Haar Basis Wavelets and Morlet Wavelets

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The Haar transform, which is one of the earliest transform functions proposed, was proposed in 1910 by a Hungarian mathematician Alfred Haar. It is found effective as it provides a simple approach for analyzing the local aspects of a signal.

Say we start with an image slice (one dimensional) of size $2^N$, so we can write the image as

$$I = \{I(1), I(2), \ldots, I(2^N)\} \quad \text{or} \quad \{I(i); \ i = 1, \ldots, 2^N\} \quad (1)$$

**Recursive Process of Decomposing an Image in terms of Sums and Differences**

Let us now group the image by consecutive pairs, i.e.,

$$\{I(i); \ i = 1, \ldots, 2^N\} \rightarrow \{[I(1), I(2)], [I(3), I(4)], \ldots, [I(2i-1), I(2i)], \ldots, [I(2^N), I(2^N-1)]\} \quad (2)$$

We can apply the following linear transformation for each pair $[I(2i-1), I(2i)]$, i.e.,

$$\begin{bmatrix} s^1(i) \\ d^1(i) \end{bmatrix} = H_2 \begin{bmatrix} I(2i-1) \\ I(2i) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} I(2i-1) \\ I(2i) \end{bmatrix} \quad (3)$$

So $s^1(i)$ stores the sum of the two elements in a pair and $d^1(i)$ stores the difference of the two elements in a pair. The upper index “1” refers to this transformation being the first step in a process that follows. Of course, this is invertible, i.e.,

$$\begin{bmatrix} I(2i-1) \\ I(2i) \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} s^1(i) \\ d^1(i) \end{bmatrix} \quad (4)$$

So we can get back the original set of pairs, the original image $\{I(i); \ i = 1, \ldots, 2^N\}$. Thus, we can represent the image $I$, of size $2^N$, as $2^{N-1}$ pairs of the form

$$I(i) \rightarrow \{[s^1(1), d^1(1)], [s^1(2), d^1(2)], \ldots, [s^1(i), d^1(i)], \ldots, [s^1(2^{N-1}), d^1(2^{N-1})]\} \quad (5)$$

We can then store the set $D^1 = \{d^1(1), d^1(2), \ldots, d^1(i), \ldots, d^1(2^{N-1})\}$ of size $2^{N-1}$ and we decompose further the complementary set

$$S^1 = \{s^1(1), s^1(2), \ldots, s^1(i), \ldots, s^1(2^{N-1})\} \quad (6)$$

We interpret $S^1$ as a new image of half the size of the original one and we represent the set of pairs
and we apply the reversible linear transformation $H_2$ to each pair $[s^1(2i-1), s^1(2i)]$, i.e.,

$$
\begin{bmatrix}
    s^2(i) \\
    d^2(i)
\end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} s^1(2i-1) \\ s^1(2i) \end{bmatrix}
$$

The upper index “2” refers to the second step in the process. We can then represent the “image” $S^1$, of size $2^{N-1}$, as

$$
S^1(i) \rightarrow \{[s^2(1), d^2(1)], [s^2(2), d^2(2)], ..., [s^2(i), d^2(i)], ..., [s^2(2^{N-2}), d^2(2^{N-2})]\}
$$

Likewise in the first step, we can store the set

$$
D^2 = \{d^2(1), d^2(2), ..., d^2(i), ..., d^2(2^{N-2})\}
$$

of size $2^{N-2}$ and decompose further the set

$$
S^2 = \{s^2(1), s^2(2), ..., s^2(i), ..., s^2(2^{N-1})\}
$$

The process can be illustrated for an image of size $2^4 = 16$ pixels as follows:

We now apply the third step of the process on the “image” set $S^2$, i.e., for each pair $[s^2(2i-1), s^2(2i)]$ we apply the linear transformation

$$
\begin{bmatrix}
    s^3(i) \\
    d^3(i)
\end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} s^2(2i-1) \\ s^2(2i) \end{bmatrix}
$$

Leading to two sets

$$
D^3 = \{d^3(1), d^3(2), ..., d^3(i), ..., d^3(2^{N-3})\} \quad ; \quad S^3 = \{s^3(1), s^3(2), ..., s^3(i), ..., s^3(2^{N-3})\}
$$

Up to the third layer of this process we are left with the following new representation for the image:
\( \{I(i); \ i = 1, \ldots, 2^N\} \iff \{D^1, D^2, D^3, S^3\} \) \hspace{1cm} (13)

where \( D^1 \) is of size \( 2^{N-1} \), \( D^2 \) of size \( 2^{N-2} \), and \( D^3, S^3 \) of sizes \( 2^{N-3} \) each. All together, of course, there are \( 2^N \) numbers. Every step is reversible, so we can quickly recover the image \( I \) from \( \{D^1, D^2, D^3, S^3\} \). We could repeat this process up to \( N \) steps to obtain \( \{D^1, D^2, \ldots, D^i, \ldots, D^N, S^N\} \), where \( S^N \) would be one number, representing the sum of all the image values.

**The Haar Transformation**

Reviewing our process, we started with equation (2), applying a linear transformation \( H_2 \) to each pair of data, or

\[
\begin{bmatrix}
    s^1(i) \\
    d^1(i)
\end{bmatrix} = H_2 \begin{bmatrix}
    I(2i - 1) \\
    I(2i)
\end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix}
    1 & 1 \\
    1 & -1
\end{bmatrix} \begin{bmatrix}
    I(2i - 1) \\
    I(2i)
\end{bmatrix} \tag{14}
\]

We then described the next step as the same linear transformation, \( H_2 \), applied to the “image” \( S^1 \) of the first layer, i.e., \( \begin{bmatrix}
    s^2(i) \\
    d^2(i) \\
    d^1(i) \\
    d^1(i + 1)
\end{bmatrix} = H_4 \begin{bmatrix}
    I(2^2 i - 3) \\
    I(2^2 i - 2) \\
    I(2^2 i - 1) \\
    I(2^2 i)
\end{bmatrix} = \frac{1}{\sqrt{4}} \begin{bmatrix}
    1 & 1 & 1 & 1 \\
    1 & 1 & -1 & -1 \\
    1 & -1 & 0 & 0 \\
    0 & 0 & 1 & -1
\end{bmatrix} \begin{bmatrix}
    I(2^2 i - 3) \\
    I(2^2 i - 2) \\
    I(2^2 i - 1) \\
    I(2^2 i)
\end{bmatrix} \tag{15}
\]

In this way, we keep simultaneously both layers (both steps) of the representation of the image. Repeating this process towards the third layer, we apply the linear transformation, \( H_2 \), to the “image” \( S^2 \) of the second layer, i.e., \( \begin{bmatrix}
    s^3(i) \\
    d^3(i)
\end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix}
    1 & 1 \\
    1 & -1
\end{bmatrix} \begin{bmatrix}
    s^2(2i - 1) \\
    s^2(2i)
\end{bmatrix} \). We can represent this third layer process as a linear transformation directly on each eight elements of the image (concatenating the three steps and concatenating four pairs of image data), i.e.,
More generally, one can write the linear transformation $H_{2i}$ that is applied to each image subset data of size $2^i$, to be

$$H_{2i} = I_l \otimes [1 \quad 1]$$

where $I_l$ is the identity matrix of size $i$ and $\otimes$ is the Kronecker product. If $A$ is an $m \times n$ matrix and $B$ is a $p \times q$ matrix, the Kronecker product is given by the $mp \times nq$ matrix

$$A \otimes B = \begin{bmatrix} a_{11}B & \ldots & a_{1n}B \\ \vdots & \vdots & \vdots \\ a_{m1}B & \ldots & a_{mn}B \end{bmatrix}$$

The output of applying $H_{2k}$ to the full set of image windows of size $2^k$ is a representation of the image in the form \{$D^1, D^2, \ldots, D^k, S^k$\}.

**The Haar Basis (the function approach)**

So far we have represented an image as a vector and the wavelet transformation as a matrix multiplication to the vector. We now consider the image as a function of the pixels. The wavelets are functions of the pixels. The result of applying the wavelet transform to the image is then described by the set of convolutions of two functions, the image and each of the wavelets. Let us be more precise. Defining the Haar wavelet basis as a mother wavelet and scaling it by $\sigma$ and translating it by $b$ we have
\[ \psi(x) = \begin{cases} 1 & 0 < x < \frac{1}{2} \\ -1 & \frac{1}{2} \leq x < 1 \\ 0 & \text{otherwise} \end{cases} \]

Scaling and Translating

\[ \psi_\sigma(x - b) = \frac{1}{\sqrt{\sigma}} \psi \left( \frac{x - b}{\sigma} \right) \]

Haar basis \( \psi(x) \)

Two wavelet properties are required: average is zero and normalization

\[ 0 = \int_{-\infty}^{\infty} \psi_\sigma(x - b) \, dx \quad \text{and} \quad 1 = \int_{-\infty}^{\infty} |\psi_\sigma(x - b)|^2 \, dx \]

If \( \psi(x) \) satisfy them, so thus\( \psi_\sigma(x - b) = \frac{1}{\sqrt{\sigma}} \psi \left( \frac{x - b}{\sigma} \right) \).

Examples with \( b=0 \), for discrete Wavelets (it is common to assign \( \sigma = 2^{-j} \))

\[ \sigma = 2^{-1} = \frac{1}{2} \quad \rightarrow \quad \psi_{1/2}(x) = \sqrt{2} \psi(2x) = \begin{cases} \sqrt{2} & 0 < 2x < \frac{1}{2} \quad \text{or} \quad 0 < x < \frac{1}{4} \\ -\sqrt{2} & \frac{1}{2} \leq 2x < 1 \quad \text{or} \quad \frac{1}{4} \leq x < \frac{1}{2} \\ 0 & \text{otherwise} \end{cases} \]
\[
\sigma = 2^1 = 2 \quad \rightarrow \quad \psi_2(x) = \frac{1}{\sqrt{2}} \psi \left( \frac{x}{2} \right) = \begin{cases} 
1/\sqrt{2} & 0 < \frac{x}{2} < \frac{1}{2} \quad \text{or} \quad 0 < x < 1 \\
-1/\sqrt{2} & \frac{1}{2} \leq \frac{x}{2} < 1 \quad \text{or} \quad 1 \leq x < 2 \\
0 & \text{otherwise}
\end{cases}
\]

\[
\sigma = 2^3 = 8 \quad \rightarrow \quad \psi_2(x) = \frac{1}{\sqrt{8}} \psi \left( \frac{x}{8} \right) = \begin{cases} 
1/\sqrt{8} & 0 < \frac{x}{8} < \frac{1}{2} \quad \text{or} \quad 0 < x < 4 \\
-1/\sqrt{8} & \frac{1}{2} \leq \frac{x}{8} < 1 \quad \text{or} \quad 4 \leq x < 8 \\
0 & \text{otherwise}
\end{cases}
\]

We can write a row associated to "d\(^j\)(i)" at (14), (15), (16) as the Haar basis convolution at \(x=0\), i.e., \(\psi_\sigma \ast I(x) = \int_{-\infty}^{\infty} \psi_\sigma(x') I(x-x') \, dx'\) for \(\sigma = 2^{-j}\), \(j = \ldots, -3, -2, -1, 0, 1, 2, 3, \ldots\), respectively (and \(b = 0\)).

The Haar wavelet transform is then the convolution

\[
W_\psi f(\sigma, b) = \int_{-\infty}^{\infty} \psi_\sigma^*(x-b) I(x) \, dx = \frac{1}{\sqrt{\sigma}} \int_{-\infty}^{\infty} \psi^* \left( \frac{x-b}{\sigma} \right) I(x) \, dx
\]

or in discrete coordinates

\[
W_\psi f(\sigma, b) = \frac{1}{\sqrt{\sigma}} \sum_{n=-\infty}^{\infty} \psi^* \left( \frac{x_n-b}{\sigma} \right) I(x_n)
\]

Where \(\psi_\sigma^*(x-b)\) is the complex conjugate of \(\psi_\sigma(x-b)\), and for the discrete case, \(\sigma = 2^{-j}\) is called the dyadic dilation and \(b = k \cdot 2^{-j}\) is the dyadic position. So the basis is described by integers \(j, k\).

**Complex Numbers**

A complex number \(z = x + i \, y\) has \(x\) and \(y\) real values and \(i = \sqrt{-1}\). It can be represented in polar coordinates representation as \(z = \rho \, e^{i \theta}\). The pair \((x, y)\) in Cartesian coordinates or the pair \((\rho, \theta)\) in polar coordinates are equivalent with \(\rho = \sqrt{x^2 + y^2}\) and \(\tan \theta = \frac{y}{x}\).
The Morlet Wavelet Basis in 1Dimension

\[ \psi^{1D}(x) = C_1 \left( e^{i \frac{2\pi}{\xi} x} - C_2 \right) e^{-\frac{x^2}{2}} \]

where \( e^{i \frac{2\pi}{\xi} x} = \cos\left(\frac{2\pi}{\xi} x\right) + i \sin\left(\frac{2\pi}{\xi} x\right) \) is a complex number, i.e., \( e^{i \frac{2\pi}{\xi} x} \) is written in polar coordinates \((\rho, \theta) = (1, \frac{2\pi}{\xi} x)\) while \( \cos\left(\frac{2\pi}{\xi} x\right) + i \sin\left(\frac{2\pi}{\xi} x\right) \) is written in Cartesian coordinates \((x, y) = \left(\cos\left(\frac{2\pi}{\xi} x\right), \sin\left(\frac{2\pi}{\xi} x\right)\right)\).

Calculating \(C_2\) and \(C_1\):

Two wavelet properties are required: average is zero and normalization

\[ 0 = \int_{-\infty}^{\infty} \psi(x) \, dx \quad \text{and} \quad 1 = \int_{-\infty}^{\infty} |\psi(x)|^2 \, dx \]

which allow us to obtain \(C_2\) and \(C_1\) as follows:

First, we obtain \(C_2\), real variable, by adjusting it so that

\[ 0 = \sum_{x=1}^{N_x} \psi(x) \rightarrow 0 = \sum_{x=1}^{N_x} \left( e^{i \frac{\pi}{2\xi} x} - C_2 \right) e^{-\frac{x^2}{2}} \rightarrow C_2 = \frac{\sum_{x=1}^{N_x} e^{i \frac{\pi}{2\xi} x} e^{-\frac{x^2}{2}}}{\sum_{x=1}^{N_x} e^{-\frac{x^2}{2}}} \]

and \(C_1\) is adjusted so that

\[ 1 = \sum_{x=1}^{N_x} \psi(x)\psi^*(x) \]
where \( \psi^*(x) = \frac{C_1}{\sigma} \left( e^{-i \frac{2\pi}{\xi} x} - C_2 \right) e^{-\frac{x^2}{2\sigma^2}} \) is the conjugate of \( \psi(x) \).

**Scaling and Translation**

The full orbit of the 1D Morlet wavelets (scaling and translating) is then

\[
\psi_{1D}(x) = \frac{1}{\sqrt{\sigma}} \psi_{1D}^D \left( \frac{x - x_0}{\sigma} \right) = \frac{C_1}{\sqrt{\sigma}} \left( e^{i \frac{2\pi}{\xi} \frac{(x-x_0)}{\sigma}} - C_2 \right) e^{-\frac{(x-x_0)^2}{2\sigma^2}}
\]

And we can plot the real and complex functions (e.g. for \( \sigma=6, \xi=4 \) centered in \( x_0=0 \) pixels)

**Convolution of Morlet Wavelet Basis in 1Dimension**

Convolving Morlet with a 1D image, I, of a step edge, i.e.,
where \((I * \psi^{1D}_\sigma)(y) = \sum_x I(y - x) \psi^{1D}_\sigma(x)\) is the complex value output shown above. The “zeros” of the real part help detect edges as well as the maximum of the complex part.

The Morlet Wavelets in 2Dimensions

The Morlet in 2D (two dimensions), assuming \(\sigma = \sigma_x = \sigma_y\), is defined as

\[
\psi_{\sigma, \theta}(u) = \frac{C_1}{\sigma} \left( e^{i \frac{2\pi}{\xi \sigma}(u \cdot e_\theta)} - C_2 \right) e^{-\frac{u^2}{2\sigma^2}}
\]

where \(u = (x, y), e_\theta = (\cos \theta, \sin \theta)\) and \(e^{i \frac{2\pi}{\xi \sigma}(u \cdot e_\theta)} = \cos \left[\frac{2\pi}{\xi \sigma}(u \cdot e_\theta)\right] + i \sin \left[\frac{2\pi}{\xi \sigma}(u \cdot e_\theta)\right].\) So \(u^2 = x^2 + y^2.\) Let us work with \(\xi = 4\) (just one peak), so

\[
\psi_{\sigma, \theta}(u) = \frac{C_1}{\sigma} \left( e^{i \frac{\pi}{2\sigma}(u \cdot e_\theta)} - C_2 \right) e^{-\frac{u^2}{2\sigma^2}}
\]

Two wavelet properties are required: average is zero and normalization

\[
0 = \int_{-\infty}^{\infty} \psi_\sigma(x - b) \, dx \quad \text{and} \quad 1 = \int_{-\infty}^{\infty} |\psi_\sigma(x - b)|^2 \, dx
\]

Which allow us to obtain \(C_2\) and \(C_1\) as follows:

First, we obtain \(C_2\), real variable, by adjusting it so that

\[
0 = \sum_x \sum_y \psi(\bar{u}) \rightarrow 0
\]

\[
= \sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \left( e^{i \frac{\pi}{2\sigma} (u \cdot e_\theta)} - C_2 \right) e^{-\frac{u^2}{2\sigma^2}} \rightarrow C_2 = \frac{\sum_{x=1}^{N_x} \sum_{y=1}^{N_y} e^{i \frac{\pi}{2\sigma} (u \cdot e_\theta)} e^{-\frac{u^2}{2\sigma^2} \sum_{x=1}^{N_x} \sum_{y=1}^{N_y} e^{-\frac{u^2}{2\sigma^2}}}}{\sum_{x=1}^{N_x} \sum_{y=1}^{N_y} e^{-\frac{u^2}{2\sigma^2}}}
\]

and \(C_1\) is adjusted so that

\[
1 = \sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \psi(\bar{u}) \psi^*(\bar{u})
\]

where \(\psi^*(\bar{u}) = \frac{C_1}{\sigma} \left( e^{-i \frac{2\pi}{\xi \sigma}(u \cdot e_\theta)} - C_2 \right) e^{-\frac{u^2}{2\sigma^2}}\) is the conjugate of \(\psi(\bar{u})\). So

\[
Z = \sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \left( e^{i \frac{\pi}{2\sigma} (u \cdot e_\theta)} - C_2 \right) e^{-\frac{u^2}{2\sigma^2}} \left( e^{-i \frac{\pi}{2\sigma} (u \cdot e_\theta)} - C_2 \right) e^{-\frac{u^2}{2\sigma^2}} \rightarrow C_1 = \frac{1}{\sqrt{Z}}
\]
\[ Z = \sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \left( 1 - C_2 \left( e^{-i \frac{\pi}{2\sigma} (u \cdot e_\theta)} + e^{i \frac{\pi}{2\sigma} (u \cdot e_\theta)} \right) + C_2^2 \right) e^{-\frac{u^2}{\sigma^2}} \]

\[ Z = \sum_{x=1}^{N_x} \sum_{y=1}^{N_y} \left( 1 - 2 C_2 \cos \left( \frac{\pi}{2\sigma} (u \cdot e_\theta) \right) + C_2^2 \right) e^{-\frac{u^2}{\sigma^2}} \rightarrow C_1 = \frac{1}{\sqrt{Z}} \]