

Wavelets and Applications

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Spring 2023

These are lecture notes from **APMA 1940Y: Wavelets and Applications** with Professor Mark Ainsworth at Brown University for the Spring 2023 semester. The most up-to-date version of the notes are maintained under my [GitHub repository](#).

These notes are taken by Mattie Ji with gracious help and input from the instructor of this course. If you find any mistakes in these notes, please feel free to direct them via email to me or send a pull request on GitHub.

The notes are last updated February 10, 2023.

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1 Lecture 1 - 1/25/2023

There's a limit of **18** people in this class, but there are only **14** seats...

1.1 Syllabus

- Instructor: Mark Ainsworth
- Best way to reach the instructor is by email
- Lectures are MWF from 10:00 am to 10:50 am
- Office hours are by appointment

The existential question every math major faces:

- Most of your math classes won't be useful in the real world - Professor Ainsworth used to study fluid mechanics in college, and it is VERY different from how they do it in industry... so why should you be studying mathematics?
- Well, mathematics studies things abstractly and allows us to solve problems faster. Even though engineers and physicists have a headstart, mathematicians can catch up really fast.
- But the interviewer won't stop you right there - they will ask you how your math degree helped you to accomplish this!
- This is the point of this class supposedly

This class is a WRIT class! So what is the WRIT component for - in the class, you will identify some applications of wavelets that interest you, and you will work a project on it and give a presentation on the selected topic in class. Professor Ainsworth will cover the theory part, and you will do the application part...

Certain applications of wavelets:

- The theory of Wavelets were all started in the 1990s.
- This is very important in the internet age! For instance, there's something called the **wavelet decomposition** of images that displays an image in finer and finer renditions. This is quite useful for data transmissions.
- You can use wavelets in seismic analysis
- A former student analyzed how to identify forgeries and watermarks in documents using wavelets
- Another student made a program that uses wavelets for music analysis
- Another student used wavelets for the stock market ... it didn't go too well

Wavelets are also really useful for theory!

- In Fourier Analysis (we will talk about this quite a bit), there's a certain defect with the subject we will exhibit that wavelets do not have.

Problem sets are due 7 days after the lecture it is assigned. You have to turn it before the **START** of the lecture, either in-person or electronically. You are supposed to work on your problem set yourself.

Lecture notes will not be handed out, unless you have a good reason to be absent. It's important to be able to take your own notes!

1.2 Time-Frequency Analysis

For the first 5 or 6 classes, we won't be knowing what a wavelet is! But we will try to build towards the subject. In order to do this, we will first show some other ways for signal analysis.

Definition 1.1. A signal is the set $\{f(t) : t \in \mathbb{R}\}$:

- Typically we will assume f is continuous, but they need not be.
- f could be either real-valued or complex-valued.

There are a few data associated to a signal:

- The **energy of signal** is

$$\|f\| := \left(\int_{-\infty}^{\infty} |f(t)|^2 dt \right)^{1/2}$$

This is pronounced “norm f”. Note this varies linearly with $|f(t)|$

- The **center of signal** is

$$t^* := \frac{\int_{-\infty}^{\infty} t \cdot |f(t)|^2 dt}{\int_{-\infty}^{\infty} |f(t)|^2 dt}$$

This roughly measures where f is most of the time. The denominator makes sure that the center is invariant up to scaling. Note that a symmetric signal has the signal at the line of symmetry.

- The **radius of signal** is

$$\Delta^2 := \frac{\int_{-\infty}^{\infty} (t - t^*)^2 |f(t)|^2 dt}{\int_{-\infty}^{\infty} |f(t)|^2 dt}$$

This is roughly a measure of how spread out a signal is, so we want the spread to be translation invariant! The denominator is again for scale invariance. The actual radius is Δ , not Δ^2 .

Remark 1.2. This has a lot of connections with probability and statistics! For example for any signal f , define

$$p(t) = \frac{|f(t)|^2}{\|f\|^2}$$

This is a probability distribution as

$$\int_{-\infty}^{\infty} p(t) dt = 1$$

The mean is exactly the center

$$\mu = \int_{-\infty}^{\infty} t p(t) dt = t^*$$

The variance is exactly the radius

$$\sigma^2 = \int_{-\infty}^{\infty} (t - \mu)^2 p(t) dt = \Delta^2$$

2 Lecture 2 - 1/27/2023

2.1 Time Frequency Analysis - Continued

Let's test our measures on an example:

Example 2.1. Define the signal $f(t)$ where

$$f(t) = \begin{cases} \frac{1}{2\epsilon}, & -\epsilon \leq t \leq \epsilon \\ 0, & \text{otherwise} \end{cases}$$

where $\epsilon > 0$. We note that as $\epsilon \rightarrow 0$, f is more localized. Hence,

$$\|f\|^2 = \int_{-\infty}^{\infty} |f(t)|^2 dt = \int_{-\epsilon}^{\epsilon} \left(\frac{1}{2\epsilon}\right)^2 dt = \frac{1}{2\epsilon} < \infty$$

$$t^* = \int_{-\epsilon}^{\epsilon} t \left(\frac{1}{2\epsilon}\right)^2 dt = 0$$

$$\Delta^2 = \frac{1}{\|f\|^2} \int_{-\infty}^{\infty} t^2 |f(t)|^2 dt = \int_{-\epsilon}^{\epsilon} t^2 \left(\frac{1}{2\epsilon}\right) dt = \frac{\epsilon^2}{3}$$

$$\Delta = \frac{\epsilon}{\sqrt{3}}$$

We note that as $\epsilon \rightarrow 0$, $\|f\|^2 \rightarrow \infty$, $t^* = 0$, and $\Delta \rightarrow 0$ is more localized. As $\epsilon \rightarrow \infty$, $\|f\|^2 \rightarrow 0$, $t^* = 0$, and $\Delta \rightarrow \infty$ is less localized.

Remark 2.2. The energy, center, radius, are really just integrals of $|f(t)|^2$ multiplied with t^0 , t^1 , and t^2 respectively (roughly). This is called the 0-th, 1-st, and 2-nd moments of the function. Suppose we try to generalize this to higher moments for all $n \in \mathbb{N}$, can we reconstruct the signal out of the moments?

It turns out that the set of polynomial functions are dense in the continuous functions from $[a, b]$ to \mathbb{R} (Stone-Weierstrass Theorem), but you can't uniformly approximate, for example, $e^x : \mathbb{R} \rightarrow \mathbb{R}$ using polynomials.

2.2 Fourier Transform

Given a signal f with finite energy, what can we do with f that tells us more information about it? Calculating all the moments is just unfeasible.

Let $\omega \in \mathbb{R}$, consider the term

$$e^{-i\omega t} f(t)$$

This term extracts the frequencies of $f(t)$, consider the function in terms of ω , $\hat{f}(\omega)$

$$\omega \mapsto \int_{-\infty}^{\infty} e^{-i\omega t} f(t) dt$$

Definition 2.3. The function $\omega \mapsto \hat{f}(\omega)$ is the **Fourier Transform** of f . This is a continuous version of Fourier Series we have dealt with before (plugging in integers to this function extracts our Fourier Coefficients).

Remark 2.4. There might be some issue with the integral not existing. Since this is an Applied Math class, all integrals exist...

Suppose we have what $\hat{f}(\omega)$ is for every ω , can we recover what f is?

Yes! This is the statement of the Fourier Inversion Theorem:

Theorem 2.5 (Fourier Inversion Theorem). Let $\hat{f}(\omega) = \int_{-\infty}^{\infty} e^{-i\omega t} f(t) dt$, then

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{+i\omega t} \hat{f}(\omega) d\omega$$

The transformation back is called the Fourier Inversion formula.

Heuristically, $\hat{f}(\omega)$ represents the frequencies of the signals, and $f(t)$ represents the time series of the signal.

Proposition 2.6 (Parseval Identity). Let $f(t), g(t) : \mathbb{R} \rightarrow \mathbb{C}$, then

$$\int_{-\infty}^{\infty} f(t) \overline{g(t)} dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{f}(\omega) \overline{\hat{g}(\omega)} d\omega$$

Proposition 2.7. $\hat{f}'(\omega) = i\omega \hat{f}(\omega)$ (For less confusion, this is Fourier transform of f')

Proof. Let $f(t), t \in \mathbb{R}$, consider $\hat{f}'(t)(\omega)$. Now recall that

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{+i\omega t} \hat{f}(\omega) d\omega$$

Taking the derivative on both sides, we have that

$$\begin{aligned} f'(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \frac{d}{dt} e^{+i\omega t} \hat{f}(\omega) d\omega \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} i\omega e^{+i\omega t} \hat{f}(\omega) d\omega \end{aligned}$$

Applying the Fourier Inversion Formula to $\hat{f}'(\omega)$, we can also write

$$f'(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{i\omega t} \hat{f}'(\omega) d\omega$$

But by the Fourier Inversion Formula, we have that

$$\frac{1}{2\pi} \int_{-\infty}^{\infty} e^{i\omega t} \hat{f}'(\omega) d\omega = f'(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{+i\omega t} i\omega \hat{f}(\omega) d\omega$$

Hence we have that

$$\hat{f}'(\omega) = i\omega \hat{f}(\omega)$$

■

Example 2.8. Suppose $f'(t) = g(t)$ where $t \in \mathbb{R}$ is in the time domain, hence we have that

$$\frac{df}{dt} = g(t)$$

What if we try to examine the frequency domain instead? Then consider taking the Fourier Transform on both sides:

$$\frac{\hat{df}}{dt}(\omega) = \hat{g}(\omega)$$

What is the Fourier Transform of a derivative? Well, we end up having that

$$i\omega \hat{f} = \hat{g}$$

Or equivalently we have

$$\hat{f}(\omega) = \frac{1}{i\omega} \hat{g}(\omega)$$

Computing the Fourier Inversion on both sides gives back our solution.

Remark 2.9. Lars Hörmander wrote a 5-volume book on PDES and dedicated Fourier Transformation to most of it.

3 Lecture 3 - 1/30/2023

Right now we have been going fairly slowly... Recall, so far, we have an underlying signal given either as

- (Time Domain Representation) - $\{f(t) : t \in \mathbb{R}\}$
- (Frequency Domain Representation) - $\{\hat{f}(\omega) : \omega \in \mathbb{R}\}$

These are essentially two sides of the same “coin” (the coin being the signal here).

In particular, we can convert time to frequency and backwards using the Fourier Transform:

$$\begin{aligned}\hat{f}(\omega) &:= \int_{-\infty}^{\infty} e^{-i\omega t} f(t) dt \\ f(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{+i\omega t} \hat{f}(\omega) d\omega\end{aligned}$$

We also have this **Parseval Identity** that gives

$$\int_{-\infty}^{\infty} f(t) \overline{g(t)} dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{f}(\omega) \overline{\hat{g}(\omega)} d\omega$$

Corollary 3.1. Choose $g = f$, then we have that

$$\|f\|^2 = \frac{1}{2\pi} \|\hat{f}\|^2$$

This gives a relationship between the energy of the signal and the L^2 norm of the frequency domain.

Example 3.2 (Frequency of the Step Function). Let $\epsilon > 0$ and define $f(t) = \begin{cases} \frac{1}{2\epsilon}, & t \in [-\epsilon, \epsilon] \\ 0, & \text{otherwise} \end{cases}$. What is $\hat{f}(\omega)$ in this case?

$$\begin{aligned}\hat{f}(\omega) &= \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt \\ &= \int_{-\epsilon}^{\epsilon} \frac{1}{2\epsilon} e^{-i\omega t} dt \\ &= \frac{-1}{2i\omega\epsilon} [e^{i\omega\epsilon} - e^{-i\omega\epsilon}] \\ &= \frac{1}{\omega\epsilon} \frac{e^{i\omega\epsilon} - e^{-i\omega\epsilon}}{2i} \\ &= \frac{\sin(\omega\epsilon)}{\omega\epsilon}, \quad \omega \in \mathbb{R} - \{0\}\end{aligned}$$

Note when $\omega = 0$, this approaches 1. Hence we have

$$\hat{f}(\omega) = \begin{cases} \frac{\sin(\omega\epsilon)}{\omega\epsilon}, & \omega \in \mathbb{R} - \{0\} \\ 1, & \omega = 0 \end{cases}$$

We note that while $f(t)$ is compactly supported in the time domain, its frequency IS NOT compactly supported in the frequency domain but it does decay as $\|\omega\epsilon\| \rightarrow \infty$.

Having a frequency of 0 means the signal's not changing at that ω . In the language of Electrical Engineering, this means there's a DC component at these roots.

$\hat{f}(\omega)$ is what's called a **sink function**! Someone wrote an entire book about how to use sink functions to approximate solutions to PDEs. The time function can be thought of as the linearly combination of all the frequencies (super-position).

We also make the following notes:

1. As $\epsilon \rightarrow 0$, $f(t)$ becomes more localized. In other words, its spread Δ is getting smaller.
2. As $\epsilon \rightarrow 0$, $\hat{f}(\omega)$ becomes less localized, its correspondent spread $\hat{\Delta}$ is getting larger.
3. In other words, the more you know about the time localizations, the less you know about the frequency localization, and vice versa.
4. As $\epsilon \rightarrow \infty$, $f(t)$ is less localized.
5. As $\epsilon \rightarrow \infty$, $\hat{f}(\omega)$ decays faster and faster, and becomes more localized.

This observation is in fact true in general, which leads us to our next section:

3.1 The Uncertainty Principle

Let $\{f(t) : t \in \mathbb{R}\}$ be real-valued and assume $|f(t)|$ and $|\hat{f}(\omega)|$ decay sufficiently fast that:

- $\|f\| < \infty$ (this implies $\|\hat{f}\|$ is finite)
- t^* (center of time domain) and ω^* (center of frequency domain) are well-defined.
- Δ and $\hat{\Delta}$ are well-defined.

You are not going to win a Field's Medal for proving these, but they do provide connections between the topics:

Proposition 3.3. If f is real-valued, then ω^* is ALWAYS 0.

Proof. Indeed we note that

$$\hat{f}(\omega) = \int_{-\infty}^{\infty} e^{-i\omega t} f(t) dt$$

Taking the complex conjugate and since $f(t)$ is real valued

$$\overline{\hat{f}(\omega)} = \int_{-\infty}^{\infty} e^{+i\omega t} f(t) dt = \hat{f}(-\omega)$$

Hence, we have that

$$|\hat{f}(\omega)|^2 = \hat{f}(\omega) \overline{\hat{f}(\omega)} = \hat{f}(\omega) \hat{f}(-\omega)$$

Hence the mapping $\omega \mapsto |\hat{f}(\omega)|^2$ is an even function. We know the average of an even function is just 0, hence

$$\omega^* \alpha \int_{-\infty}^{\infty} \omega |\hat{f}(\omega)|^2 d\omega = 0$$

■

But this result tells us that knowing $\omega^* = 0$ gives us very little information about what $f(t)$ is.

Question 3.4. What about $\hat{\Delta}$? Does this tell us anything?

Consider the following translation function of f

$$f_{\alpha}(t) := f(t - \alpha), t \in \mathbb{R}$$

Proposition 3.5. Let $\hat{f}_\alpha(\omega)$ denote the Fourier Transform of $f_\alpha(t)$, then

$$\hat{f}_\alpha(\omega) = e^{-i\omega\alpha} \hat{f}(\omega)$$

Proof. What is $\hat{f}_\alpha(\omega)$? Well

$$\begin{aligned} \hat{f}_\alpha(\omega) &= \int_{-\infty}^{\infty} e^{-i\omega t} f(t - \alpha) dt \\ &= \int_{-\infty}^{\infty} e^{-i\omega(s+\alpha)} f(s) ds && \text{Let } s = t - \alpha \\ &= e^{-i\omega\alpha} \int_{-\infty}^{\infty} e^{-i\omega s} f(s) ds \\ &= e^{-i\omega\alpha} \hat{f}(\omega) \end{aligned}$$

■

Thus, translation in the time domain corresponds to a phase shift (ie. some rotation) in the frequency domain!

Proposition 3.6. Let $\hat{\Delta}_\alpha^2$ be the spread of \hat{f}_α , then

$$\hat{\Delta}_\alpha^2 = \hat{\Delta}^2$$

In other words, shifting in the time domain has no effect on the spread of the frequency domain.

Proof. To compute $\hat{\Delta}_\alpha^2$, we have

$$\begin{aligned} \hat{\Delta}_\alpha^2 &= \int_{-\infty}^{\infty} (\omega - \omega^*)^2 |\hat{f}_\alpha(\omega)|^2 d\omega \\ &= \int_{-\infty}^{\infty} (\omega)^2 |\hat{f}_\alpha(\omega)|^2 d\omega \\ &= \int_{-\infty}^{\infty} (\omega)^2 |1| |\hat{f}(\omega)|^2 d\omega \\ &= \int_{-\infty}^{\infty} (\omega)^2 |\hat{f}(\omega)|^2 d\omega && e^{iat} \text{ has complex norm of 1} \\ &= \hat{\Delta}^2 \end{aligned}$$

■

$\hat{\Delta}_\alpha = \hat{\Delta}$ is true for all α ! So again, knowing $\hat{\Delta}$ tells us very little about the time domain. Knowing the mean and variance of the frequency domain tells us almost nothing about the time domain.

Remark 3.7. It turns out that there's a **fundamental limit** on what we can know about the time domain representation and the frequency domain representation simultaneously.

There is in fact a quantitative statement about this, let $f(t)$ be a function, then

$$\Delta_f \hat{\Delta}_f \geq \frac{1}{2}$$

This is known as the **Time-Frequency Uncertainty Principle**.

4 Lecture 4 - 2/1/2023

4.1 Cauchy-Schwarz For Integrals

Theorem 4.1 (Cauchy-Schwarz for Integrals). Let f, g be real-valued functions then

$$(f, g) \leq \|f\| \|g\|$$

where $(f, g) := \int f g$.

Proof. Let f, g be real-valued and let $\lambda \in \mathbb{R}$, then

$$0 \leq \int (f - \lambda g)^2$$

Or equivalently we have that

$$0 \leq \|f\|^2 - 2\lambda(f, g) + \lambda^2 \|g\|^2$$

This is really a quadratic equation in variable λ . Now choose λ to be the value that minimizes the expression $\|f\|^2 - 2\lambda(f, g) + \lambda^2 \|g\|^2$. In deed, this is achieved when

$$\lambda = \frac{(f, g)}{\|g\|^2}$$

So we have that

$$0 \leq \|f\|^2 - \frac{2(f, g)^2}{\|g\|^2} + \frac{(f, g)^2}{\|g\|^2}$$

Equivalently we have that

$$(f, g)^2 \leq \|f\|^2 \cdot \|g\|^2$$

■

4.2 Deriving the Time Frequency Uncertainty Principle

Theorem 4.2. Let f be real-valued signal (note the result still holds for complex valued signal), then

$$\Delta_f \hat{\Delta}_f \geq 1/2$$

Proof. If f doesn't decay fast enough, the inequality on the left side would be infinite. Otherwise, suppose f does decay fast enough, consider $\|f\|^2 = \int_{-\infty}^{\infty} |f(t)|^2 dt$. Let $u = |f(t)|^2$ and $dv = 1$, then $v = (t - t^*)$, and integration by parts gives

$$\begin{aligned} \|f\|^2 &= \int_{-\infty}^{\infty} |f(t)|^2 dt \\ &= [(t - t^*)|f(t)|^2]_{-\infty}^{\infty} - 2 \int_{-\infty}^{\infty} (t - t^*) f(t) f'(t) dt \end{aligned}$$

Since t^* is finite, then $(t - t^*)|f(t)|^2$ is integrable, so we have that the first term $[(t - t^*)|f(t)|^2]_{-\infty}^{\infty} = 0$. So we have that

$$\begin{aligned} \|f\|^2 &= \left| -2 \int_{-\infty}^{\infty} (t - t^*)f(t)f'(t)dt \right| \\ &\leq 2 \sqrt{\int_{-\infty}^{\infty} (t - t^*)^2 |f(t)|^2 dt} \sqrt{\int_{-\infty}^{\infty} |f'(t)|^2 dt} && \text{Cauchy Schwartz Inequality} \\ &= 2(\Delta_f \|f\|) \sqrt{\int_{-\infty}^{\infty} |f'(t)|^2 dt} \end{aligned}$$

What is $\int_{-\infty}^{\infty} |f'(t)|^2 dt$? Well, recall we have previously proven that $\widehat{f'(\omega)} = i\omega \widehat{f}(\omega)$, then Parseval's Identity tells us that

$$\begin{aligned} \int_{-\infty}^{\infty} |f'(t)|^2 dt &= \frac{1}{2\pi} \|i\omega \widehat{f}(\omega)\|^2 \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} (\omega)^2 |\widehat{f}(\omega)|^2 d\omega \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} (\omega - 0)^2 |\widehat{f}(\omega)|^2 d\omega \\ &= \frac{1}{2\pi} \widehat{\Delta}_f^2 \|f\|^2 && \text{Since } \omega^* = 0 \text{ as } f \text{ is real valued} \\ &= \widehat{\Delta}_f^2 \|f\|^2 \end{aligned}$$

Thus, we have that

$$\|f\|^2 \leq 2\Delta_f \|f\| \widehat{\Delta}_f \|f\|$$

Hence we have that

$$\Delta_f \widehat{\Delta}_f \geq 1/2$$

■

Proposition 4.3 (Principle of Maximum Laziness). Mark Ainsworth's favorite principle - avoid all work at as much as possible.

Remark 4.4. Note that the inequality is a very tight inequality! Since the only part where it becomes an inequality is when we applied to Cauchy-Schwarz Inequality. Hence

$$1/2 = \Delta_f \widehat{\Delta}_f$$

if and only if the condition for Cauchy-Schwarz Inequality to become an equality is true. This happens when $(t - t^*)f(t)$ and $f'(t)$ differs by a constant! This probably gives you an idea of what function you can use to make this an equality.

The mathematical proof of the Uncertainty Principle isn't too bad, what's tricky is how we would interpret this in the context of applications.

In the context of Heisenberg's Uncertainty Principle, we have that

$$\Delta_f \sim \text{position of particle}$$

$$\widehat{\Delta}_f \sim \text{momentum of particle}$$

Up to some appropriate scaling, we have that the constant that bounds below the product is the Planck's constant. This really has nothing to do with physics but rather a consequence of the Cauchy-Schwarz Inequality.

In the context of time-frequency analysis, this means that the more narrow you examine in the time domain, the less you know about how the frequency at the place works, and vice versa. This is a HUGE problem in signal processing. You know everything with Fourier Analysis if you have what $f(t)$ or $\hat{f}(\omega)$ are, but in the real world, you don't know what $f(t)$ or $\hat{f}(\omega)$ are, you only have localized data about the waves.

4.3 Bandwidths and Filtering

Suppose we have a signal with time domain representation $\{f(t) : t \in \mathbb{R}\}$ with f being real-valued.

Therefore, the frequency representation

$$\hat{f}(\omega) = \int_{-\infty}^{\infty} e^{-i\omega t} f(t) dt$$

Ideally a frequency representation would capture all the frequencies. Unfortunately, due to limitations in the real world, we can't do that, our machines just can't measure low and high frequencies up to some number, so we are dealing with the following type of signals:

Definition 4.5. A signal $f(t)$ is **band limited** if

$$\hat{f}(\omega) = 0, \forall \omega \text{ such that } |\omega| \geq \alpha > 0$$

The smallest of such α is the **bandwidth** of the signal.

Example 4.6. Given $\alpha > 0$, we set

$$\hat{f}_\alpha(\omega) := \begin{cases} \hat{f}(\omega), & |\omega| \leq \alpha \\ 0, & |\omega| > \alpha \end{cases}$$

, then $\hat{f}_\alpha(\omega)$ is band limited with bandwidth α .

Question 4.7. What can we infer about $f(t)$ given $\hat{f}(\omega)$?

5 Lecture 5 - 2/3/2023

5.1 Bandwidths and Filtering

Given a signal $\{f(t) : t \in \mathbb{R}\}$ or $\hat{f}(\omega) : \omega \in \mathbb{R}$, we recall that we said the signal is **band-limited** with **bandwidth** α if

$$\hat{f}(\omega) = 0, \forall |\omega| > \alpha$$

where α is the smallest such value.

Given a frequency $\hat{f}(\omega)$ and $\alpha > 0$, we can construct the **cut-off frequencies** at α as:

$$\hat{f}_\alpha(\omega) = \begin{cases} \hat{f}(\omega), & |\omega| < \alpha \\ 0, & |\omega| > \alpha \end{cases}$$

Question 5.1. What happens in time domain? What can we infer about $f(t)$ based on $\hat{f}_\alpha(\omega)$.

We observe that $\hat{f}_\alpha(\omega)$ decreases the radius of the frequency space and localizes this, by the Uncertainty Principle, this should intuitive make the time domain less localized.

Remark 5.2. A negative frequency really just represents a wave in another direction. In the interpretation in its Fourier transform, a negative and positive frequency are respectively e^{-it} and e^{it} , their sum is exactly $\cos(t)$, which is what we interpret to be as the standing wave.

Assuming all signals decay fast enough, we observe that

$$\begin{aligned} f_a(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{f}_a(\omega) e^{i\omega t} d\omega \\ &= \frac{1}{2\pi} \int_{-a}^a \hat{f}(\omega) e^{i\omega t} d\omega \\ &= \frac{1}{2\pi} \int_{-a}^a e^{i\omega t} d\omega \int_{-\infty}^{\infty} e^{-i\omega s} f(s) ds \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} f(s) ds \int_{-a}^a e^{i\omega(t-s)} dt \end{aligned} \quad \text{Fubini's Theorem}$$

We observe that

$$\frac{1}{2\pi} \int_{-a}^a e^{i\omega(t-s)} dt = \frac{1}{2\pi} \left[\frac{e^{i\omega(t-s)}}{i(t-s)} \right]_{-a}^a = \frac{1}{\pi(t-s)} \frac{e^{ia(t-s)} - e^{-a(t-s)}}{2i} = \ell_a(t-s)$$

We define

$$\ell_a(t) = \frac{\sin at}{\pi t}$$

as the **Shannon Sampling Function**.

Thus, we have that

$$f_a(t) = \int_{-\infty}^{\infty} f(s) \ell_a(t-s) ds = (f * \ell_a)(t)$$

This is indeed the convolution of $f(t)$ and $\ell_a(t)$.

- Every value of $f(s)$ affects $f_a(t)$, apart from when $\sin at = 0$ (which is a discrete set)
- $f_a(t)$ is most affected by $f(t)$

Question 5.3. What happens if we vary the value of α ?

For α getting larger, we should expect that $\hat{f}_a(\omega)$ gets closer and closer to $\hat{f}(\omega)$, so $f_a(t)$ should be closer to $f(t)$. In fact, $\ell_a(t)$ becomes more and more like the Dirac Delta function as $a \rightarrow \infty$.

For α getting smaller, we should expect $f_a(t)$ getting less and less localized.

We also have a corresponding formulation of filtering by considering the time signal $f(t)$ and

Definition 5.4. We have a corresponding formulation of filtering - $\hat{f} \rightarrow \hat{f}_\alpha(\omega)$, where we can define

$$\hat{f}_\alpha(\omega) := \hat{f}(\omega)H(\omega)$$

where $H(\omega)$ is the indicator function of $[-\alpha, \alpha]$. H is called the **frequency representation of the filter**.

In the Frequency Domain, we have that

$$\hat{f} \mapsto \hat{f}_a = \hat{f}H$$

In the Time Domain, we have that

$$f \mapsto f_a = f * h$$

where we note that $H = \hat{h}$!

Remark 5.5. So who is Claude Shannon? His contribution to signal processing was figuring out - given a bandlimited signal, how many points do you need to sample, so that others can reconstruct the signal based on the points. This is sometimes called the Shannon Sampling Theorem, and we will discuss more about this later.

5.2 Filter Design

Recall we have $\hat{f} \rightarrow \hat{f}_a(\omega) = H(\omega)\hat{f}(\omega) \sim \hat{f}(\omega)$.

How should we choose an appropriate $H(\omega)$? Well we ideally want

- We know that $\hat{f}(0) = \int_{-\infty}^{\infty} f(t)dt$ (average value of f), hence we want f_a and f to have the same average, hence

$$\hat{f}_a(0) = H(0)\hat{f}(0)$$

This is true if and only if $H(0) = 1$.

- We want to preserve moments as before, so we want to preserve higher order moments, for example $\int_{-\infty}^{\infty} tf(t)dt$. We observe that

$$\hat{f}(\omega) = \int_{-\infty}^{\infty} e^{i\omega t} f(t)dt$$

Thus we have that

$$\frac{d\hat{f}}{d\omega}(\omega) = \int_{-\infty}^{\infty} -ite^{i\omega t} tf(t)dt$$

Hence we have that

$$\hat{f}'(0) = \int_{-\infty}^{\infty} tf(t)dt$$

So we really want to preserve $\hat{f}'_a(0) = \hat{f}'(0)$, which we have

$$\hat{f}'_a(0) = H(0)\hat{f}'(0) + H'(0)\hat{f}(0)$$

The equality we want is preserved if and only if $H(0) = 1$ and $H'(0) = 0$.

- By Engineering's Induction, (you can also generalize this rigorously), we have that H preserves all moments up to order m if and only if

$$H(0) = 1, H'(0) = H''(0) = \dots = H^{(m)}(0) = 0$$

This type of filter is called a **BUTTERWORTH FILTER** of order m .

6 Lecture 6 - 2/6/2023

6.1 Gábor Transform

Recall in last lecture, we have previously demonstrated the following equivalence:

Given a function f in the time domain, where h is a real-valued filter with the assumption:

- h is real-valued
- $t^* = 0$
- $\Delta_h < \infty$

Then what get's filtered in the time domain is

$$g = h * f$$

In the frequency world, we achieve the same with $\hat{g} = H\hat{f}$, where $H = \hat{h}$ (Note our convolution becomes multiplication).

We also have the uncertainty principle, which tells us that there's a limit on the localization we can get simultaneously in time and frequency. What does this mean for filtering?

We have

$$g(\alpha) = \int_{-\infty}^{\infty} f(t)h(\alpha - t)dt, \alpha \in \mathbb{R}$$

where $h(\alpha - t)$ represents the localization around α .

We know the Fourier Transform of $h(\alpha - t)$ is just

$$\begin{aligned} \int_{-\infty}^{\infty} e^{-i\omega t} h(\alpha - t)dt &= \int_{-\infty}^{\infty} e^{-\omega(w-s)} h(s)ds && \text{Let } s = \alpha - t \\ &= e^{-i\omega\alpha} \int_{-\infty}^{\infty} e^{-i\omega s} h(s)ds \\ &= e^{-i\omega\alpha} \overline{H(\omega)} \end{aligned}$$

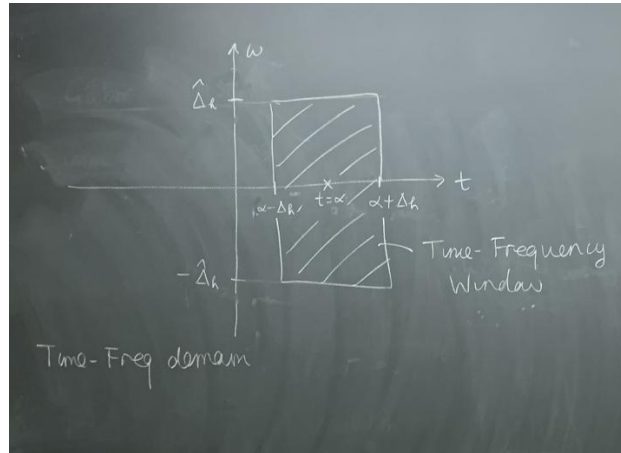
Parserval's Identity tells us that

$$\int_{-\infty}^{\infty} f(t)h(\alpha - t)dt = g(\alpha) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{f}(\omega)e^{i\omega\alpha} \overline{H(\omega)}d\omega$$

In the time domain, we have the localization of $f(t)$ around $t = \alpha$ over a radius Δ_h (the role of $h(\alpha - t)$ is the sampler).

In the frequency domain, this is the sampling of \hat{f} over a radius $\hat{\Delta}_h$ centered around $\omega = 0$.

What happens in the time-frequency domain:



This is called the Time-Frequency Window on $(\alpha - \Delta_h, \alpha + \Delta_h) \times (-\hat{\Delta}_h, \hat{\Delta}_h)$. In other words, filtering gives information about $f(t)$ and $\hat{f}(\omega)$ over a time-frequency window.

We note that the area of this window is bounded by

$$(2\Delta_h)(2\hat{\Delta}_h) \geq 2$$

We have two significant issues:

- The area of the time-frequency window is limited
- We have flexibility to shift the time-window by varying α , but there's no flexibility to vary the frequency as it is always centered on $\omega = 0$.

Question 6.1. Can we try to limit the area of the time-frequency window?

Example 6.2. Here are some possible attempts:

1. Try $h(t) = \begin{cases} \frac{1}{2\epsilon}, & |t| \leq \epsilon \\ 0, & \text{otherwise} \end{cases}$, then $\hat{h}(\omega) \sim \frac{\sin(\omega t)}{\omega t}$. Then we have that

$$\begin{aligned} \hat{\Delta}_h &= \lim_{R \rightarrow \infty} \int_{-\infty}^{\infty} |\omega| |\hat{f}(\omega)|^2 d\omega \\ &= \infty \end{aligned}$$

So the radius is not good.

2. Let's try the Gaussian filter $h(t) = e^{-t^2/2}$, then $\Delta_h \cdot \hat{\Delta}_h = 1/2$. This suggests that a Gaussian filter should be optimal, but this function is globally supported. We do have rapid decay, and

$$h(\alpha - t) = e^{-(t-\alpha)^2/2} \approx 0 \text{ when } |t - \alpha| \text{ is "large"}$$

In practice, we would just approximate using a Gaussian filter.

Question 6.3. Can we try to move the time-frequency window vertically so that it can be centered on a given frequency ξ ?

Answer. Yes! This is solved by what's known as the Gabor transform. Gabor actually won a Nobel Prize for discovering holograms. He was also a member of Fellows of the Royal Society. ■

Now, let's consider

$$g(t) = (h * f)(t) \text{ or } \widehat{g}(\omega) = H(\omega)\widehat{f}(\omega)$$

given information around $\omega = 0$.

Idea 6.4. Let's try to shift the spectrum of f before filtering!

Recall we have that

$$f(s) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{i\omega s} \widehat{f}(\omega) d\omega$$

This is a super-position of frequencies. Hence

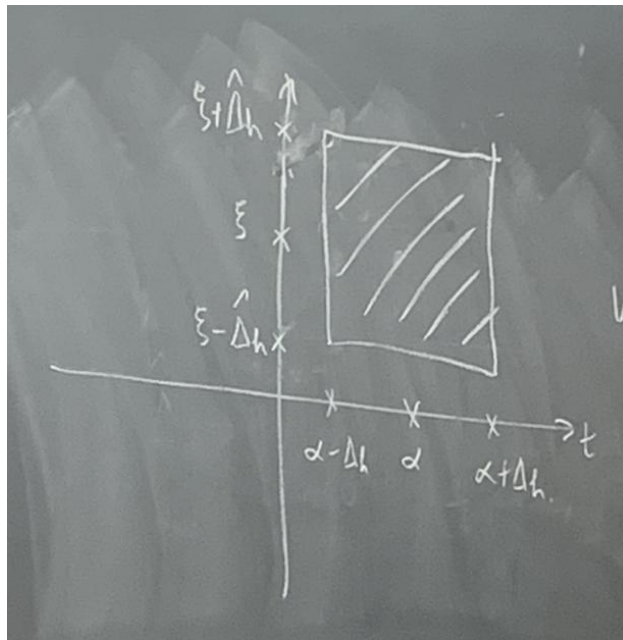
$$\begin{aligned} e^{-i\xi s} f(s) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{i(\omega - \xi)s} \widehat{f}(\omega) d\omega \\ &= \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{i\omega s} \widehat{f}(\omega + \xi) d\omega \end{aligned}$$

This shows that the spectrum of f is shifted by an amount ξ (since $\widehat{f}(\omega) \rightarrow \widehat{f}(\omega + \xi)$).

Definition 6.5. Applying the filter to the resulting function gives the **Gabor transform**:

$$G_h(\alpha, \xi) := (h * e^{-i\xi s} f(s))(\alpha) = \int_{-\infty}^{\infty} e^{-i\xi s} f(s) h(\alpha - s) ds$$

In the time-frequency window, we now have



This is also a special case of what's known as a “short time Fourier transform”.

7 Lecture 7 - 2/8/2023

Recall last lecture - given a special filter $\{h(t) : t \in \mathbb{R}\}$, then we define the Gabor transform as

$$(G_h f)(\alpha, \xi) = \int_{-\infty}^{\infty} ds f(s) e^{-i\xi s} h(\alpha - s)$$

The idea is that - by varying α and ξ , we can shift the window horizontally and vertically across the time-frequency domain, around spatial location α and frequency ξ .

Proposition 7.1. The Gabor transform gives a time-frequency window

$$(\alpha - \Delta_h, \alpha + \Delta_h) \times (\xi - \widehat{\Delta}_h, \xi + \widehat{\Delta}_h)$$

ie. window has area

$$2\Delta_h 2\widehat{\Delta}_h \geq \frac{2 \cdot 2}{2} = 2$$

Proof. We note that $h(\alpha - s)$ is centered on α with spread being Δ_h and $e^{-i\xi s}$ has no contribution to the time domain, thus clearly the temporal window is given by $(\alpha - \Delta_h, \alpha + \Delta_h)$.

By Parseval's Identity, we note that

$$(G_h f)(\alpha, \xi) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega \widehat{f}(\omega) \bar{?}$$

where the term under the complex conjugation is exactly the Fourier transform of $e^{+i\omega s} h(\alpha - s)$, which is

$$\begin{aligned} \int_{-\infty}^{\infty} e^{-i\omega s} e^{i\xi s} h(\alpha - s) ds &= \int_{-\infty}^{\infty} e^{-i(-\xi)s} h(\alpha - s) ds \\ &= \int_{-\infty}^{\infty} e^{-i(\omega - \xi)\alpha} e^{i(\omega - \xi)t} h(t) dt && \text{Let } t = \alpha - s \\ &= e^{-i(\omega - \xi)\alpha} \int_{-\infty}^{\infty} e^{-i(\xi - \omega)t} h(t) dt \\ &= e^{-i(\omega - \xi)\alpha} \widehat{h}(\xi - \omega) \end{aligned}$$

Thus, we have that

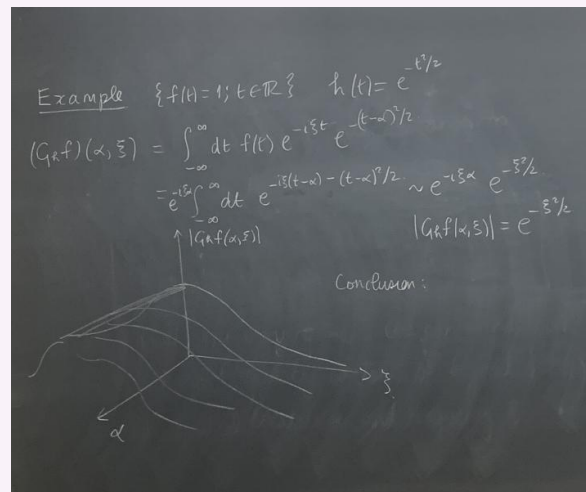
$$(G_h f)(\alpha, \xi) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega \widehat{f}(\omega) e^{+i(\omega - \xi)\alpha} \overline{\widehat{h}(\xi - \omega)}$$

Hence, we have centering on $\omega = \xi$ on the frequency domain and width of window $\widehat{\Delta}_h$. ■

Example 7.2. Consider a signal $\{f(t) = 1 : t \in \mathbb{R}\}$ and $h(t) = e^{-t^2/2}$, then

$$\begin{aligned} (G_h f)(\alpha, \xi) &= \int_{-\infty}^{\infty} dt f(t) e^{-i\xi t} e^{-(t - \alpha)^2/2} \\ &= e^{-i\xi \alpha} \int_{-\infty}^{\infty} e^{-(t - \alpha)^2/2 - i\xi t} \\ &\sim e^{-i\xi \alpha} e^{-\xi^2/2} \end{aligned}$$

In particular, we note that $|G_h f| = e^{-\xi^2/2}$ with the graph:



Just analyzing the graph, we see that $|G_h f|$ is not varying in intensity in time, so there's no spatial localization at all. $|G_h f|$ is largest when $\xi = 0$, so the largest frequency content of the signal is around where $\xi = 0$, hence the dominant frequency is $\xi = 0$.

Question 7.3. How to compute/approximate $G_h f$ when f is not so simple?

We always make $h(t) = e^{-t^2/2}$ as our filter, to compute a numerical approximation, here are a few issues:

1. $f(t)$ may be given only partially, e.g. only at certain points or on a limited range. Suppose we have $\{f(t) : -w < t < w\}$ for some w . So the first approximation we need is

$$(G_h f)(\alpha, \xi) \approx \int_{-w}^w dt f(t) e^{-i\xi t} e^{-(t-\alpha)^2/2}$$

This is a good approximation if $f(t)$ decays rapidly outside. We also expect this to be a good approximation even if f does not decay, provided that α is located "well-inside" $(-w, w)$.

2. We still can't compute analytically. Let's try to use the Trapezoidal Rule with nodes indexed by $-N, -N+1, \dots, 0, \dots, N$ (choose N large enough), then

$$\approx \frac{W}{N} \sum_{m=-N}^N {}'' e^{-i\xi t_m} e^{-(t_m-\alpha)^2/2} f(t_m)$$

where $t_m = mW/N$ for $m = -N, \dots, N$ (the \sum'' means the first and the last term are halved).

3. This could be very expensive if $N \gg 1$ and/or $W \gg 1$, we note that

$$e^{-t^2/2} < 10^{-6} \text{ when } |t| > 5.6$$

Therefore we are only going to sum over N such that $|t_m - \alpha| < 6$, ie. only when

$$-6N/W < m - \frac{N\alpha}{W} < 6N/W$$

Hence combining our approximations gives

$$(G_h f)(\alpha, \xi) \approx \frac{W}{N} \sum_{m=Lo}^{m=Hi} e^{-i\xi t_m} e^{-(t_m-\alpha)^2/2} f(t_m)$$

where

$$Lo := \max(-N, \lfloor \frac{NW(\alpha - 6)}{W} \rfloor)$$

$$Hi = \min(N, \lceil \frac{NW(\alpha + 6)}{W} \rceil)$$

$$t_m = mW/N$$

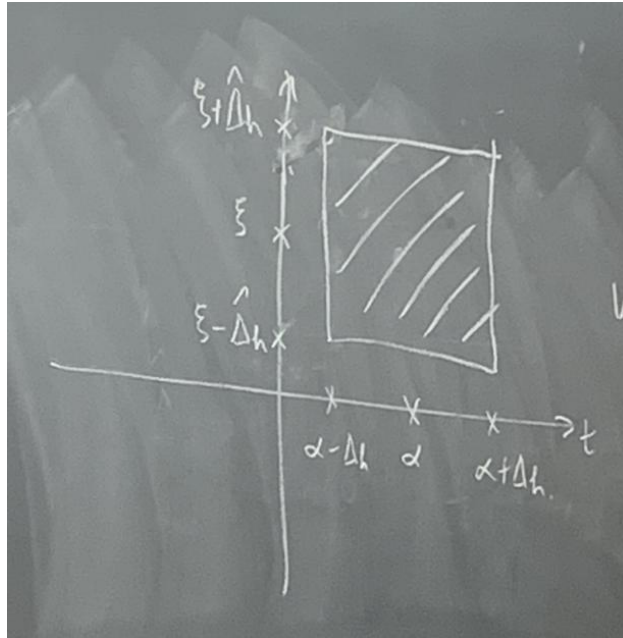
8 Lecture 8 - 2/10/2023

8.1 Gabor Transform (Continued)

We recall that the Gabor transform was defined

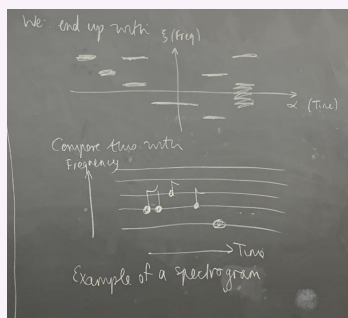
$$(G_h f)(\alpha, \xi) = \int_{-\infty}^{\infty} f(t) e^{-i\xi t} e^{-(t-\alpha)^2/2} dt$$

The Gabor Transform enable us to do time-frequency analysis. In particular we can plot the following **spectrogram** and center on some window (α, ξ) with width $2\Delta_h$ and height $2\hat{\Delta}_h$:



But since we have this fundamental restriction on the area of the window, $(G_h f)(\alpha, \xi) \sim$ average of f and \hat{f} over the window.

Example 8.1. We can't concentrate this around points because of the fundamental limit on the area of the window, hence the spectrogram has some imperfections going on:



We can compare this with a music sheet. In particular, a music sheet is really an example of a spectrogram and is in fact a perfect spectrogram, as you know exactly what frequencies should occur at each time.

Unfortunately, Gabor transform is limited by the time-frequency uncertainty principle, but we can change the aspect ratio of the time-frequency window to focus on localization in either time or frequency.

To decrease Δ_h , we want to decay our $e^{-t^2/2}$ faster, to do this we can consider $e^{-\epsilon t^2/2}$. If we choose $\epsilon > 1$, we tighten the time window. If $\epsilon < 1$, we tighten the frequency window.

A discontinuity at time t corresponds to the existence of all frequencies around time t .

Claim 8.2. Varying ϵ is more useful than varying ξ and/or α .

Question 8.3. Why don't we try to sacrifice a parameter?

8.2 Varying $t - \omega$ Aspect Ratio Transform

Let $\{h(t) : t \in \mathbb{R}\}$ be a given filter and define a new transform

$$W_h(\alpha, a) = \int_{-\infty}^{\infty} f(t) h\left(\frac{\alpha - t}{a}\right) dt$$

By varying 'a', we can change the aspect ratio of the window (we are not normalizing yet)

$$\Delta_h^2 \sim \int_{-\infty}^{\infty} (t - t^*) |h(t)|^2 dt \quad (a = 1)$$

$$\Delta_{h,a}^2 \sim \int_{-\infty}^{\infty} (t - t^*)^2 |h(t/a)|^2 dt$$

Without loss of generality, let's say $t^* = 0$, then

$$\begin{aligned} \Delta_{h,a}^2 &\sim \int_{-\infty}^{\infty} t^2 |h(t/a)|^2 dt \\ &= a^3 \int_{-\infty}^{\infty} (t/a)^2 |h(t/a)|^2 d(t/a) \\ &= a^3 \int_{-\infty}^{\infty} s^2 |h(s)|^2 ds \end{aligned}$$

Recall we also have to normalize this, and

$$\|h(t/a)\|^2 = a \int_{-\infty}^{\infty} |h(t/a)|^2 \frac{dt}{a} = a \|h\|^2$$

Hence, we have that

$$\Delta_{h,a}^2 \sim a^2 \Delta_h^2$$

Let's try to rescale h so that $h(\frac{\bullet}{a})$ is independent of $|a|$, ie. let's define

$$h_a(t) = \frac{1}{\sqrt{a}} h(t/a)$$

Hence we note that

$$\|h_a(t)\|^2 = \frac{1}{a} \int_{-\infty}^{\infty} |h(t/a)|^2 dt = \int_{-\infty}^{\infty} |h(s)|^2 ds$$

This value is now independent of a !

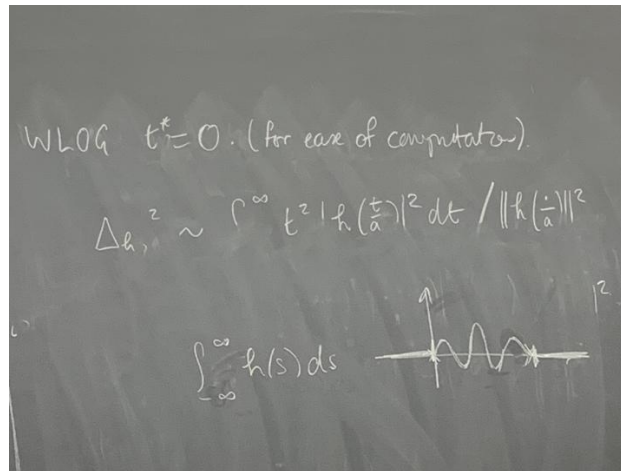
We now arrive at a new type of transform

$$(W_h f)(\alpha, a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) h\left(\frac{\alpha - t}{a}\right) dt$$

This is also called the **continuous Wavelet transform**. In particular, h is the **analyzing wavelet**! We want to choose h so that it doesn't pick up any DC components, namely that

$$\int_{-\infty}^{\infty} h(s) ds = 0$$

For convenience, we also want $h(s)$ to be compactly supported. So we want something like:



Which looks like the shape of a wavelet!