, *Digital Image Processing*, Chap. 7, 4th edition, Prentice Hall, New Jersey, 2017. (適合初學者閱讀)

- [2] S. Mallat, *A Wavelet Tour of Signal Processing*, Academic Press, 3rd edition, 2009. (適合想深入研究的人閱讀)
(若對時頻分析已經有足夠的概念，可以由這本書 Chapter 4 開始閱讀)

- [3] I. Daubechies, “Orthonormal bases of compactly supported wavelets,” *Comm. Pure Appl. Math.*, vol. 41, pp. 909-996, Nov. 1988.
- [4] S. Mallat, “Multiresolution approximations and wavelet orthonormal bases of $L^2(\mathbb{R})$,” *Trans. Amer. Math. Soc.*, vol. 315, pp. 69-87, Sept. 1989.
- [5] C. Heil and D. Walnut, “Continuous and discrete wavelet transforms,” *SIAM Rev.*, vol. 31, pp. 628-666, 1989.
- [6] I. Daubechies, “The wavelet transform, time-frequency localization and signal analysis,” *IEEE Trans. Information Theory*, pp. 961-1005, Sept. 1990.
- [7] R. K. Young, *Wavelet Theory and Its Applications*, Kluwer Academic Pub., Boston, 1995.
- [8] S. Qian and D. Chen, *Joint Time-Frequency Analysis: Methods and Applications*, Chapter 4, Prentice-Hall, New Jersey, 1996.
- [9] L. Debnath, *Wavelet Transforms and Time-Frequency Signal Analysis*, Birkhäuser, Boston, 2001.
- [10] B. E. Usevitch, “A Tutorial on Modern Lossy Wavelet Image Compression: Foundations of JPEG 2000,” *IEEE Signal Processing Magazine*, vol. 18, pp. 22-35, Sept. 2001.
- [11] A. Kirsanov, “Wavelets: A mathematical microscope,” 影片：
<https://www.youtube.com/watch?v=jnxqHcObNK4>

(1) Conventional method for signal analysis

- Fourier transform : $X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi f t} dt$
- Cosine and Sine transforms: if $x(t)$ is even and odd
- Orthogonal Polynomial Expansion

傳統方法共通的問題：

(2) Time frequency analysis

例如，STFT

$$X(t, f) = \int_{-\infty}^{\infty} w(t - \tau) x(\tau) e^{-j2\pi f \tau} d\tau$$

Time frequency analysis 共通的問題：

12-A Haar Transform

一種最簡單又可以反應 time-variant spectrum 的 signal representation

8-point Haar transform

$$H[m,n] = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix}$$

8-point Haar transform

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \\ y_8 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{bmatrix}$$

 y_1 : low frequency component $y_2 \sim y_8$: high frequency component

$$y_1 = x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8$$

$$y_2 = x_1 + x_2 + x_3 + x_4 - x_5 - x_6 - x_7 - x_8$$

$$y_3 = x_1 + x_2 - x_3 - x_4$$

$$y_4 = x_5 + x_6 - x_7 - x_8$$

$$y_5 = x_1 - x_2$$

$N=2$

$$\mathbf{H}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

 $N=4$

$$\mathbf{H}_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$

 $N=8$

$$\mathbf{H}_8 = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 \\ 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix}$$

General way to generate the Haar transform:

$$\mathbf{H}_{2N} = \begin{bmatrix} \mathbf{H}_N \otimes [1, 1] \\ \mathbf{I}_N \otimes [1, -1] \end{bmatrix}$$

where \otimes means the Kronecker product

$$\mathbf{I}_N = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix}$$

$$\mathbf{A} \otimes \mathbf{B} = \begin{bmatrix} a_{1,1}\mathbf{B} & a_{1,2}\mathbf{B} & \cdots & a_{1,N}\mathbf{B} \\ a_{2,1}\mathbf{B} & a_{2,2}\mathbf{B} & \cdots & a_{2,N}\mathbf{B} \\ \vdots & \vdots & \ddots & \vdots \\ a_{M,1}\mathbf{B} & a_{M,2}\mathbf{B} & \cdots & a_{M,N}\mathbf{B} \end{bmatrix}$$

where

$$\mathbf{A} = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,N} \\ a_{2,1} & a_{2,2} & \cdots & a_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ a_{M,1} & a_{M,2} & \cdots & a_{M,N} \end{bmatrix}$$

$N = 2^k$ 時

$$\mathbf{H} = \begin{bmatrix} \phi \\ h_{0,1} \\ h_{1,1} \\ h_{1,2} \\ \vdots \\ \vdots \\ h_{k-1,1} \\ h_{k-1,2} \\ \vdots \\ h_{k-1,2^{k-1}} \end{bmatrix}$$

\mathbf{H} 除了第 1 個row 為 $\phi = \underbrace{[1 \ 1 \ 1 \ \cdots \ 1]}_{N \text{ 個 } 1}$ 以外
 第 $2^p + q$ 個row 為 $h_{p,q}[n]$
 $p = 0, 1, \dots, k-1, \quad q = 1, 2, \dots, 2^p$
 $k = \log_2 N$
 $h_{p,q}[n] = 1 \quad \text{when } (q-1)2^{k-p} < n \leq (q-1/2)2^{k-p}$
 $h_{p,q}[n] = -1 \quad \text{when } (q-1/2)2^{k-p} < n \leq q2^{k-p}$

- Inverse 2^k -point Haar Transform

$$\mathbf{H}^{-1} = \mathbf{H}^T \mathbf{D}$$

$$D[m, n] = 0 \text{ if } m \neq n$$

$$D[1, 1] = 2^{-k}, D[2, 2] = 2^{-k},$$

$$D[n, n] = 2^{-k+p} \text{ if } 2^p < n \leq 2^{p+1}$$

When $k = 3$,

$$\mathbf{D} = \begin{bmatrix} 1/8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/8 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1/2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/2 \end{bmatrix}$$

- (1) No multiplications
- (2) Input 和 Output 點數相同
- (3) 頻率只分兩種：低頻 (全為 1) 和高頻 (一半為 1，一半為 -1)
- (4) 可以分析一個信號的 localized feature
- (5) Very fast, but not accurate

Example:

$$\mathbf{H} \begin{bmatrix} 1.2 \\ 1.2 \\ 1.8 \\ 0.8 \\ 2 \\ 2 \\ 1.9 \\ 2.1 \end{bmatrix} = \begin{bmatrix} 13 \\ -3 \\ -0.2 \\ 0 \\ 0 \\ 1 \\ 0 \\ -0.2 \end{bmatrix}$$

Transforms	Running Time	terms required for NRMSE < 10^{-5}
DFT	9.5 sec	43
Haar Transform	0.3 sec	128

References

- A. Haar, “Zur theorie der orthogonalen funktionensysteme ,” *Math. Annal.*, vol. 69, pp. 331-371, 1910.
- H. F. Harmuth, *Transmission of Information by Orthogonal Functions*, Springer-Verlag, New York, 1972.

The Haar Transform is closely related to the Wavelet transform (especially the discrete wavelet transform).

12-C History of the Wavelet Transform

- 1910, Haar families.
- 1981, Morlet, wavelet concept.
- 1984, Morlet and Grossman, "wavelet".
- 1985, Meyer, "orthogonal wavelet".
- 1987, International conference in France.
- 1988, Mallat and Meyer, multiresolution.
- 1988, Daubechies, compact support orthogonal wavelet.
- 1989, Mallat, fast wavelet transform.
- 1990s, Discrete wavelet transforms
- 1999, Directional wavelet transform
- 2000, JPEG 2000

12-D Three Types of Wavelets

Wavelet 以 continuous / discrete 來分，有 3 種

	Input	Output	Name
Type 1	Continuous	Continuous	Continuous Wavelet Transform
Type 2	Continuous	Discrete	有時被稱為 discrete wavelet transform，但其實是 continuous wavelet transform with discrete coefficients
Type 3	Discrete	Discrete	Discrete Wavelet Transform

比較：Fourier
transform 有四種

12-E Continuous Wavelet Transform (WT)

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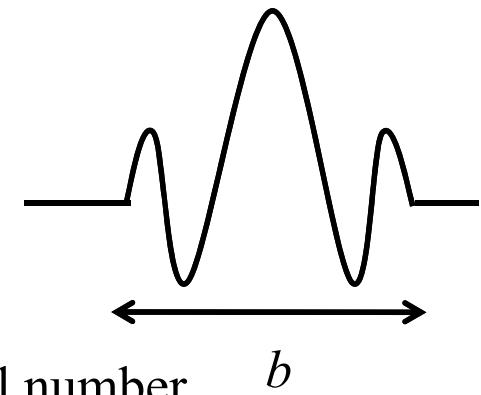
Definition: $X_w(a, b) = \frac{1}{\sqrt{b}} \int_{-\infty}^{\infty} x(t) \psi\left(\frac{t-a}{b}\right) dt$

$x(t)$: input, $\psi(t)$: mother wavelet

a : location, b : scaling

a is any real number, b is any positive real number

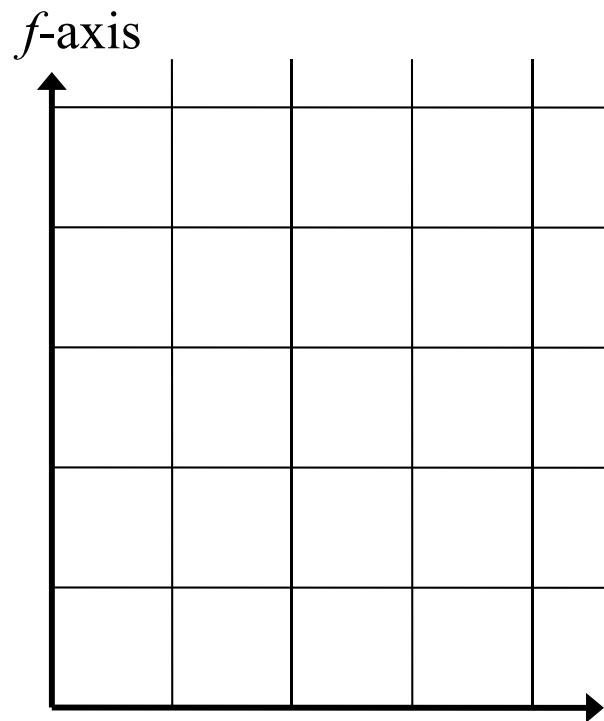
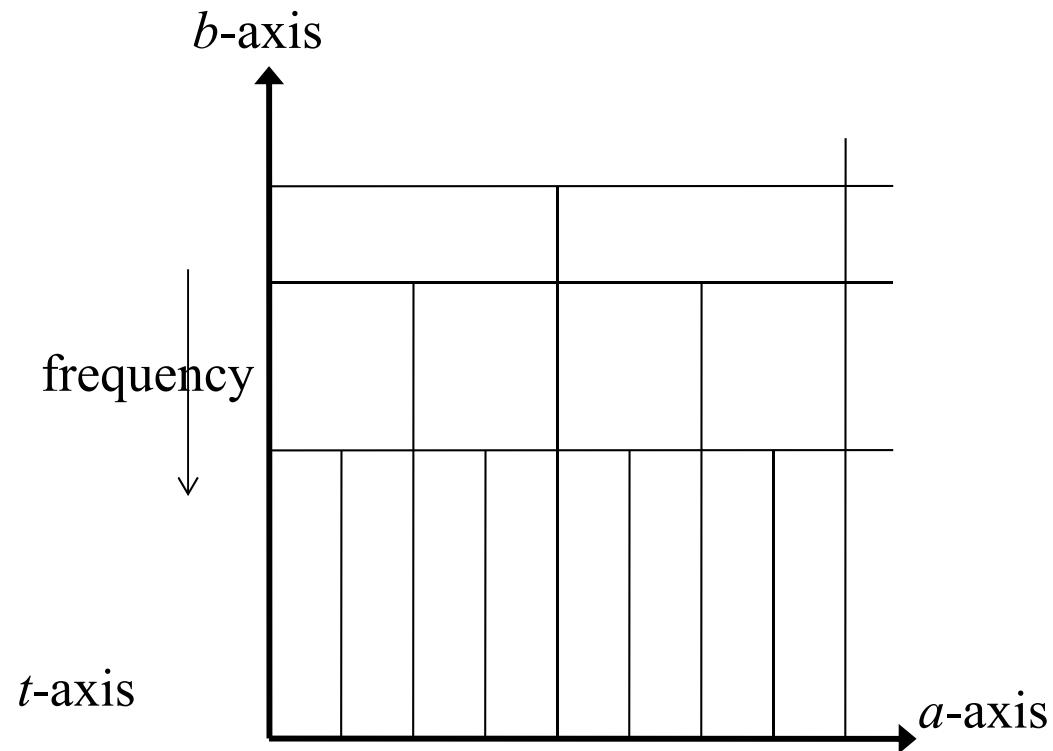
$a \in (-\infty, \infty)$, $b \in (0, \infty)$.



Compare with time-frequency analysis:

location + modulation

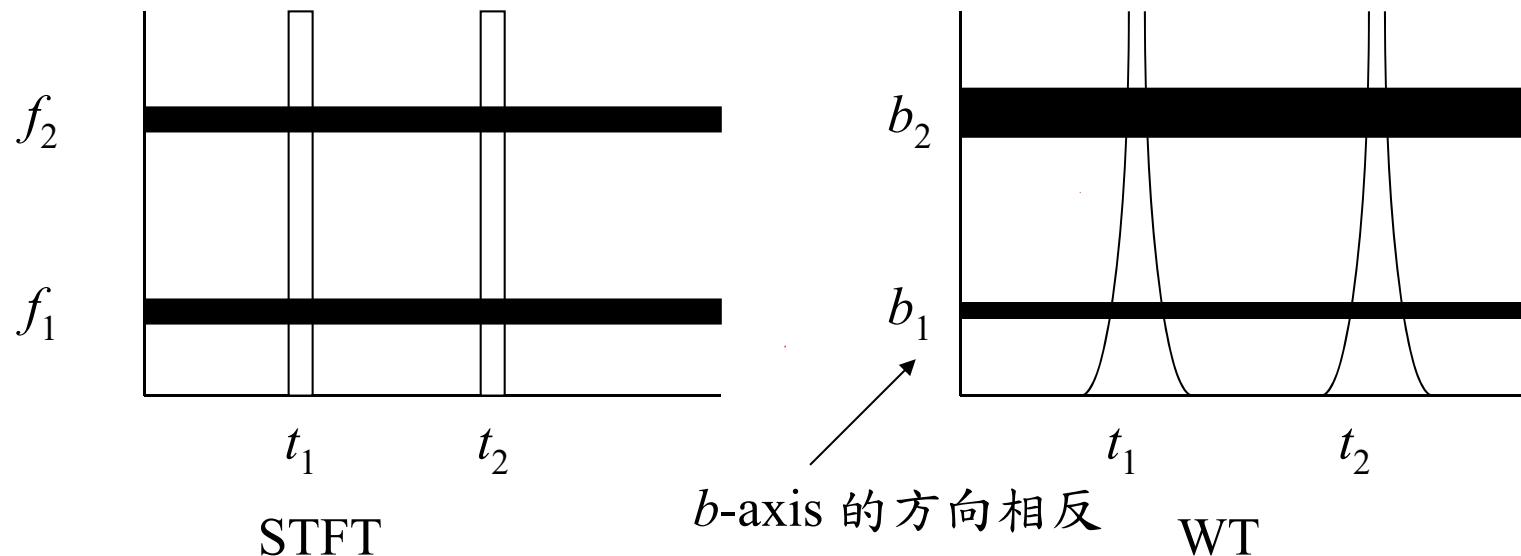
Gabor Transform $G_x(t, f) = \int_{-\infty}^{\infty} e^{-\pi(\tau-t)^2} e^{-j2\pi f\tau} x(\tau) d\tau$

Gabor**Wavelet transform**

$$X_w(a, b) = \frac{1}{\sqrt{b}} \int_{-\infty}^{\infty} x(t) \psi\left(\frac{t-a}{b}\right) dt \quad a: \text{location}, \ b: \text{scaling}$$

- The resolution of the wavelet transform is invariant along a (location-axis) but variant along b (scaling axis).

If $x(t) = \delta(t - t_1) + \delta(t - t_2) + \exp(j2\pi f_1 t) + \exp(j2\pi f_2 t)$,

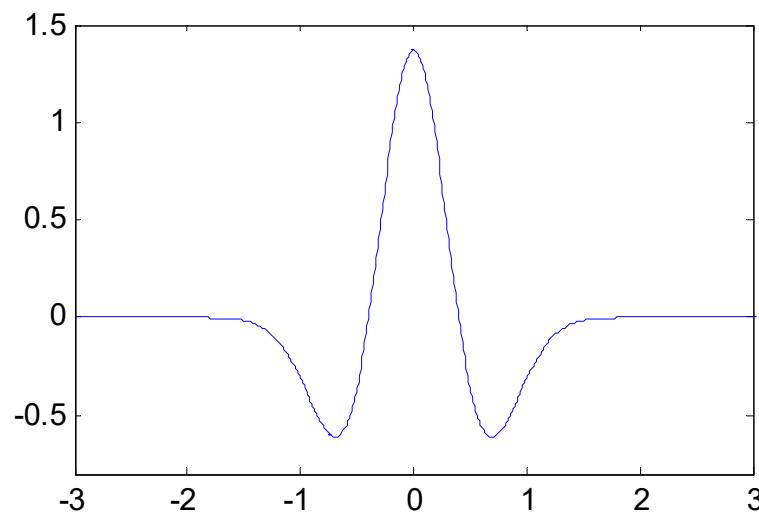


12-F Mother Wavelet

There are many ways to choose the mother wavelet. For example,

- Haar basis
- Mexican hat function $\psi(t) = \frac{2^{5/4}}{\sqrt{3}}(1 - 2\pi t^2)e^{-\pi t^2}$

In fact, the Mexican hat function is the 2nd order derivation of the Gaussian function.

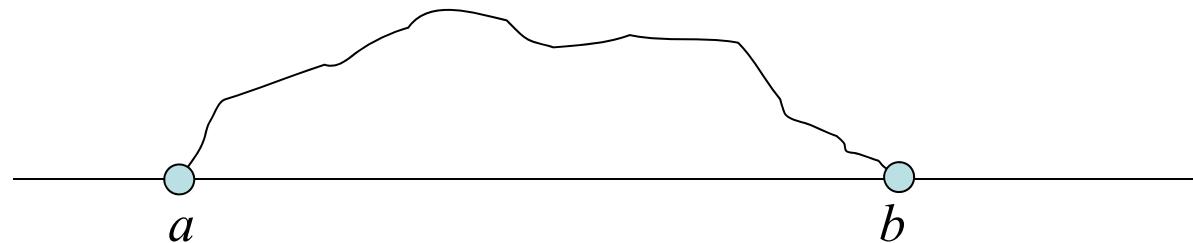


Constraints for the mother wavelet:

(1) Compact Support

support: the region where a function is not equal to zero

compact support: the width of the support is not infinite



(2) Real

(3) Even Symmetric or Odd Symmetric

(4) Vanishing Moments

$$k^{\text{th}} \text{ moment: } m_k = \int_{-\infty}^{\infty} t^k \psi(t) dt$$

If $m_0 = m_1 = m_2 = \dots = m_{p-1} = 0$, we say $\psi(t)$ has p vanishing moments.

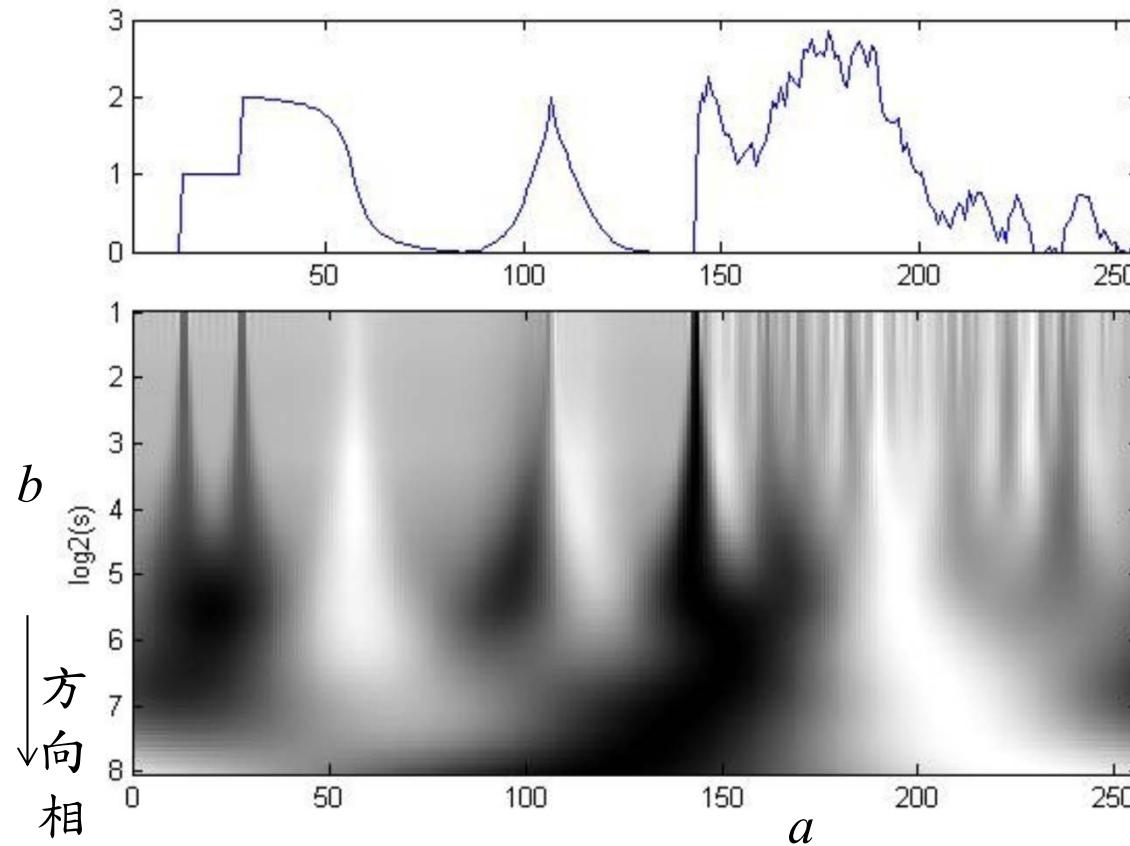
Vanishing moment 越高，經過內積後被濾掉的低頻成分越多

Question : 為什麼要求 $\int_{-\infty}^{\infty} \psi(t) dt = 0$?

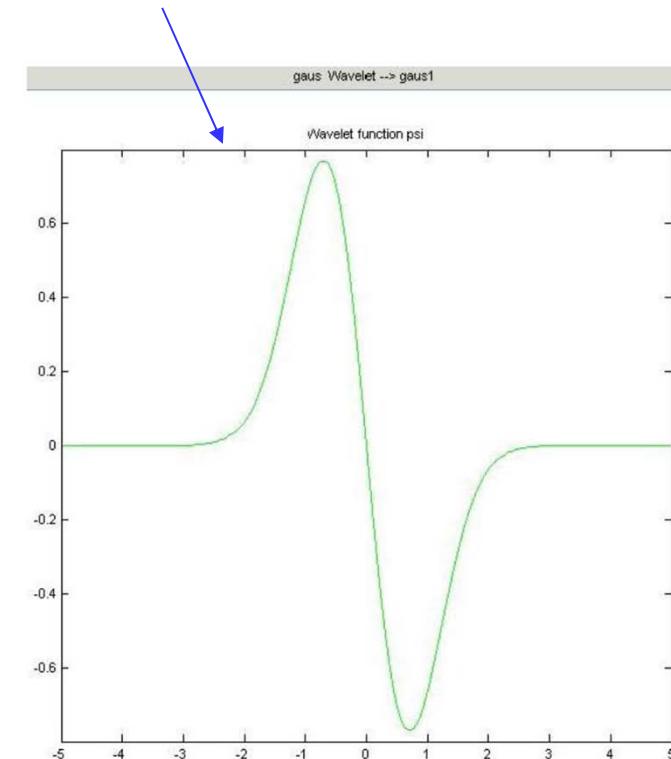
註：感謝 2006 年修課的張育思同學

the 1st order derivation of
the Gaussian function

vanishing moment = 1

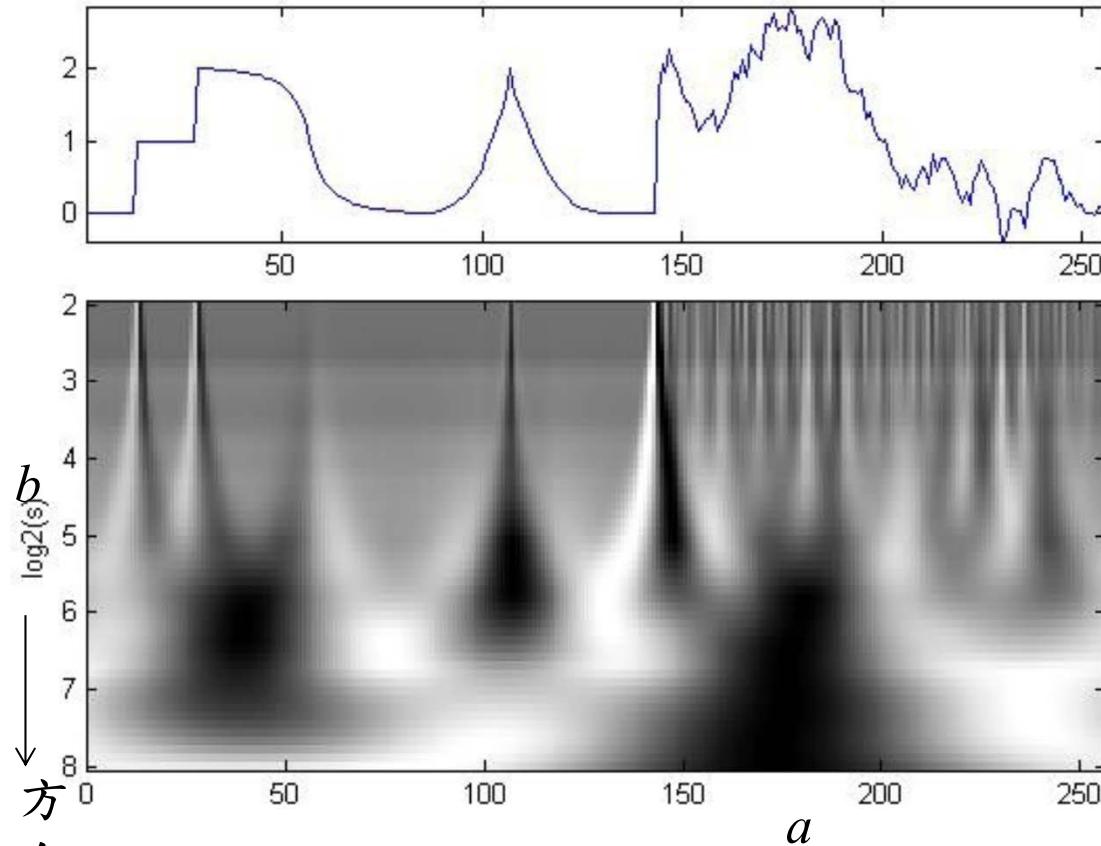


[Ref] S. Mallat, *A Wavelet Tour of Signal Processing*, 2nd Ed., Academic Press, San Diego, 1999.

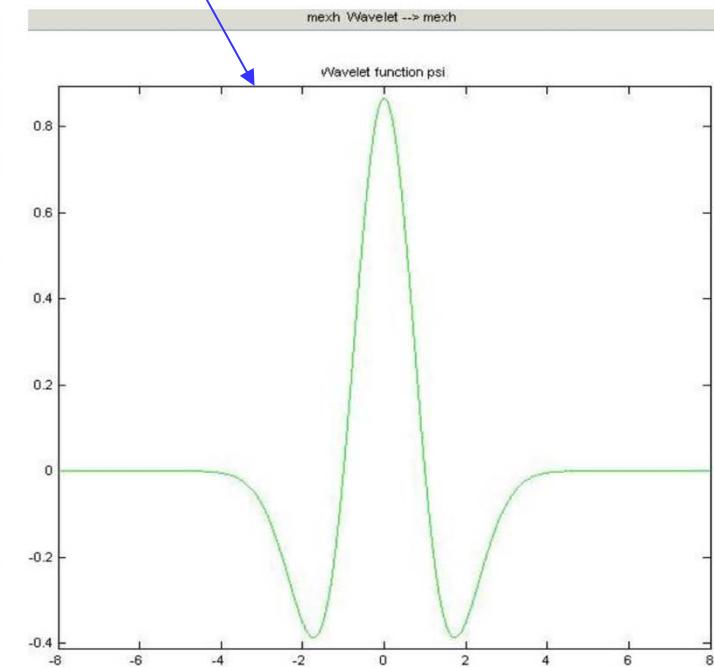


the 2nd order derivation of
the Gaussian function

vanishing moment = 2



方向相反



Similarly, when

$$\psi(t) = \frac{d^p}{dt^p} e^{-\pi t^2}$$

the vanishing moment is p

\

(5) Admissibility Criterion

$$C_\psi = \int_0^\infty \frac{|\Psi(f)|^2}{|f|} df < \infty, \text{ where } \Psi(f) \text{ is the Fourier transform of } \psi(t)$$

For reversible

[Ref] A. Grossman and J. Morlet, “Decomposition of hardy functions into square integrable wavelets of constant shape,” *SIAM J. Appl. Math.*, vol. 15, pp. 723-736, 1984.

$$x(t) = \frac{1}{C_\psi} \int_0^\infty \int_{-\infty}^\infty \frac{1}{b^{5/2}} X_w(a, b) \psi\left(\frac{t-a}{b}\right) da db$$

where $C_\psi = \int_0^\infty \frac{|\Psi(f)|^2}{|f|} df < \infty$

simplified $x(t) = \frac{1}{C_\psi} \int_0^\infty \int_{t-bt_0}^{t+bt_0} \frac{1}{b^{5/2}} X_w(a, b) \psi\left(\frac{t-a}{b}\right) da db$ if $\psi(t) \cong 0$ for $|t| > t_0$

(Proof): Since $X_w(a, b) = x(a) * \frac{1}{\sqrt{b}} \psi\left(\frac{-a}{b}\right)$

if $y(t) = \frac{1}{C_\psi} \int_0^\infty \int_{-\infty}^\infty \frac{1}{b^{5/2}} X_w(a, b) \psi\left(\frac{t-a}{b}\right) da db$

then $y(t) = \frac{1}{C_\psi} \int_0^\infty x(t) * \psi\left(\frac{-t}{b}\right) * \psi\left(\frac{t}{b}\right) \frac{db}{b^3}$

$$y(t) = \frac{1}{C_\psi} \int_0^\infty x(t) * \psi\left(\frac{-t}{b}\right) * \psi\left(\frac{t}{b}\right) \frac{db}{b^3}$$

$$Y(f) = \frac{1}{C_\psi} \int_0^\infty X(f) \Psi(-bf) \Psi(bf) \frac{db}{b} \quad \text{where} \quad \begin{aligned} Y(f) &= FT[y(t)] \\ X(f) &= FT[x(t)] \\ \Psi(f) &= FT[\psi(t)] \end{aligned}$$

If $\psi(t)$ is real, $\Psi(-f) = \Psi^*(f)$, $\Psi(-bf) \Psi(bf) = \Psi^*(bf) \Psi(bf) = |\Psi(bf)|^2$

$$\begin{aligned} Y(f) &= X(f) \frac{1}{C_\psi} \int_0^\infty |\Psi(bf)|^2 \frac{db}{b} \\ &= X(f) \frac{1}{C_\psi} \int_0^\infty |\Psi(f_1)|^2 \frac{df_1}{bf} \quad (f_1 = bf, df_1 = fdb) \\ &= X(f) \frac{1}{C_\psi} \int_0^\infty |\Psi(f_1)|^2 \frac{df_1}{f_1} \\ &= X(f) \end{aligned}$$

Therefore, $y(t) = x(t)$.

12-H Scaling Function

定義 scaling function 為

$$\phi(t) = \int_{-\infty}^{\infty} \Phi(f) e^{j2\pi f t} df$$

where $|\Phi(f)|^2 = \int_f^{\infty} \frac{|\Psi(f_1)|^2}{|f_1|} df_1$ for $f > 0$, $\Phi(-f) = \Phi^*(f)$

$\phi(t)$ is usually a lowpass filter (Why?)

修正型的 Wavelet transform

$$(1) \quad X_w(a, b) = \frac{1}{\sqrt{b}} \int_{-\infty}^{\infty} x(t) \psi\left(\frac{t-a}{b}\right) dt$$

a is any real number, $0 < b < b_0$

$$(2) \quad LX_w(a, b_0) = \frac{1}{\sqrt{b_0}} \int_{-\infty}^{\infty} x(t) \phi\left(\frac{t-a}{b_0}\right) dt$$

reconstruction:

$$x(t) = \frac{1}{C_\psi} \left[\int_0^{b_0} \int_{-\infty}^{\infty} \frac{1}{b^{5/2}} X_w(a, b) \psi\left(\frac{t-a}{b}\right) da db + \int_{-\infty}^{\infty} \frac{1}{b_0^{3/2}} LX_w(a, b_0) \phi\left(\frac{t-a}{b_0}\right) da \right]$$

由 b_0 至 ∞ 的積分被第二項取代

If $\psi(t) \approx 0$ for $|t| > t_0$, $\phi(t) \approx 0$ for $|t| > t_1$

$$x(t) \approx \frac{1}{C_\psi} \left[\int_0^{b_0} \int_{t-bt_0}^{t+bt_0} \frac{1}{b^{5/2}} X_w(a, b) \psi\left(\frac{t-a}{b}\right) da db + \int_{t-b_0t_1}^{t+b_0t_1} \frac{1}{b_0^{3/2}} LX_w(a, b_0) \phi\left(\frac{t-a}{b_0}\right) da \right]$$

$$(\text{Proof}): \text{If } y_1(t) = \frac{1}{C_\psi} \int_0^{b_0} \int_{-\infty}^{\infty} \frac{1}{b^{5/2}} X_w(a, b) \psi\left(\frac{t-a}{b}\right) da db$$

$$y_2(t) = \frac{1}{C_\psi} \int_{-\infty}^{\infty} \frac{1}{b_0^{3/2}} L X_w(a, b_0) \phi\left(\frac{t-a}{b_0}\right) da$$

$$Y_1(f) = X(f) \frac{1}{C_\psi} \int_0^{b_0} |\Psi(bf)|^2 \frac{db}{b}$$

$$= X(f) \frac{1}{C_\psi} \int_0^{b_0 f} |\Psi(f_1)|^2 \frac{df_1}{f_1}$$

(from the similar process on
pages 392 and 393)

$$y_2(t) = \frac{1}{b_0^2 C_\psi} x(t) * \phi\left(\frac{-t}{b_0}\right) * \phi\left(\frac{t}{b_0}\right)$$

$$Y_2(f) = X(f) \frac{1}{C_\psi} \Phi(-b_0 f) \Phi(b_0 f) = X(f) \frac{1}{C_\psi} \Phi^*(b_0 f) \Phi(b_0 f)$$

$$= X(f) \frac{1}{C_\psi} |\Phi(b_0 f)|^2$$

$$= X(f) \frac{1}{C_\psi} \int_{b_0 f}^{\infty} \frac{|\Psi(f_1)|^2}{|f_1|} df_1$$

關鍵

Therefore, if $y(t) = y_1(t) + y_2(t)$,

$$\begin{aligned}
 Y(f) &= Y_1(f) + Y_2(f) \\
 &= X(f) \frac{1}{C_\psi} \int_0^{b_0 f} |\Psi(f_1)|^2 \frac{df_1}{f_1} + X(f) \frac{1}{C_\psi} \int_{b_0 f}^\infty |\Psi(f_1)|^2 \frac{df_1}{f_1} \\
 &= X(f) \frac{1}{C_\psi} \int_0^\infty |\Psi(f_1)|^2 \frac{df_1}{f_1} \\
 &= X(f)
 \end{aligned}$$

$$y(t) = x(t)$$

- (1) real input \longrightarrow real output
- (2) If $x(t) \longrightarrow X_w(a, b)$, then $x(t - \tau) \longrightarrow X_w(a - \tau, b)$,
- (3) If $x(t) \longrightarrow X_w(a, b)$, then $x(t/\sigma) \longrightarrow \sqrt{\sigma}X_w(a/\sigma, b/\sigma)$
- (4) Parseval's Theory:

$$\int |x(t)|^2 dt = \frac{1}{C} \int_0^\infty \int_{-\infty}^\infty \frac{1}{b^2} |X_w(a, b)|^2 da db$$

12-J Scalogram

Scalogram 即 Wavelet transform 的絕對值平方

$$Sc_x(a, b) = |X_w(a, b)|^2 = \frac{1}{|b|} \left| \int_{-\infty}^{\infty} x(t) \psi\left(\frac{t-a}{b}\right) dt \right|^2$$

有時，會將 Scalogram 定義成

$$Sc_x(a, \zeta) = \left| X_w\left(a, \frac{\eta}{\zeta}\right) \right|^2$$

$$\eta = \frac{\int_0^{\infty} f |\Psi(f)|^2 df}{\int_0^{\infty} |\Psi(f)|^2 df}$$

$$\Psi(f) = \int_{-\infty}^{\infty} \psi(t) e^{-j2\pi f t} dt$$

12-K Problems

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Problems of the continuous WT

- (1) hard to implement
- (2) hard to find $\phi(t)$

Continuous WT is good in mathematics.

In practical, the discrete WT and the continuous WT with discrete coefficients are more useful.

附錄十二 電機 + 資訊領域的中研院院士

- 王兆振 (電子物理學家，1968年當選院士)
- 葛守仁 (電子電路理論奠基者之一，1976年當選院士)
- 朱經武 (超導體，1987年當選院士)
- 田炳耕 (微波放大器，1987年當選院士)
- 崔琦 (量子霍爾效應，1992年當選院士，1998年諾貝爾物理獎)
- 王佑曾 (資料庫管理理論先驅，1992年當選院士)
- 高錕 (光纖通訊，1992年當選院士，2009年諾貝爾物理獎)
- 方復 (半導體，1992年當選院士)
- 厲鼎毅 (光電科技，1994年當選院士)
- 湯仲良 (光電科技，1994年當選院士)
- 施敏 (Non-volatile semiconductor memory 發明者，手機四大發明者之一，1994年當選院士)
- 張俊彥 (半導體，1996年當選院士)
- 薩支唐 (MOS and CMOS，1998年當選院士)
- 林耕華 (光電科技，1998年當選院士)
- 劉兆漢 (跨領域，電機與地球科學，1998年當選院士)
- 虞華年 (微電子科技，2000年當選院士)
- 蔡振水 (光電與磁微波，2000年當選院士)

- 王文一 (奈米與應用物理，2002年當選院士)
- 胡正明 (微電子科技，2004年當選院士)
- 黃鍔 (Hilbert Huang Transform，2004年當選院士)
- 胡玲 (奈米科技，2004年當選院士)
- 李德財 (演算法設計，2004年當選院士)
- 劉必治 (多媒體信號處理，2006年當選院士)
- 莊炳湟 (語音信號處理，2006年當選院士)
- 黃煦濤 (圖形辨識，2006年當選院士)
- 舒維都 (信號處理與人工智慧，2006年當選院士)
- 李雄武 (電磁學，2006年當選院士)
- 孟懷榮 (無線通信與信號處理，2010年當選院士)
- 李澤元 (電力電子，2012年當選院士)
- 馬佐平 (微電子，2012年當選院士)
- 張懋中 (電子元件，2012年當選院士)
- 林本堅 (積體電路與傅氏光學，2014年當選院士)
- 陳陽闡 (高速半導體，2016年當選院士)
- 王康隆 (自旋電子學，2016年當選院士)
- 李琳山 (語音訊號處理，2016年當選院士)
- 戴聿昌 (微積電系統與醫工，2016年當選院士)

張世富 (多媒體信號處理，2018年當選院士)

盧志遠 (半導體技術，2018年當選院士)

吳詩聰 (光電技術，2022年當選院士)

郭宗杰 (多媒體信號處理，2022年當選院士)

陳自強 (半導體技術，2022年當選院士)

註：歷年中研院院士當中，屬於電機+資訊相關領域的有41人，佔了全部的 8 %

其中和通信、信號處理、影像處理相關的有10位，大多是2004年以後當選院士