

Distribution Theory and Applications — Summary

Lucas Riedstra

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1 Distributions

1.1 Test functions and distributions

Definition 1.1. Let $X \subseteq \mathbb{R}^n$ be open, then we define the set of *test functions* on X as

$$\mathcal{D}(X) := C_0^\infty(X) = \{f: X \rightarrow \mathbb{C} \mid f \text{ is smooth with compact support}\}.$$

Definition 1.2. Let $(\varphi_m) \subseteq \mathcal{D}(X)$. We say that $(\varphi_m) \rightarrow 0$ in $\mathcal{D}(X)$ if

1. there exists a compact $K \subseteq X$ such that $\text{supp } \varphi_m \subseteq K$ for all m ;
2. $\partial^\alpha \varphi_m \rightarrow 0$ uniformly for each multi-index α .

Note that, for any $\varphi, \psi \in \mathcal{D}(X)$ and any multi-index α we have

$$\int_X \varphi \cdot \partial^\alpha \psi \, dx = (-1)^{|\alpha|} \int_X \psi \cdot \partial^\alpha \varphi \, dx,$$

which follows from partial integration and the fact that all boundary terms vanish since φ and ψ have compact support.

Also, by Taylor's theorem, for any $\varphi \in \mathcal{D}(X)$, $x, h \in X$ and $N \in \mathbb{N}$ we have

$$\varphi(x+h) = \sum_{|\alpha| \leq N} \frac{h^\alpha}{\alpha!} \partial^\alpha \varphi(x) + R_N(x, h) \quad \text{where } R_N(x, h) = o(|h|^N) \text{ uniformly in } x.$$

Definition 1.3. A *distribution* on X is a linear map $u: \mathcal{D}(X) \rightarrow \mathbb{C}$ if for every compact set $K \subseteq X$ there exist constants C, N such that for all $\varphi \in \mathcal{D}(X)$ with $\text{supp } \varphi \subseteq K$ we have

$$|u(\varphi)| \leq C \sum_{|\alpha| \leq N} \sup |\partial^\alpha \varphi|. \quad (1)$$

Condition 1 is called the *seminorm condition*. If, in the seminorm condition, the same N can be used for every compact set $K \subseteq X$, then the least such N is called the *order* of u , written $\text{ord}(u)$.

The set of all distributions in X is denoted $\mathcal{D}'(X)$.

If $u \in \mathcal{D}'(X)$ and $\varphi \in \mathcal{D}(X)$, then instead of $u(\varphi)$ we usually write $\langle u, \varphi \rangle$.

Recap 1.4. A function $f: X \rightarrow \mathbb{C}$ is called *locally integrable* if $\int_K |f| \, dx < \infty$ for all compact $K \subseteq X$.

The set of locally integrable functions on X is denoted $L_{\text{loc}}^1(X)$.

Example 1.5. Let $M \in \mathbb{N}$ and let $f_\alpha \in L_{\text{loc}}^1(X)$ for all $|\alpha| \leq M$. Define the linear map $T: \mathcal{D}(X) \rightarrow \mathbb{C}$ by

$$\langle T, \varphi \rangle := \sum_{|\alpha| \leq M} \int_X f_\alpha \cdot \partial^\alpha \varphi \, dx.$$

It is trivial that T is linear, and we verify that T is a distribution as follows: take $\varphi \in \mathcal{D}(X)$ with $\text{supp } \varphi \subseteq K$. Then we have

$$\begin{aligned} |\langle T, \varphi \rangle| &\leq \sum_{|\alpha| \leq M} \int_K |f_\alpha| \cdot |\partial^\alpha \varphi| \, dx \\ &\leq \sum_{|\alpha| \leq M} \sup |\partial^\alpha \varphi| \cdot \int_K |f_\alpha| \, dx \\ &\leq \left(\max_\alpha \int_K |f_\alpha| \, dx \right) \sum_{|\alpha| \leq M} \sup |\partial^\alpha \varphi|. \end{aligned}$$

Therefore, the seminorm condition is satisfied with $N = M$. From this, it also follows that $\text{ord}(T) \leq M$.

A special case of the previous example is the case $M = 0$: in this case the distribution simply becomes

$$\langle \tau_f, \varphi \rangle = \int_X f \varphi \, dx.$$

Henceforth we will abuse notation: if $f \in L^1_{\text{loc}}(X)$, then we will write f instead of τ_f , i.e., $\langle f, \varphi \rangle = \int_X f \varphi \, dx$.

Lemma 1.6 (Sequential continuity). *Let $u: \mathcal{D}(X) \rightarrow \mathbb{C}$ be a linear map. Then u is a distribution if and only if, for every sequence $(\varphi_m) \subseteq \mathcal{D}(X)$ with $\varphi_m \rightarrow 0$ as in definition 1.2, we have $\langle u, \varphi_m \rangle \rightarrow 0$.*

Proof. ‘ \implies ’ If u is a distribution and $(\varphi_m) \rightarrow 0$, then $\text{supp } \varphi_m \subseteq K$ for some compact K , and by eq. (1) there exist C, N such that

$$|\langle u, \varphi_m \rangle| \leq C \sum_{|\alpha| \leq N} \sup |\partial^\alpha \varphi_m| \rightarrow 0.$$

‘ \impliedby ’ Suppose there is a compact set K such that eq. (1) is not valid for any C, N . Let $m \in \mathbb{N}$ and $C = N = m$, then there is some φ_m with $\text{supp } (\varphi_m) \subseteq K$, and

$$|\langle u, \varphi_m \rangle| > m \sum_{|\alpha| \leq m} \sup |\partial^\alpha \varphi_m|.$$

By dividing φ_m by $\langle u, \varphi_m \rangle \neq 0$, we may assume w.l.o.g. that $\langle u, \varphi_m \rangle = 1$. We now have a sequence (φ_m) such that

$$\frac{1}{m} > \sum_{|\alpha| \leq m} \sup |\partial^\alpha \varphi_m| \implies |\partial^\alpha \varphi_m| < \frac{1}{m} \quad \text{for } |\alpha| \leq m \implies \partial^\alpha \varphi_m \rightarrow 0 \text{ uniformly for all } \alpha.$$

Since each φ_m also satisfies $\text{supp } \varphi_m \subseteq K$, by definition 1.2 we have that $\varphi_m \rightarrow 0$, but also $\langle u, \varphi_m \rangle \rightarrow 1$, a contradiction. \square

1.2 Limits in the distribution space

Definition 1.7. We say that a sequence $(u_m) \subseteq \mathcal{D}'(X)$ converges to $u \in \mathcal{D}'(X)$ and write $u_m \rightarrow u$ if

$$\langle u_m, \varphi \rangle \rightarrow \langle u, \varphi \rangle \quad \text{for all } \varphi \in \mathcal{D}(X).$$

The following theorem is non-examinable but interesting:

Theorem 1.8. *Let (u_m) be a sequence in $\mathcal{D}'(X)$ such that $\lim_{m \rightarrow \infty} \langle u_m, \varphi \rangle$ exists for all $\varphi \in \mathcal{D}(X)$. Then the map $\langle u, \varphi \rangle := \lim_{m \rightarrow \infty} \langle u_m, \varphi \rangle$ is a distribution in X .*

Proof. This is a direct application of the uniform boundedness principle. \square

Example 1.9. Let $X = \mathbb{R}$ and consider the sequence of functions $u_m \in L^1_{\text{loc}}(\mathbb{R})$ defined by $u_m(x) = \sin(mx)$. Then, for all $\varphi \in \mathcal{D}(\mathbb{R})$, we have

$$\langle u_m, \varphi \rangle = \int_{\mathbb{R}} \sin(mx) \varphi(x) \, dx = \frac{1}{m} \int_{\mathbb{R}} \cos(mx) \varphi'(x) \, dx \leq \frac{1}{m} \int_{\mathbb{R}} |\varphi'(x)| \, dx \rightarrow 0.$$

Therefore, it holds that $u_m \rightarrow 0$ in $\mathcal{D}'(\mathbb{R})$. With our abuse of notation we write this as $\lim_{m \rightarrow \infty} \sin(mx) = 0$ in $\mathcal{D}'(\mathbb{R})$.

1.3 Basic operations

1.3.1 Differentiation and multiplication by smooth functions

For $u \in C^\infty(X)$ and $\varphi \in \mathcal{D}(X)$, we have noted that

$$\langle \partial^\alpha u, \varphi \rangle = \int_X \partial^\alpha u \cdot \varphi \, dx = (-1)^{|\alpha|} \int_X u \cdot \partial^\alpha \varphi \, dx = \langle u, (-1)^{|\alpha|} \partial^\alpha \varphi \rangle.$$

Since the RHS makes sense for any distribution u , we define

Definition 1.10. For $f \in C^\infty(X)$, $u \in \mathcal{D}'(X)$, we define $\partial^\alpha(fu)$ by

$$\langle \partial^\alpha(fu), \varphi \rangle := \langle u, (-1)^{|\alpha|} f \cdot \partial^\alpha \varphi \rangle$$

Remark. This definition outlines a more general pattern when working with distributions: first we take some well-defined operator on the collection of smooth maps, then we rewrite it to a form that is sensible for any distribution, and then we *define* that new form as the operator on distributions. This process is called *extending the definition by duality*.

Example 1.11. Let $u = \delta_x$, then we have

$$\langle \partial^\alpha \delta_x, \varphi \rangle = \langle \delta_x, (-1)^{|\alpha|} \partial^\alpha \varphi \rangle = (-1)^{|\alpha|} \partial^\alpha \varphi(x)$$

Furthermore, consider the Heaviside function $H(x) = \mathbb{1}_{x \geq 0}$. We have

$$\langle H', \varphi \rangle = -\langle H, \varphi' \rangle = -\int_{\mathbb{R}} H(x) \varphi'(x) \, dx = -\int_0^\infty \varphi'(x) \, dx = \varphi(0) = \langle \delta_0, \varphi \rangle,$$

so we write $H' = \delta_0$ in the distributional sense.

Lemma 1.12. Suppose $u' \in \mathcal{D}'(\mathbb{R})$ satisfies $u' = 0$. Then u is constant (i.e., $\langle u, \varphi \rangle = \langle c, \varphi \rangle = c \int_{\mathbb{R}} \varphi \, dx$ for some c).

Proof. Fix any $\vartheta \in \mathcal{D}(\mathbb{R})$ with $\langle 1, \vartheta \rangle = 1$. Let $\varphi \in \mathcal{D}(\mathbb{R})$ and define

$$\varphi_A := \varphi - \langle 1, \varphi \rangle \vartheta, \quad \varphi_B := \langle 1, \varphi \rangle \vartheta \quad \text{such that } \varphi = \varphi_A + \varphi_B.$$

Note that $\langle 1, \varphi_A \rangle = \langle 1, \varphi \rangle - \langle 1, \varphi \rangle \langle 1, \vartheta \rangle = 0$.

We claim that the function $\Phi_A(x) := \int_{-\infty}^x \varphi_A(y) \, dy$ has compact support: since $\text{supp } \varphi_A \subseteq [a, b]$ for some $a, b \in \mathbb{R}$, clearly $\Phi_A(x) = 0$ for $x < a$, while for $x > b$ we have $\Phi_A(x) = \langle 1, \varphi_A \rangle = 0$. Obviously, it holds that $\Phi'_A = \varphi_A$. Now we compute

$$\langle u, \varphi \rangle = \langle u, \varphi_A \rangle + \langle u, \varphi_B \rangle = \langle u, \Phi'_A \rangle + \langle 1, \varphi \rangle \langle u, \vartheta \rangle = -\langle u', \Phi_A \rangle + c \langle 1, \varphi \rangle = \langle c, \varphi \rangle.$$

Since φ was chosen arbitrarily this shows that u is constant. □

1.3.2 Reflection and translation

For $\varphi \in \mathcal{D}(\mathbb{R}^n)$, $h \in \mathbb{R}^n$, define the *translation of φ by h* by

$$(\tau_h \varphi)(x) := \varphi(x - h),$$

and the *reflection of φ* by $\check{\varphi}(x) := \varphi(-x)$.

Extending the definitions of translation and reflection by duality yields the following:

Definition 1.13. For $u \in \mathcal{D}'(\mathbb{R}^n)$, $h \in \mathbb{R}^n$, $\varphi \in \mathcal{D}(\mathbb{R}^n)$, define

$$\langle \tau_h u, \varphi \rangle := \langle u, \tau_{-h} \varphi \rangle \quad \text{and} \quad \langle \check{u}, \varphi \rangle := \langle u, \check{\varphi} \rangle.$$

Lemma 1.14. For $u \in \mathcal{D}'(\mathbb{R}^n)$, define $V_h \in \mathcal{D}'(\mathbb{R}^n)$ for $0 \neq h \in \mathbb{R}^n$ by

$$V_h := \frac{\tau_{-h}u - u}{\|h\|}$$

If $(h_j) \subseteq \mathbb{R}^n$ is a sequence for which $\lim_{j \rightarrow \infty} \frac{h_j}{\|h_j\|} = m \in S^{n-1}$, then $V_{h_j} \rightarrow \sum_i m_i \frac{\partial u}{\partial x_i}$ in $\mathcal{D}'(\mathbb{R}^n)$.

Proof. By definition, we can write $\langle V_h, \varphi \rangle = \frac{1}{\|h\|} \langle u, \tau_h \varphi - \varphi \rangle$. Now Taylor's theorem tells us that

$$(\tau_h \varphi - \varphi)(x) = \varphi(x - h) - \varphi(x) = - \sum_i h_i \frac{\partial \varphi}{\partial x_i} + R(x, h),$$

where $R(x, h) = o(\|h\|)$ in $D(\mathbb{R}^n)$ (exercise sheet 1, question 2).

By sequential continuity, we have

$$\lim_{j \rightarrow \infty} \langle V_{h_j}, \varphi \rangle = \langle u, - \sum_i m_i \frac{\partial \varphi}{\partial x_i} \rangle = \langle \sum_i m_i \frac{\partial u}{\partial x_i}, \varphi \rangle,$$

which shows that $V_{h_j} \rightarrow \sum_i m_i \frac{\partial u}{\partial x_i}$ in $\mathcal{D}'(\mathbb{R}^n)$. □

1.3.3 Convolution

For $\varphi \in \mathcal{D}(\mathbb{R}^n)$, note that $(\tau_x \check{\varphi})(y) = \check{\varphi}(y - x) = \varphi(x - y)$.

Definition 1.15. For $u \in C^\infty(\mathbb{R}^n)$, $\varphi \in \mathcal{D}(\mathbb{R}^n)$, we define the *convolution* $u * \varphi: \mathbb{R}^n \rightarrow \mathbb{C}$ as

$$(u * \varphi)(x) := \int_{\mathbb{R}^n} u(x - y) \varphi(y) dy = \int_{\mathbb{R}^n} u(y) \varphi(x - y) dy = \langle u, \tau_x \check{\varphi} \rangle.$$

Since the RHS makes sense for any $u \in \mathcal{D}'(\mathbb{R}^n)$, we extend the definition this way: for $u \in \mathcal{D}'(\mathbb{R}^n)$, $\varphi \in \mathcal{D}(\mathbb{R}^n)$, we define the convolution $u * \varphi$ as

$$(u * \varphi)(x) := \langle u, \tau_x \check{\varphi} \rangle.$$

Lemma 1.16. Let $\varphi \in C^\infty(\mathbb{R}^n \times \mathbb{R}^m)$ and define $\Phi_x(y) := \varphi(x, y)$. Suppose for any $x \in \mathbb{R}^n$ there exists a neighbourhood $N(x)$ and a compact $K \subseteq \mathbb{R}^m$ such that $\varphi(x, y)$ for all $x \in N(x)$, $y \notin K$.

Then $x \mapsto \langle u, \Phi_x \rangle$ is differentiable with

$$\partial_x^\alpha \langle u, \Phi_x \rangle = \langle u, \partial_x^\alpha \Phi_x \rangle$$

for any $u \in \mathcal{D}'(\mathbb{R}^m)$.

Proof. Fix $x \in \mathbb{R}^n$, then by Taylor's formula we have

$$\Phi_{x+h}(y) = \Phi_x(y) + \sum_{i=1}^n h_i \frac{\partial \varphi}{\partial x_i} + R(x, y, h),$$

where $\partial_y^\alpha R(x, y, h) = o(\|h\|)$, uniformly in y , for any multi-index α . Furthermore, by assumption there exists a compact K such that for h small enough, $\text{supp } R(x, \cdot, h) \subseteq K$. Therefore, $R(x, \cdot, h)$ is a test function for h small enough.

Combining the previous two facts shows that $R(x, \cdot, h) = o(\|h\|)$ in $\mathcal{D}(\mathbb{R}^m)$ as $h \rightarrow 0$.

Let $u \in \mathcal{D}'(\mathbb{R}^m)$, then we find by sequential continuity that $\langle u, R(x, \cdot, h) \rangle$ is also $o(\|h\|)$, and therefore

$$\langle u, \Phi_{x+h} \rangle = \langle u, \Phi_x \rangle + \sum_{i=1}^n h_i \langle u, \frac{\partial \Phi_x}{\partial x_i} \rangle + o(\|h\|).$$

This shows that $x \mapsto \langle u, \Phi_x \rangle$ is differentiable with

$$\frac{\partial}{\partial x_i} \langle u, \Phi_x \rangle = \langle u, \frac{\partial \Phi_x}{\partial x_i} \rangle.$$

From this the result follows. □

Corollary 1.17. *If $u \in \mathcal{D}'(\mathbb{R}^n)$, $\varphi \in \mathcal{D}(\mathbb{R}^n)$, then $u * \varphi$ is differentiable with $\partial^\alpha(u * \varphi) = u * \partial^\alpha \varphi$.*

Proof. Apply the previous lemma with $\Phi_x(y) := \varphi(x - y)$. \square

Due to the previous corollary, we often call $u * \varphi$ a *regularisation* of u .

Convention. If $u \in \mathcal{D}'(X)$ and $\varphi \in \mathcal{D}(X)$, then instead of $\langle u, \varphi \rangle$ we also write $\langle u(t), \varphi(t) \rangle$ (or with any other dummy variable) when the variable used for φ is not directly clear.

1.4 Density of test functions in distribution space

Lemma 1.18. *If $u \in \mathcal{D}'(\mathbb{R}^n)$ and $\varphi, \psi \in \mathcal{D}(\mathbb{R}^n)$, then*

$$(u * \varphi) * \psi = u * (\varphi * \psi).$$

Proof. Fix $x \in \mathbb{R}^n$. Now we write

$$\begin{aligned} ((u * \varphi) * \psi)(x) &= \int_{\mathbb{R}^n} \langle u(z), (\tau_y \check{\varphi})(z) \rangle \cdot \psi(x - y) \, dy \\ &= \int_{\mathbb{R}^n} \langle u(z), (\tau_{x-y} \check{\varphi})(z) \rangle \cdot \psi(y) \, dy \\ &= \int_{\mathbb{R}^n} \langle u(z), \psi(y) (\tau_{x-y} \check{\varphi})(z) \rangle \, dy. \end{aligned}$$

We would like to interchange integral and application of u , and we will have to justify this using Riemann sums:

$$\begin{aligned} \int_{\mathbb{R}^n} \langle u(z), \psi(y) (\tau_{x-y} \check{\varphi})(z) \rangle \, dy &= \lim_{\varepsilon \downarrow 0} \sum_{m \in \mathbb{Z}^n} \langle u(z), \psi(\varepsilon m) \varphi(x - z - \varepsilon m) \rangle \varepsilon^n \\ &\stackrel{*}{=} \lim_{\varepsilon \downarrow 0} \langle u(z), \sum_{m \in \mathbb{Z}^n} \psi(\varepsilon m) \varphi(x - z - \varepsilon m) \varepsilon^n \rangle \\ &\stackrel{**}{=} \left\langle u(z), \int_{\mathbb{R}^n} \psi(y) \varphi(x - z - y) \, dy \right\rangle \\ &= \langle u(z), (\varphi * \psi)(x - z) \rangle = \langle u(z), \widetilde{(\tau_x \varphi * \psi)}(z) \rangle = (u * (\varphi * \psi))(x). \end{aligned}$$

Here, $*$ is by the fact that the sum is finite since ψ has compact support, while $**$ is by sequential continuity of u and the fact that the Riemann sum converges to the convolution integral *in the space of test functions* (non-examinable fact). \square

We will use the following trick many times:

Proposition 1.19. *For any $u \in \mathcal{D}'(\mathbb{R}^n)$, $\varphi \in \mathcal{D}(\mathbb{R}^n)$ we have $\langle u, \varphi \rangle = (u * \check{\varphi})(0)$.*

Proof. We have $(u * \check{\varphi})(0) = \langle u, \tau_0 \varphi \rangle = \langle u, \varphi \rangle$. \square

For example, from this trick it follows that if $u * \varphi = 0$ for all φ , then $u = 0$.

Theorem 1.20. *If $u \in \mathcal{D}'(\mathbb{R}^n)$, there exists a sequence $(\varphi_k) \subseteq \mathcal{D}(\mathbb{R}^n)$ such that $\varphi_k \rightarrow u$ in $\mathcal{D}'(\mathbb{R}^n)$.*

Proof. Fix $\psi \in \mathcal{D}(\mathbb{R}^n)$ with $\int_{\mathbb{R}^n} \psi \, dx = 1$, and set $\psi_k(x) := k^n \psi(kx)$. Note that $\int_{\mathbb{R}^n} \psi_k \, dx = 1$.

Now, fix any $\chi \in \mathcal{D}(\mathbb{R}^n)$ with $\chi \equiv 1$ on $\{\|x\| < 1\}$ and $\chi \equiv 0$ on $\{\|x\| > 2\}$. Define $\chi_k(x) := \chi(x/k)$, so that $\lim_{k \rightarrow \infty} \chi_k(x) = 1$ for all x . We will set

$$\varphi_k(x) := \chi_k(x)(u * \psi_k)(x).$$

Clearly we have $\varphi_k \in \mathcal{D}(\mathbb{R}^n)$ since each χ_k has compact support.

Now, take any $\vartheta \in \mathcal{D}(\mathbb{R}^n)$, then we have

$$\begin{aligned}\langle \varphi_k, \vartheta \rangle &= \langle \chi_k(u * \psi_k), \vartheta \rangle = \langle u * \psi_k, \chi_k \vartheta \rangle = \left[(u * \psi_k) * \widetilde{\chi_k \vartheta} \right](0) \\ &= \left[u * (\psi_k * \widetilde{\chi_k \vartheta}) \right](0).\end{aligned}$$

Now we compute $\psi_k * \widetilde{\chi_k \vartheta}$: note that

$$\begin{aligned}(\psi_k * \widetilde{\chi_k \vartheta})(x) &= \int_{\mathbb{R}^n} k^n \psi(k(x-y)) \chi\left(-\frac{y}{k}\right) \vartheta(-y) \, dy \\ &= \int_{\mathbb{R}^n} \psi(y) \chi\left(\frac{y}{k^2} - \frac{x}{k}\right) \vartheta\left(\frac{y}{k} - x\right) \, dy \\ &= \vartheta(-x) + R_k(-x) = (\vartheta + \widetilde{R_k})(x)\end{aligned}$$

where $R_k(x) = \int_{\mathbb{R}^n} \psi(y) \left[\chi\left(\frac{y}{k^2} + \frac{x}{k}\right) \vartheta\left(\frac{y}{k} + x\right) - \vartheta(x) \right] \, dy$.

So

$$\langle \varphi_k, \vartheta \rangle = (u * (\vartheta + \widetilde{R_k}))(0) = (u * \check{\vartheta})(0) + (u * \widetilde{R_k})(0) = \langle u, \vartheta \rangle + \langle u, R_k \rangle.$$

We must now only prove that $R_k \rightarrow 0$ in $\mathcal{D}(\mathbb{R}^n)$, and then by sequential continuity it follows that $\varphi_k \rightarrow u$ in $\mathcal{D}'(\mathbb{R}^n)$. \square

2 Distributions with compact support

Definition 2.1. Let $Y \subseteq X$ be open and $u \in \mathcal{D}'(X)$. We say that u *vanishes* on Y if $\langle u, \varphi \rangle = 0$ for all $\varphi \in \mathcal{D}(Y)$.

Definition 2.2. For $u \in \mathcal{D}'(X)$, we define the *support* of u as

$$\text{supp } u := X \setminus \bigcup \{Y \subseteq X \mid Y \text{ open, } u \text{ vanishes on } Y\}.$$

For example, the support of δ_x is simply $\{x\}$.

2.1 Test functions and distributions

We will now consider a bigger space of test functions, which yields a smaller space of distributions.

Definition 2.3. We define $\mathcal{E}(X)$ as the space of smooth functions $\varphi: X \rightarrow \mathbb{C}$. We say that a sequence $(\varphi_m) \subseteq \mathcal{E}(X)$ converges to 0 if $\partial^\alpha \varphi \rightarrow 0$ uniformly on compact subsets of X for every multi-index α .

Definition 2.4. We define $\mathcal{E}'(X)$ as the space of linear maps $u: \mathcal{E}(X) \rightarrow \mathbb{C}$ for which there exists a compact $K \subseteq X$ and nonnegative constants C, N such that

$$|\langle u, \varphi \rangle| \leq C \sum_{|\alpha| \leq N} \sup_K |\partial^\alpha \varphi| \quad (2)$$

for all $\varphi \in \mathcal{E}(X)$.

Lemma 2.5 (Sequential continuity). *Let $u: \mathcal{E}(X) \rightarrow \mathbb{C}$ be a linear map. Then $u \in \mathcal{E}'(X)$ if and only if, for every sequence $(\varphi_m) \subseteq \mathcal{E}(X)$ with $\varphi_m \rightarrow 0$, we have $\langle u, \varphi_m \rangle \rightarrow 0$.*

Proof. **TODO:** □

Lemma 2.6. *If $u \in \mathcal{E}'(X)$, then $u|_{\mathcal{D}(X)}$ defines an element of $\mathcal{D}'(X)$ with compact support and finite order.*

Conversely, for each $u \in \mathcal{D}'(X)$ with compact support there exists a unique extension $\tilde{u} \in \mathcal{E}'(X)$ with $\text{supp}(\tilde{u}) = \text{supp}(u)$ and $\tilde{u}|_{\mathcal{D}(X)} = u$.

Proof. Let $u \in \mathcal{E}'(X)$, so that there exists a compact $K \subseteq X$ with $|\langle u, \varphi \rangle| \leq C \sum_{|\alpha| \leq N} \sup_K |\partial^\alpha \varphi|$. Now, for any compact $K' \subseteq X$ and any φ with $\text{supp } \varphi \subseteq K'$, eq. (1) is clearly satisfied, and we can use the same N for all compact K' , so clearly $u|_{\mathcal{D}(X)}$ is an element of $\mathcal{D}'(X)$ with finite order. Finally, suppose φ is supported in $X \setminus K$, then it is clear that $\langle u, \varphi \rangle = 0$, which proves that $\text{supp } u \subseteq K$ and therefore that u has compact support.

Now suppose $u \in \mathcal{D}'(X)$ has compact support, let $\rho \in \mathcal{D}(X)$ be 1 in a neighbourhood of $\text{supp } u$, and define $\tilde{u} \in \mathcal{E}'(X)$ by

$$\langle \tilde{u}, \varphi \rangle := \langle u, \rho \varphi \rangle \quad \forall \varphi \in \mathcal{E}(X).$$

Clearly \tilde{u} is an element of $\mathcal{E}'(X)$ since $\text{supp}(\rho \varphi) \subseteq \text{supp } \rho$ and

$$|\langle \tilde{u}, \varphi \rangle| = |\langle u, \rho \varphi \rangle| \leq C \sum_{|\alpha| \leq N} \sup_{\text{supp}(\rho)} |\partial^\alpha (\rho \varphi)| \stackrel{*}{\leq} C' \sum_{|\alpha| \leq N} \sup_{\text{supp } \rho} |\partial^\alpha \varphi|,$$

where \star follows from the Leibniz rule. It is also clear that $\text{supp } \tilde{u} = \text{supp } u$.

Finally we will show uniqueness: suppose \tilde{v} is an extension of u with $\text{supp } \tilde{v} = \text{supp } u$, and write any $\varphi \in \mathcal{E}(X)$ as $\varphi = \rho \varphi + (1 - \rho) \varphi = \varphi_0 + \varphi_1$. Then since $\varphi_0 \in \mathcal{D}(X)$ and φ_1 vanishes on a neighbourhood of $\text{supp } u$, we find

$$\langle \tilde{v}, \varphi \rangle = \langle \tilde{v}, \varphi_0 + \varphi_1 \rangle = \langle \tilde{v}, \varphi_0 \rangle = \langle u, \varphi_0 \rangle,$$

which is independent of choice of extension. □

2.2 Convolution between distributions

Definition 2.7. Define for $u \in \mathcal{E}'(\mathbb{R}^n), \varphi \in \mathcal{E}(\mathbb{R}^n)$ the *convolution*

$$(u * \varphi)(x) = \langle u, \tau_x \tilde{\varphi} \rangle.$$

This convolution satisfies the same properties as the convolution between $\mathcal{D}'(\mathbb{R}^n)$ and $\mathcal{D}(\mathbb{R}^n)$. Also, if $\varphi \in \mathcal{D}(\mathbb{R}^n)$, then $u * \varphi \in \mathcal{D}(\mathbb{R}^n)$.

Definition 2.8. Let $u, v \in \mathcal{D}'(\mathbb{R}^n)$, at least one of which has compact support, define $u * v : \mathcal{D}(\mathbb{R}^n) \rightarrow \mathcal{E}(\mathbb{R}^n)$ by

$$(u * v) * \varphi = u * (v * \varphi) \quad \forall \varphi \in \mathcal{D}(\mathbb{R}^n).$$

We will show (example sheet 2, question 1) that $u * v$ is uniquely defined and gives rise to an element of $\mathcal{D}'(\mathbb{R}^n)$ via $\langle u * v, \varphi \rangle := [(u * v) * \tilde{\varphi}](0)$.

Lemma 2.9. Given $u, v \in \mathcal{D}'(\mathbb{R}^n)$, at least one of which has compact support, we have $u * v = v * u$.

Proof. First we note that $(u * \varphi) * \psi = u * (\varphi * \psi)$ holds if u has compact support and at least one of φ, ψ has compact support.

Fix $\varphi, \psi \in \mathcal{D}(\mathbb{R}^n)$, we see from our earlier shown properties that

$$(u * v) * (\varphi * \psi) = u * (v * (\varphi * \psi)) = u * ((v * \varphi) * \psi) = u * (\psi * (v * \varphi)) = (u * \psi) * (v * \varphi).$$

If we interchange u and v in the above, that is equivalent to interchanging φ and ψ , which we know must yield the same result. This shows $u * v$ and $v * u$ agree on $\varphi * \psi$ for all $\varphi, \psi \in \mathcal{D}(\mathbb{R}^n)$. Defining $E = u * v - v * u$, we find that $0 = E * (\varphi * \psi) = (E * \varphi) * \psi$ for all $\varphi, \psi \in \mathcal{D}(\mathbb{R}^n)$, so $E * \varphi = 0$ for all $\varphi \in \mathcal{D}(\mathbb{R}^n)$, so $E = 0$. \square

3 Tempered distributions and Fourier analysis

3.1 Functions of rapid decay

Definition 3.1. For any $f : \mathbb{R}^n \rightarrow \mathbb{C}$ and multi-indices α, β we define $\|f\|_{\alpha, \beta} := \sup_{x \in \mathbb{R}^n} |x^\alpha \partial^\beta f|$.

We define the *Schwartz space*

$$\mathcal{S}(\mathbb{R}^n) := \left\{ f \in C^\infty(\mathbb{R}^n) : \|f\|_{\alpha, \beta} < \infty \text{ for all } \alpha, \beta \right\}.$$

We say that a sequence $(\varphi_n) \subseteq \mathcal{S}(\mathbb{R}^n)$ converges to 0 if $\|\varphi_n\|_{\alpha, \beta} \rightarrow 0$ for every α, β .

Example 3.2. The function $x \mapsto \exp(-\|x\|^2)$ lies in $\mathcal{S}(\mathbb{R}^n)$.

Proposition 3.3. For all n we have that $\mathcal{S}(\mathbb{R}^n) \subseteq L^1(\mathbb{R}^n)$.

Proof. Let $\varphi \in \mathcal{S}(\mathbb{R}^n)$, then for all $N \in \mathbb{N}$ we have

$$\int_{\mathbb{R}^n} |\varphi(x)| dx = \int_{\mathbb{R}^n} (1 + \|x\|)^{-N} (1 + \|x\|)^N |\varphi(x)| dx \stackrel{?}{\leq} C \sum_{|\alpha| \leq N} \|\varphi\|_{\alpha, 0} \int_{\mathbb{R}^n} (1 + \|x\|)^{-N} dx.$$

Since $\int_{\mathbb{R}^n} (1 + \|x\|)^{-N} dx$ is finite for N large enough (??), this proves the claim. \square

Definition 3.4. A linear map $u : \mathcal{S}(\mathbb{R}^n) \rightarrow \mathbb{C}$ is called a *tempered distribution* if there exists constants C, N such that

$$|\langle u, \varphi \rangle| \leq C \sum_{|\alpha|, |\beta| \leq N} \|\varphi\|_{\alpha, \beta} \quad \text{for all } \varphi \in \mathcal{S}(\mathbb{R}^n).$$

The space of tempered distributions is denoted by $\mathcal{S}'(\mathbb{R}^n)$.

This definition is equivalent to sequential continuity.

3.2 The Fourier transform on Schwartz functions

Convention. We write $D := -i\partial$ and $D^\alpha = (-i)^{|\alpha|}\partial^\alpha$.

Definition 3.5. For $f \in L^1(\mathbb{R}^n)$, define the *Fourier transform* of f by

$$[\mathcal{F}(f)](\lambda) = \hat{f}(\lambda) := \int_{\mathbb{R}^n} e^{-i\lambda \cdot x} f(x) \, dx \quad \text{where } \lambda \in \mathbb{R}^n.$$

Lemma 3.6. If $f \in L^1(\mathbb{R}^n)$, then \hat{f} is continuous.

Proof. If $\lambda_m \rightarrow \lambda \in \mathbb{R}^n$, then by the dominated convergence theorem we have

$$\hat{f}(\lambda_m) = \int_{\mathbb{R}^n} e^{-i\lambda_m \cdot x} f(x) \, dx \stackrel{\text{DCT}}{=} \int_{\mathbb{R}^n} e^{-i\lambda \cdot x} f(x) \, dx = \hat{f}(\lambda),$$

where we were able to use the dominated convergence theorem since the integrand is absolutely bounded by $|f|$ and $f \in L^1$. \square

It turns out that this idea generalises: the faster the function f decays, the smoother the Fourier transform \hat{f} is.

Lemma 3.7. For $\varphi \in \mathcal{S}(\mathbb{R}^n)$, we have $\mathcal{F}[D_x^\alpha \varphi](\lambda) = \lambda^\alpha \hat{\varphi}(\lambda)$ and $\mathcal{F}[x^\beta \varphi](\lambda) = (-1)^{|\beta|} D_\lambda^\beta \hat{\varphi}(\lambda)$.

Proof. Since $|x^\alpha D^\beta \varphi| \rightarrow 0$ as $\|x\| \rightarrow \infty$, we have using integration by parts

$$\begin{aligned} \mathcal{F}[D_\lambda^\alpha \varphi](\lambda) &= \int_{\mathbb{R}^n} e^{-i\lambda \cdot x} D_x^\alpha \varphi(x) \, dx \\ &= (-1)^{|\alpha|} \int_{\mathbb{R}^n} D_x^\alpha (e^{-i\lambda \cdot x}) \varphi(x) \, dx \\ &= \lambda^\alpha \hat{\varphi}(\lambda). \end{aligned}$$

For the second part of the lemma, by differentiation under the integral sign we get

$$\begin{aligned} \mathcal{F}[x^\beta \varphi](\lambda) &= \int_{\mathbb{R}^n} e^{-i\lambda \cdot x} x^\beta \varphi(x) \, dx \\ &= \int_{\mathbb{R}^n} ((-D_\lambda)^\beta e^{-i\lambda \cdot x}) \varphi(x) \, dx \\ &= (-1)^{|\beta|} D_\lambda^\beta \hat{\varphi}(\lambda). \end{aligned}$$

\square

We define the *inverse Fourier transform* by

$$\mathcal{F}^{-1}[\hat{f}](x) := \frac{1}{(2\pi)^n} \int_{\mathbb{R}^n} e^{i\lambda \cdot x} \hat{f}(\lambda) \, d\lambda.$$

We will now show that on $\mathcal{S}(\mathbb{R}^n)$, the inverse Fourier transform is indeed an inverse:

Theorem 3.8. The Fourier transform \mathcal{F} defines a continuous isomorphism from $\mathcal{S}(\mathbb{R}^n)$ to itself.

Proof. Let $\varphi \in \mathcal{S}(\mathbb{R}^n)$. First, we show that $\hat{\varphi} \in \mathcal{S}(\mathbb{R}^n)$: by the previous lemma we have for multi-indices α, β that

$$\begin{aligned} |\lambda^\alpha (-D_\lambda)^\beta \hat{\varphi}(\lambda)| &= |\lambda^\alpha \mathcal{F}[x^\beta \varphi](\lambda)| = |\mathcal{F}[D_x^\alpha (x^\beta \varphi)](\lambda)| = \left| \int_{\mathbb{R}^n} e^{-i\lambda \cdot x} D^\alpha (x^\beta \varphi) \, dx \right| \\ &\leq \int_{\mathbb{R}^n} |D^\alpha (x^\beta \varphi)| \, dx, \end{aligned} \tag{3}$$

which is finite since $D^\alpha(x^\beta\varphi)$ is also a Schwartz function and therefore integrable.

From the previous lemma we also infer that $\hat{\varphi}$ is smooth, so indeed we have $\hat{\varphi} \in \mathcal{S}(\mathbb{R}^n)$. From eq. (3) it is also easily seen that if $\varphi_m \rightarrow 0$ in $\mathcal{S}(\mathbb{R}^n)$, then $\hat{\varphi}_m \rightarrow 0$ in $\mathcal{S}(\mathbb{R}^n)$ also, which shows that \mathcal{F} is continuous.

To prove surjectivity and injectivity, we will show that $\mathcal{F}^{-1}[\mathcal{F}[f]](x) = f(x)$ (???). Indeed we have

$$\begin{aligned}\mathcal{F}^{-1}[\mathcal{F}[\varphi]](x) &= \frac{1}{(2\pi)^n} \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} e^{i\lambda \cdot (x-y)} \varphi(y) \, dy \, d\lambda \\ &= \frac{1}{(2\pi)^n} \lim_{\varepsilon \downarrow 0} \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} e^{i\lambda \cdot (x-y) - \varepsilon \|\lambda\|^2} \varphi(y) \, dy \, d\lambda \\ &\stackrel{*}{=} \frac{1}{(2\pi)^n} \lim_{\varepsilon \downarrow 0} \int_{\mathbb{R}^n} \varphi(y) \int_{\mathbb{R}^n} e^{i\lambda \cdot (x-y) - \varepsilon \|\lambda\|^2} \, d\lambda \, dy,\end{aligned}$$

where \star follows from Fubini's theorem.

Now we note that

$$\int_{\mathbb{R}^n} e^{i\lambda \cdot (x-y) - \varepsilon \|\lambda\|^2} \, d\lambda = \prod_{i=1}^n \int_{\mathbb{R}} e^{i\lambda_j(x_j - y_j) - \varepsilon \lambda_j^2} \, d\lambda \stackrel{**}{=} \prod_{i=1}^n \left(\frac{\pi}{\varepsilon}\right)^{1/2} e^{-\frac{(x_i - y_i)^2}{4\varepsilon}} = \left(\frac{\pi}{\varepsilon}\right)^{n/2} e^{-\frac{\|x-y\|^2}{4\varepsilon}}.$$

To explain $**$, **TODO:** .

and plugging that into the above yields

$$\begin{aligned}\mathcal{F}^{-1}[\mathcal{F}[\varphi]](x) &= \lim_{\varepsilon \downarrow 0} 2^{-n} (\pi\varepsilon)^{-n/2} \int_{\mathbb{R}^n} \varphi(y) e^{-\|x-y\|^2/(4\varepsilon)} \, dy \\ &\stackrel{***}{=} \pi^{-n/2} \lim_{\varepsilon \downarrow 0} \int_{\mathbb{R}^n} \varphi(x - 2\sqrt{\varepsilon}y') e^{-\|y'\|^2} \, dy \\ &\stackrel{\text{DCT}}{=} \pi^{-n/2} \varphi(x) \int_{\mathbb{R}^n} e^{-\|y'\|^2} \, dy = \varphi(x),\end{aligned}$$

where $***$ follows from the substitution $x - y = 2\sqrt{\varepsilon}y'$.

Finally, continuity of \mathcal{F}^{-1} is easily shown with an argument analogous to that for continuity of \mathcal{F} (????). \square

3.3 The Fourier transform on tempered distributions

Lemma 3.9. For $\varphi, \psi \in \mathcal{S}(\mathbb{R}^n)$, we have $\int_{\mathbb{R}^n} \varphi(x) \hat{\psi}(x) \, dx = \int_{\mathbb{R}^n} \hat{\varphi}(x) \psi(x) \, dx$.

Proof. This follows from Fubini's theorem:

$$\int_{\mathbb{R}^n} \varphi(x) \hat{\psi}(x) \, dx = \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \varphi(x) \psi(\lambda) e^{-i\lambda \cdot x} \, d\lambda \, dx = \int_{\mathbb{R}^n} \int_{\mathbb{R}^n} \psi(\lambda) \varphi(x) e^{-i\lambda \cdot x} \, dx \, d\lambda = \psi(\lambda) \psi(\lambda) \hat{\varphi}(\lambda) \, d\lambda.$$

\square

The above result can be rewritten as $\langle \hat{\varphi}, \psi \rangle = \langle \varphi, \hat{\psi} \rangle$, which motivates the definition of the Fourier transform for tempered distributions:

Definition 3.10. For $u \in \mathcal{S}'(\mathbb{R}^n)$, we define its Fourier transform by

$$\langle \hat{u}, \varphi \rangle := \langle u, \hat{\varphi} \rangle \quad \text{for all } \varphi \in \mathcal{S}(\mathbb{R}^n).$$

Using sequential continuity and theorem 3.8, it is easily seen that \hat{u} is indeed an element of $\mathcal{S}'(\mathbb{R}^n)$.

Example 3.11. It is easily checked that $\delta_0 \in \mathcal{S}'(\mathbb{R}^n)$, and we can compute

$$\langle \hat{\delta}_0, \varphi \rangle = \langle \delta_0, \hat{\varphi} \rangle = \hat{\varphi}(0) = \int_{\mathbb{R}^n} \varphi(x) dx = \langle 1, \varphi \rangle,$$

so we can write $\hat{\delta}_0 = 1$. Analogously, by the Fourier inversion theorem we have

$$\langle \hat{1}, \varphi \rangle = \langle 1, \hat{\varphi} \rangle = \int_{\mathbb{R}^n} \hat{\varphi}(\lambda) d\lambda = (2\pi)^n \varphi(0) = \langle (2\pi)^n \delta_0, \varphi \rangle,$$

so we write $\hat{1} = (2\pi)^n \delta_0$.

We can easily generalise lemma 3.7 to the Fourier transform on $\mathcal{S}'(\mathbb{R}^n)$, so

$$\mathcal{F}[D^\alpha u] = \lambda^\alpha \hat{u}, \quad \mathcal{F}[x^\beta u] = (-D^\beta) \hat{u}.$$

Theorem 3.12. *The Fourier transform \mathcal{F} extends to a continuous isomorphism on $\mathcal{S}'(\mathbb{R}^n)$.*

Proof. We claim that $\check{u} = (2\pi)^{-n} \mathcal{F}[\mathcal{F}[u]]$. To check this, note that by the Fourier inversion theorem we have for $\varphi \in \mathcal{S}(\mathbb{R}^n)$ that

$$\check{\varphi}(x) = \varphi(-x) = (2\pi)^{-n} \int_{\mathbb{R}^n} e^{-i\lambda \cdot x} \hat{\varphi}(\lambda) d\lambda = (2\pi)^{-n} \mathcal{F}[\mathcal{F}[\varphi]](x),$$

and therefore

$$\langle \check{u}, \varphi \rangle = \langle u, \check{\varphi} \rangle = \langle u, (2\pi)^{-n} \mathcal{F}[\mathcal{F}[\varphi]] \rangle = \langle (2\pi)^{-n} \mathcal{F}[\mathcal{F}[u]], \varphi \rangle.$$

This shows that \mathcal{F} is bijective (since $\mathcal{F} \circ \mathcal{F}$ is bijective). For continuity of \mathcal{F} and its inverse: using theorem 3.8, we find

$$\begin{aligned} u_m &\rightarrow 0 \text{ in } \mathcal{S}'(\mathbb{R}^n) \\ \iff \langle u_m, \varphi \rangle &\rightarrow 0 \quad \forall \varphi \in \mathcal{S}(\mathbb{R}^n) \\ \iff \langle u_m, \hat{\varphi} \rangle &\rightarrow 0 \quad \forall \varphi \in \mathcal{S}(\mathbb{R}^n) \\ \iff \langle \hat{u}_m, \varphi \rangle &\rightarrow 0 \quad \forall \varphi \in \mathcal{S}(\mathbb{R}^n) \\ \iff \hat{u}_m &\rightarrow 0 \text{ in } \mathcal{S}'(\mathbb{R}^n). \end{aligned}$$

□

3.4 Sobolev spaces

Convention. We write $\langle \lambda \rangle := (1 + \|\lambda\|)^2$ for $\lambda \in \mathbb{R}^n$. Note that $\langle \lambda \rangle \sim 1$ as $\|\lambda\| \rightarrow 0$ and $\langle \lambda \rangle \rightarrow \|\lambda\|$ as $\|\lambda\| \rightarrow \infty$.

Definition 3.13. For $s \in \mathbb{R}$, define the *Sobolev space* $H^s(\mathbb{R}^n)$ to be the set of tempered distributions $u \in \mathcal{S}'(\mathbb{R}^n)$ for which \hat{u} can be identified with a measurable function $\hat{u}: \mathbb{R}^n \rightarrow \mathbb{C}$ such that $\langle \lambda \rangle^s \hat{u} \in L^2(\mathbb{R}^n)$.

Lemma 3.14 (Sobolev lemma). *If $u \in H^s(\mathbb{R}^n)$ with $s > \frac{n}{2}$, then u is continuous.*

Proof. We will show that \hat{u} is integrable. By Cauchy-Schwarz, we have

$$\begin{aligned} \int_{\mathbb{R}^n} |\hat{u}(\lambda)| d\lambda &= \int_{\mathbb{R}^n} \langle \lambda \rangle^{-s} \langle \lambda \rangle^s |\hat{u}(\lambda)| d\lambda \\ &\leq \left(\int_{\mathbb{R}^n} \langle \lambda \rangle^{-2s} d\lambda \right)^{1/2} \|u\|_{H^s} \\ &= C \|u\|_{H^s} \left(\int_0^\infty r^{n-1} (1 + r^2)^{-s} dr \right)^{1/2}, \end{aligned}$$

where the last line follows from using polar coordinates and C is the area of the $(n-1)$ -sphere.

Writing $s = \frac{n}{2} + \varepsilon$, we find that the integrand $r^{n-1}(1+r^2)^{-s}$ is of order $O(r^{-1-2\varepsilon})$ as $r \rightarrow \infty$, and therefore the integral is finite, so indeed we have $\hat{u} \in L^1(\mathbb{R}^n)$.

By applying theorem 3.8 to a test function, we can show that $u = (2\pi)^{-n} \int_{\mathbb{R}^n} e^{i\lambda \cdot x} \hat{u}(\lambda) \, d\lambda$, which is continuous by the dominated convergence theorem. \square