Technische Universität München
Lehrstuhl für Informatik V
Univ.-Prof. Dr. M. Bader
M.Sc. J.-M. Gallard, M.Sc. M. Obersteiner

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Worksheet 8
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Algorithms of Scientific Computing (Algorithmen des Wissenschaftlichen Rechnens)

Haar Wavelets

The wavelet families we look at (e.g. Haar wavelets) are constructed around a *mulitresolution analysis*, a nested sequence V_n of function spaces some of which properties are

$$\begin{aligned} V_j &\subset V_{j+1},\ j\in\mathbb{Z} && (1)\\ \bigcap_{j=-\infty}^{\infty} V_j &= \{0\} && (2)\\ f(t)\in V_l &\Leftrightarrow f(2^{-l}t)\in V_0 && (3)\\ V_l &= V_{l-1}\oplus W_{l-1}\\ &= V_{l-2}\oplus W_{l-2}\oplus W_{l-1}\\ &= V_0\oplus W_0\oplus W_1\oplus\cdots\oplus W_{l-1}, && (4)\end{aligned}$$

with *orthogonal* functions $f\in V_j$ and $g\in W_j$, i.e. $< f,g >= 0$.
The theory of multiresolution analysis further states the existence of a unique function ϕ which satisfies a so-called *dilation equation* of the form

$$\phi(t)=\sum_{k\in\mathbb{Z}} c_k\cdot\phi(2t-k) \qquad (5)$$

for coefficients c_k with $c_k\neq 0$ for $k\in[0,N]$ and $c_k=0$ for every $k\notin[0,N]$.

Define another function, known as the **mother wavelet** or the **wavelet function** of the form

$$\psi(t):=\sum_{k\in\mathbb{Z}}(-1)^k c_{1-k}\cdot\phi(2t-k). \qquad (6)$$

In case N is odd, i.e. we have a even number of coefficients that are not zero, the c_{1-k} changes to c_{N-k}!

With the help of ϕ and ψ, we can define *orthonormal nodal bases* $\{\ \phi_{l,k}\ \}$ for V_l with

$$\begin{aligned}\phi_{l,k}(t) &= \phi(2^l\,t-k)\\ span\{\ \phi_{l,k}\ \} &= V_l,\ <\phi_{l,k},\phi_{l,m}>=\delta_{k,m}\ \ k,m\in\mathbb{Z}. && (7)\end{aligned}$$

The function ϕ is called **father wavelet** or the **scaling function**, and together with a **mother wavelet** ψ, they define the wavelet family. It is not necessary to know a specific formula for ϕ, the dilation equation (5) with its coefficients c_k together with the theory of multiresolution analysis provide enough information to derive the mother wavelet ψ as well as *orthonormal wavelet bases* $\{\ \psi_{l,m}\ \}$ for the W_l with

$$\begin{aligned} \psi_{l,k}(t) &= \psi(2^l\, t - k) \\ span\{\ \psi_{l,k}\ \} &= W_l,\ <\psi_{l,k}, \psi_{l,m}> = \delta_{k,m}\ \ k,m \in \mathbb{Z}. \end{aligned} \tag{8}$$

Excercise 1: Cranking the Machine

Typically the scaling function ϕ is not known explicitly, and sometimes a closed-form analytic formula does not even exist. However, for continuous ϕ we can approximate the function to arbitrarily high precision using the "Cascade Algorithm", a fixed-point method for functions.

In this exercise we want to implement this algorithm by iterating over the expression

$$F(\gamma)(t) = \sum_k c_k \cdot \gamma(2t - k) \tag{9}$$

in order to find the fixed point γ of F. That is, at iteration n

$$\gamma_{n+1}(t) = \sum_k c_k \cdot \gamma_n(2t - k) \tag{10}$$

Our starting point γ_0 will be the hat function

$$\gamma_0(t) = \max\{1 - |x|, 0\}. \tag{11}$$

(i) Over the interval $[-1,4]$ plot the approximations of the scaling function ϕ for the Haar wavelet family obtained in the first 7 iterations of the cascade algorithm. Do so by plugging the refinements coefficients $c_k,\ k = 0,1$ in (12) into (9) resp. (5).

$$c_0 = c_1 = 1 \tag{12}$$

(ii) Over the interval $[-1,4]$ plot the approximations of the scaling function ϕ for the Daubechies wavelet family obtained in the first 7 iterations of the cascade algorithm. Do so by plugging the refinements coefficients $c_k,\ k = 0,\dots,3$ in (13) into (9) resp. (5).

$$c_0 = \frac{1+\sqrt{3}}{4} \qquad c_1 = \frac{3+\sqrt{3}}{4} \qquad c_2 = \frac{3-\sqrt{3}}{4} \qquad c_3 = \frac{1-\sqrt{3}}{4} \tag{13}$$

Excercise 2: The Haar Wavelet Basis

We derive the *mother wavelet* ψ as well as *orthonormal wavelet bases* $\{\ \psi_{l,m}\ \}$ with

$$\begin{aligned} \psi_{l,k}(t) &= \psi(2^l\, t - k) \\ span\{\ \psi_{l,k}\ \} &= W_l,\ <\psi_{l,k}, \psi_{l,m}> = \delta_{k,m}\ \ k,m \in \mathbb{Z}. \end{aligned} \tag{14}$$

In this exercise we want to compute the 1-d wavelet transform for the Haar wavelet family and apply it to a signal vector $\vec{s}$ of length $m = 2^n$. The transform can be implemented very efficiently as a "pyramidal algorithm" taking $\mathcal{O}(m)$ steps. For educational purpose we focus on the $\mathcal{O}(m^2)$ matrix-based algorithm.

(i) Write a function that constructs the transformation matrix M consisting of the basis vectors $\psi_{l,k},\ l \leq n,\ 0 \leq k \leq 2^n - 1$.

(ii) Use Python's package *numpy.linalg* to invert the matrix.

(iii) Use the program to compute the transform $\vec{d} = M^{-1}\vec{s}$ as well as the reconstructed signal $\vec{s} = M\vec{d}$ of the vector

$$\vec{s} = [1, 2, 3, -1, 1, -4, -2, 4]^T$$

(iv) Verify the program's output tracing the steps by hand.

The following two exercises will be done by hand. Feel free to verify you results via a Python implementation.

Exercise 3: Discrete Wavelet Transform

Compute the DWT for the Haar wavelets for the signal $s = [8, 4, -1, 1, 0, 4, 1, 7, -\frac{5}{2}, -\frac{3}{2}, 0, -4, -2, -2, 1, -5]$ using the Pyramidal Algorithm. Discuss the computation complexity of this method.

Exercise 4: Discrete Wavelet Transform 2D

Compute the DWT for the Haar wavelets for the 2D signal $s = \begin{bmatrix} 4 & 2 & 3 & 5 \\ 1 & -7 & 0 & 8 \\ -1 & -3 & 9 & -3 \\ 6 & -2 & -1 & 1 \end{bmatrix}$.