1. Fourier’s treatment of the heat equation

The heat equation on \([0, 1] \times [0, +\infty)\), thinking \(x \in [0, 1]\) as the physical coordinate and \(t \in [0, +\infty)\) as time, is

\[
\Delta_x u = \frac{\partial}{\partial t} u \quad \text{with} \quad u(x, 0) = f(x) \text{ prescribed}
\]

Fourier solved this equation by expressing \([1]\)

\[
u(x, t) = \sum_n c_n(t) e^{2\pi i n x} \]

Assuming we can differentiate termwise in \(x\),

\[
\Delta u(x, t) = \Delta_x \sum_n c_n(t) e^{2\pi i n x} = \sum_n c_n(t) \Delta_x e^{2\pi i n x} = \sum_n (2\pi i n)^2 \cdot c_n(t) e^{2\pi i n x}
\]

Differentiating term-wise in \(t\), apparently the differential equation is

\[
\sum_n (2\pi i n)^2 \cdot c_n(t) e^{2\pi i n x} = \frac{\partial}{\partial t} \sum_n c_n(t) e^{2\pi i n x} = \sum_n c'_n(t) e^{2\pi i n x}
\]

Assuming uniqueness of Fourier expansions, we find

\[
c'_n(t) = (2\pi i n)^2 \cdot c_n(t) \quad \text{(for all} \quad n \in \mathbb{Z})
\]

This first-order constant-coefficient differential equation has a one-dimensional solution space \([2]\)

\[
c_n(t) = b_n \cdot e^{-4\pi^2 n^2 t} \quad \text{(for some constant} \quad b_n )
\]

\[1\] Naturally, Fourier used sines and cosines, not complex exponentials.

\[2\] The Mean Value Theorem proves uniqueness.
The initial condition \( u(x, 0) = f(x) \) gives

\[
\sum_n b_n e^{2\pi inx} = f(x)
\]

That is, the constants \( b_n \) are determined by the Fourier coefficients of the initial condition data \( f \).

The Fourier coefficients \( \hat{f}(n) \) of a function are the coefficients in a Fourier expansion

\[
f(x) = \sum_n \hat{f}(n) e^{2\pi inx} \quad \text{(convergence in what sense???)}
\]

Even before Fourier, Euler and others already knew a formula for the Fourier coefficients, and this formula can be derived under the assumption that \( f \) has such a Fourier expansion. Namely, integrate against \( e^{-2\pi in_0x} \), assuming we can exchange the sum and integral:

\[
\int_0^1 e^{-2\pi in_0x} f(x) \, dx = \int_0^1 e^{-2\pi in_0x} \sum_n \hat{f}(n) e^{2\pi inx} \, dx = \sum_n \hat{f}(n) \int_0^1 e^{-2\pi in_0x} e^{2\pi inx} \, dx = \hat{f}(n_0)
\]

because of the orthonormality

\[
\int_0^1 e^{-2\pi imx} e^{2\pi inx} = \begin{cases} 1 & \text{for } m = n \\ 0 & \text{for } m \neq n \end{cases}
\]

This discussion already raises many issues. One further issue was raised by the goal of showing that with a point source as the initial condition, the heat is asymptotically evenly distributed. From our viewpoint, this is asking how to express a version of Dirac’s \( \delta \) in Fourier series.

2. Issues

The exponentials \( e^{cx} \) are eigenvectors/eigenfunctions for the differential operator \( d/dx \). Among them, the exponentials \( \psi_n(x) = e^{2\pi inx} \) are exactly the those that are periodic in the sense that \( \psi_n(x + \ell) = \psi_n(x) \) for \( \ell \in \mathbb{Z} \). Thus, to the extent everything makes sense, a Fourier series naturally gives the periodic extension (denoted here by the same symbol) of a function \( f \) on \([0, 1]\) by defining \( f(x + n) = f(x) \) for \( n \in \mathbb{Z} \) and \( x \in [0, 1] \).

Therefore, here and in the sequel, to examine Fourier series of functions, we consider functions on the interval \([0, 1]\) as being extended by periodicity. Yes, there is potential conflict in the definition at endpoints/integers!

Yes, a function \( f \) that is continuous on \([0, 1]\) will produce a non-continuous periodic extension unless \( f(0) = f(1) \). A function \( f \) that is \( C^1 \) on \([0, 1]\) will produce a non-\( C^1 \) extension unless \( f(0) = f(1) \) and \( f'(0) = f'(1) \), and so on. Attention to these distinctions is necessary, since the behavior of Fourier series of a function \( f \) on \([0, 1]\) reflects the behavior of its periodic extension.
Some even-more-fundamental issues are:

In what sense(s) can a function be expressed as a Fourier series?

Do Fourier series give pointwise values of functions?

Can a Fourier series be differentiated term-by-term?

How cautious must we be in differentiating functions that are only piecewise differentiable?

What will derivatives of discontinuous functions be?

What is the Fourier expansion of the periodic version of Dirac’s δ?

Several further issues are implicit, and the best answers need viewpoints created first in 1906 by Beppo Levi, 1907 by G. Frobenius, in the 1930’s by Sobolev, and Schwartz post-1949, enabling legitimate discussion of generalized functions (also known as distributions).

There are natural technical questions, like

Why define generalized functions as dual spaces?

In brief, Schwartz’ 1940’s insight to define generalized functions as dual spaces is a natural consequence of one natural relaxation of the notion of function. Rather than demand that functions produce pointwise values, which precipitated endless classical discussion of what to do with jump discontinuities, instead declare that functions in the broadest sense are merely things that can be integrated against. For given φ, the map that integrates against φ,

$$f \rightarrow \int f(x) \varphi(x) \, dx$$

is a functional (a C-valued linear map), and is, or ought to be, probably continuous in a reasonable topology. To consider the collection of all continuous linear functionals is a reasonable way to enlarge the collection of functions, as things to be integrated against.

From the other side, it might have been that this generalization of function is needlessly extravagant, but it turns out that every distribution on the circle $\mathbb{T}$ is a high-order derivative of a continuous function. Thus, since we do want to be able to take derivatives indefinitely, there is no waste.

Further, in any of the several natural topologies on distributions, very nice ordinary functions are dense, and the space of distributions is complete in a sense subsuming that for metric spaces. Thus, taking limits yields all distributions, and produces no excess.

This discussion is easiest on the circle $\mathbb{T}$, or products $\mathbb{T}^n$ of circles, making use of Fourier series, and clarifying many technical questions about Fourier series. This story is a prototype for more complicated examples.

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[3] At about the time Fourier was promoting Fourier series, Abel proved that convergent power series can be differentiated term-by-term in the interior of their interval (on $\mathbb{R}$) or disk (in $\mathbb{C}$) of convergence, and are infinitely-differentiable functions. Abel’s result fit the optimistic expectations of the time, but created unreasonable expectations for the behavior of Fourier series.

[4] K. Friedrichs’ important 1934-5 discussions of semi-bounded unbounded operators on Hilbert spaces used norms defined in terms of derivatives, but only internally in proofs, while for Levi, Frobenius, and Sobolev these norms were significant objects themselves.

[5] The classic reference is A. Zygmund, *Trigonometric Series, I, II*, first published in Warsaw in 1935, reprinted several times, including a 1959 Cambridge University Press edition. The present discussion neglects many interesting details, but is readily adaptable to more complicated situations, so necessarily our treatment is different from Zygmund’s.
There is an important auxiliary technical point. Natural spaces of functions do not have structures of Hilbert spaces, but typically, of Banach spaces. Nevertheless, the simplicity of Hilbert spaces motivates comparisons of natural function spaces with related Hilbert spaces. Such comparisons are Levi-Sobolev imbeddings or Levi-Sobolev inequalities.

The present discussion presumes acquaintance with the basics of Fourier series, namely, the Fourier-Dirichlet kernel, the theorem of Fourier-Dirichlet on pointwise convergence for finitely-piecewise-continuous at points with left derivative and right derivative, Féjer’s kernel, Féjer’s theorem on the density of finite Fourier series in $C^\infty(T)$, and completeness of exponentials in $L^2(T)$.

We also presume that the notion of (projective) limit of Banach spaces is appreciated to some degree, at least in examples such as the nested intersection

$$C^\infty(T) = \bigcap_k C^k(T) = \lim_k C^k(T)$$

We recall this, and introduce colimits, especially in the case of ascending unions of spaces of duals of limits.

3. Provocative example

Let $s(x)$ be the sawtooth function\footnote{One may also take $s(x) = x$ for $-\frac{1}{2} < x < \frac{1}{2}$ and extend by periodicity. This definition avoids the subtraction of $\frac{1}{2}$, and has the same operational features. In the end, it doesn’t matter.} $s(x) = x - \frac{1}{2}$ (for $0 \leq x < 1$) and made periodic by demanding $s(x + n) = s(x)$ for all $n \in \mathbb{Z}$. In other words, letting $\lfloor x \rfloor$ be the greatest integer less than or equal $x$,

$$s(x) = x - \lfloor x \rfloor - \frac{1}{2} \quad \text{(for } x \in \mathbb{R})$$

Away from $x \in \mathbb{Z}$, the sawtooth function is infinitely differentiable, with derivative 1. At $x \in \mathbb{Z}$ the sawtooth jumps down from value $\frac{1}{2}$ to value $-\frac{1}{2}$. There is no reason to worry about defining a value at $x \in \mathbb{Z}$.

The exponential functions $\psi_n(x) = e^{2\pi inx}$ are an orthonormal basis for the Hilbert space $L^2[0, 1]$. Anticipating that Fourier coefficients $\hat{f}(n)$ of $\mathbb{Z}$-periodic functions $f$ are computed\footnote{Apparently at first Fourier did not have this expression for the Fourier coefficients!} by integrating against $\psi_n(x) = e^{2\pi inx}$ (conjugated):

$$\hat{f}(n) = \int_0^1 f(x) e^{-2\pi inx} \, dx$$

integration by parts gives

$$\hat{s}(n) = \int_0^1 s(x) \cdot e^{-2\pi inx} \, dx = \begin{cases} \frac{1}{-2\pi in} & (\text{for } n \neq 0) \\ 0 & (\text{for } n = 0) \end{cases}$$

Thus, in whatever sense a function is its Fourier expansion, we anticipate that

$$s(x) \sim \sum_{n \in \mathbb{Z}} \hat{s}(n) \cdot e^{2\pi inx} = \sum_{n \neq 0} \frac{1}{-2\pi in} \cdot e^{2\pi inx}$$
Even though this series does not converge absolutely for any value of $x$, we already know (by Fourier-Dirichlet) that it does converge to the value of $s(x)$ for $x \notin \mathbb{Z}$. Since $s(x)$ has discontinuities at $\mathbb{Z}$ anyway, this is hardly surprising. Nothing disturbing has happened.

Now differentiate. The sawtooth function is differentiable away from $\mathbb{Z}$, with value 1, and with uncertain value at $\mathbb{Z}$. With exogenous reasons to differentiate the Fourier series term-by-term, with or without confidence in doing so, and the blatant differentiability of $s(x)$ away from $\mathbb{Z}$ suggests it’s not entirely ridiculous to differentiate term-by-term. Then

$$s'(x) = \begin{cases} 1 \text{ (for } x \notin \mathbb{Z}) \\ ? \text{ (for } x \in \mathbb{Z}) \end{cases} \sim - \sum_{n \neq 0} e^{2\pi inx}$$

The right-hand side is hard to interpret, certainly as having pointwise values. On the other hand, reasonably interpreted, it is still ok to integrate against this sum: letting $\hat{f}(n)$ be the $n^{th}$ Fourier coefficient of a smooth function $f$, and not worrying about justifications,

$$\int_0^1 f(x) \left( - \sum_{n \neq 0} e^{2\pi inx} \right) \, dx = - \sum_{n \neq 0} \int_0^1 f(x) e^{2\pi inx} \, dx = - \sum_{n \neq 0} \hat{f}(-n)$$

$$= \hat{f}(0) - \sum_{n \in \mathbb{Z}} \hat{f}(n) e^{2\pi in0} = \hat{f}(0) - f(0) = \int_0^1 f(x) \, dx - f(0)$$

The map

$$f \rightarrow \int_0^1 f(x) \, dx - f(0)$$

has a sense for continuous $f$, and gives a functional. That the derivative of the sawtooth is mostly 1 gives the integral of $f$ (against 1) over $[0,1]$. Further, the $-f(0)$ term forcefully suggests that the derivative of the discontinuity of the sawtooth function is the (periodic) evaluation-at-0 functional $f \rightarrow f(0)$ multiplied by $-1$. [8]

[3.1] Remark: A truly disastrous choice at this point would be to think that since $s'(x)$ is almost everywhere 1 (in a measure-theoretic sense) that its singularities are somehow removable, and thus pretend that $s'(x) = 1$. This would give $s''(x) = 0$, and make the following worse than it is, and impossible to explain.

Still, $s'(x)$ is differentiable away from $\mathbb{Z}$, and by repeated differentiation

$$s^{(k+1)}(x) = \begin{cases} 0 \text{ (for } x \notin \mathbb{Z}) \\ ? \text{ (for } x \in \mathbb{Z}) \end{cases} \sim -(2\pi i)^k \sum_{n \neq 0} n^k \cdot e^{2\pi inx}$$

By now the right-hand sides are vividly not convergent. The summands do not go to zero, in fact, are unbounded.

One can continue differentiating in this symbolic sense, but the meaning is unclear.

One reaction is to simply object to differentiating a non-differentiable function, even if its discontinuities are mild. This is not productive.

Another unproductive viewpoint is to deny that Fourier series reliably represent the functions that produced their coefficients.

[8] The jump is downward rather than upward.
A happier and more useful response is to suspect that the above computation is correct, though the question mark needs explanation, and that the right-hand side is correct and meaningful, despite its divergence in classical senses. The question is what meaning to attach. This requires preparation.

We will establish a context in which the derivatives of the sawtooth, and derivatives of other discontinuous functions, are things to integrate against, rather than things to evaluate pointwise, and see that termwise differentiation of Fourier series does capture an extended notion of function and derivative.

4. **Natural function spaces on the circle $\mathbb{T} = \mathbb{R}/\mathbb{Z}$**

We review natural families of functions. In all cases, the object is to give the vector space of functions a metric (if possible) which makes it complete, to allow taking limits inside the same class of functions. For example, pointwise limits of continuous functions easily fail to be continuous, but uniform pointwise limits of continuous functions are continuous.\[9\]

4.1 **Continuous functions and sup-norm**

First, we care about continuous complex-valued functions. Although we have in mind continuous functions on the circle $\mathbb{T} = \mathbb{R}/\mathbb{Z}$, the basic result depends only upon the compactness of $\mathbb{R}/\mathbb{Z}$.

As usual, we give the set $C^0(K)$ of (complex-valued) continuous functions on a compact topological space $K$ the metric

$$d(f, g) = \sup_{x \in K} |f(x) - g(x)|$$

The sup is finite because $K$ is compact and $f - g$ is continuous. The right-hand side of this last equation arises from the (sup) norm

$$|f|_{\infty} = |f|_{C^0} = \sup_{x \in K} |f(x)|$$

and $d(f, g) = |f - g|_{C^0}$. A main feature of continuous functions is that they have pointwise values. Recall the unsurprising but important

4.2 **Claim:** With the $C^0(K)$ topology, for $x \in K$ the evaluation functional\[10\] $C^0(K) \to \mathbb{C}$ by $f \to f(x)$ is continuous.

**Proof:** The inequality

$$|f(x) - g(x)| \leq \sup_{y \in K} |f(y) - g(y)|$$

(for $f, g \in C^0(K)$)

proves the continuity of evaluation. ///

Also, recall, yet again, the iconic

4.3 **Theorem:** The space $C^0(K)$ of (complex-valued) continuous functions on a compact topological space $K$ is complete.

4.4 **Remark:** Thus, being complete with respect to the metric arising in this fashion from a norm, by definition $C^0(K)$ is a Banach space.

---

\[9\] Awareness of such possibilities and figuring out how to avoid them was the fruit of embarrassing errors and experimentation throughout the 19th century. Unifying abstract notions such as metric space and general topological space only became available in the early 20th century, with the work of Hausdorff, Fréchet, and others.

\[10\] As usual, a (continuous) functional is a (continuous) linear map to $\mathbb{C}$. 
**Proof:** This is a typical three-epsilon argument. The point is the completeness, namely that a Cauchy sequence of continuous functions has a pointwise limit which is a continuous function. First we observe that a Cauchy sequence $f_i$ does have a pointwise limit. Given $\varepsilon > 0$, choose $N$ large enough such that for $i, j \geq N$ we have $|f_i - f_j| < \varepsilon$. Then, for any $x$ in $K$, $|f_i(x) - f_j(x)| < \varepsilon$. Thus, the sequence of values $f_i(x)$ is a Cauchy sequence of complex numbers; so has a limit $f(x)$. Further, given $\varepsilon' > 0$, choose $j \geq N$ sufficiently large such that $|f_j(x) - f(x)| < \varepsilon'$. Then for all $i \geq N$

$$|f_i(x) - f(x)| \leq |f_i(x) - f_j(x)| + |f_j(x) - f(x)| < \varepsilon + \varepsilon'$$

Since this is true for every positive $\varepsilon'$

$$|f_i(x) - f(x)| \leq \varepsilon \quad \text{(for all } i \geq N)$$

This holds for every $x$ in $K$, so the pointwise limit is uniform in $x$.

Now prove that $f(x)$ is continuous. Given $\varepsilon > 0$, let $N$ be large enough so that for $i, j \geq N$ we have $|f_i - f_j| < \varepsilon$. From the previous paragraph

$$|f_i(x) - f(x)| \leq \varepsilon \quad \text{(for every } x \text{ and for } i \geq N)$$

Fix $i \geq N$ and $x \in K$, and choose a small enough neighborhood $U$ of $x$ such that $|f_i(x) - f_i(y)| < \varepsilon$ for any $y$ in $U$. Then

$$|f(x) - f(y)| \leq |f(x) - f_i(x)| + |f_i(x) - f_i(y)| + |f(y) - f_i(y)| < \varepsilon + \varepsilon + \varepsilon$$

Thus, the pointwise limit $f$ is continuous at every $x$ in $U$. ///

### 4.5 Differentiation on $\mathbb{T} = \mathbb{R}/\mathbb{Z}$

To talk about differentiability return to the concrete situation of $\mathbb{R}$ and its quotient $\mathbb{T} = \mathbb{R}/\mathbb{Z}$.

The continuous quotient map $q : \mathbb{R} \to \mathbb{R}/2\pi\mathbb{Z}$ yields continuous functions under composition $f \circ q$ for $f \in C^\infty(\mathbb{T}) = C^\infty(\mathbb{R}/\mathbb{Z})$. More is true, namely, that a continuous function $F$ on $\mathbb{R}$ is of the form $f \circ q$ if and only if $F$ is periodic in the sense that $F(x + n) = F(x)$ for all $x \in \mathbb{R}$ and $n \in \mathbb{Z}$. Indeed, the periodicity gives a well-defined function $f$ on $\mathbb{R}/\mathbb{Z}$. Then the continuity of $f$ follows immediately from the definition of the quotient topology on $\mathbb{T} = \mathbb{R}/\mathbb{Z}$.

As usual, a real-valued or complex-valued function $f$ on $\mathbb{R}$ is continuously differentiable if it has a derivative itself a continuous function. That is, the limit

$$\frac{df}{dx}(x) = f'(x) = \lim_{h \to 0} \frac{f(x + h) - f(x)}{h}$$

is required to exist for all $x$, and the function $f'$ is in $C^\infty(\mathbb{R})$. Let $f^{(1)} = f'$, and inductively define

$$f^{(i)} = (f^{(i-1)})' \quad \text{(for } i > 1)$$

when the corresponding limits exist.

We can make explicit the expectation that differentiation on the circle $\mathbb{T} = \mathbb{R}/\mathbb{Z}$ is descended from differentiation on the real line. That is, characterize differentiation on $\mathbb{T} = \mathbb{R}/\mathbb{Z}$ in terms of such a compatibility relation. Thus, for $f \in C^k(\mathbb{T})$, require that the differentiation $D$ on $\mathbb{T}$ be related to the differentiation on $\mathbb{R}$ by

$$(Df) \circ q = \frac{d}{dx}(f \circ q)$$
Via the quotient map $q : \mathbb{R} \to \mathbb{R}/\mathbb{Z}$, make a *preliminary* definition of the collection of $k$-times continuously differentiable functions on $T$, with a topology, by

$$C^k(T) = \{ f \text{ on } T : f \circ q \in C^k(\mathbb{R}) \}$$

with the $C^k$-norm\[^{11}\] \[|f|_{C^k} = \sum_{0 \leq i \leq k} |(f \circ q)^{(i)}|_{\infty} = \sum_{0 \leq i \leq k} \sup_x |(f \circ q)^{(i)}(x)|\]

where $F^{(i)}$ is the (continuous!) $i^{th}$ derivative of $F$ on $\mathbb{R}$. The *associated metric* on $C^k(T)$ is

$$d(f, g) = |f - g|_{C^k}$$

\[4.6\] Remark: Among other features, the norm on the spaces $C^k$ makes continuity of the differentiation map $C^k \to C^{k-1}$ clear.

\[4.7\] Remark: Implicit in this definition is that, viewed as functions on $[0, 1]$, the values and derivatives *must agree at the endpoints*: $f(0) = f(1)$ for $f$ continuous on $T$, $f'(0) = f'(1)$ for $f \in C^1(T)$, and so on. This is not whimsical, but is intrinsic to the structure of $T$.

An often-seen equivalent version of the norm is

$$|f|_{C^k}^\text{var} = \sup_{0 \leq i \leq k} |(f \circ q)^{(i)}|_{\infty} = \sup_{0 \leq i \leq k} \sup_x |(f \circ q)^{(i)}(x)|$$

These two norms give the same topology, since for complex numbers $a_0, \ldots, a_k$

$$\sup_{0 \leq i \leq k} |a_i| \leq \sum_{0 \leq i \leq k} |a_i| \leq (k + 1) \cdot \sup_{0 \leq i \leq k} |a_i|$$

\[4.8\] Claim: There is a unique, well-defined, continuous (differentiation) map $D : C^k(T) \to C^{k-1}(T)$ giving a commutative diagram

$$\begin{array}{ccc}
C^k(\mathbb{R}) & \xrightarrow{\frac{d}{dx}} & C^{k-1}(\mathbb{R}) \\
\downarrow{-q} & & \downarrow{-q} \\
C^k(T) & \xrightarrow{D} & C^{k-1}(T)
\end{array}$$

\[4.9\] Remark: One might feel that the following proof is needlessly complicated. However, it is worthwhile to do it this way. This approach applies broadly, and is as terse as possible without ignoring important details.

Proof: The point is that differentiation of periodic functions yields periodic functions. That is, we claim that, for $f \in C^k(T)$, the pullback $f \circ q$ has derivative $\frac{d}{dx}(f \circ q)$ which is the pullback $g \circ q$ of a unique function $g \in C^{k-1}(T)$. To see this, first recall that, by definition of the quotient topology, a continuous function $F$ on $\mathbb{R}$ descends to a continuous function on $T = \mathbb{R}/\mathbb{Z}$ if and only if it is $\mathbb{Z}$-invariant, that is $F(x + n) = F(x)$ for all $x \in \mathbb{R}$ and $n \in \mathbb{Z}$. Then, from our definition of $C^k(T)$, a function $F \in C^k(\mathbb{R})$ is a pullback via $q$ from

\[11\] Granting that the sup norm on continuous functions is a norm, verification that the $C^k$-norm is a norm is straightforward.
$C^k(\mathbb{R}/\mathbb{Z})$ exactly when $F^{(i)}(x+n) = F^{(i)}(x)$ for all $x \in \mathbb{R}$, $n \in \mathbb{Z}$, and $0 \leq i \leq k$, since then these continuous functions descend to the circle. Let

$$(TyF)(x) = F(x+y) \quad \text{for } x, y \in \mathbb{R}$$

Since $\frac{d}{dx}$ is a linear, constant-coefficient differential operator, the operations $Ty$ and $\frac{d}{dx}$ commute, that is, $\frac{dF}{dx}(x+y) = \frac{d}{dx}(F(x+y))$, which is to say

$$Ty \circ \frac{d}{dx} = \frac{d}{dx} \circ Ty$$

In particular, for $n \in \mathbb{Z}$,

$$T_n(\frac{d}{dx}(f \circ q)) = \frac{d}{dx}(T_n(f \circ q)) = \frac{d}{dx}(f \circ q)$$

This shows that a (continuous) derivative is periodic when the (continuously differentiable) function is periodic.

From the definition of the $C_k$-norm,

$$|Df|_{C_k} = \sum_{0 \leq i \leq k} |f^{(i)}|_\infty = \sum_{0 \leq i \leq k} \sup_{x} |f^{(i)}(x)|$$

so differentiation is continuous.

[4.10] Remark: In light of the uniqueness of differentiation on $\mathbb{T}$, from now on write $d/dx$ for the differentiation $D$ on $\mathbb{T}$, and $f^{(k)}$ for $D^k f$, and rewrite the description of $C^k(\mathbb{T})$ more simply, as

$$C^k(\mathbb{T}) = \{ f \text{ on } \mathbb{T} : f \circ q \in C^k(\mathbb{R}) \}$$

with the $C_k$-norm

$$|f|_{C_k} = \sum_{0 \leq i \leq k} |f^{(i)}|_\infty = \sum_{0 \leq i \leq k} \sup_{x} |f^{(i)}(x)|$$

where $f^{(i)}$ is the (continuous!) $i^{th}$ derivative of $f$. The associated metric on $C^k(\mathbb{T})$ still is

$$d(f, g) = |f - g|_{C_k}$$

There is the alternative norm

$$|f|_{C_k}^{\text{var}} = \sup_{0 \leq i \leq k} \sup_{x} |f^{(i)}(x)| = \sup_{0 \leq i \leq k} |f^{(i)}|_\infty$$

These two norms give the same topology for the same reason as before.

We recall the argument for

[4.11] Claim: With the topology above, the space $C^k(\mathbb{T})$ is complete, so is a Banach space.

Proof: The case $k = 1$ illustrates all the points. For a Cauchy sequence $\{f_n\}$ in $C^1(\mathbb{T})$, both $\{f_n\}$ and $\{f'_n\}$ are Cauchy in $C^0(\mathbb{T})$, so converge uniformly pointwise: let

$$f(x) = \lim_n f_n(x) \quad g(x) = \lim_n f'_n(x)$$

The convergence is uniformly pointwise, so $f$ and $g$ are $C^0$. If we knew that $f$ were pointwise differentiable, then the demonstrated continuity of $\frac{d}{dx} : C^1(\mathbb{T}) \to C^0(\mathbb{T})$ gives the expected conclusion, that $f' = g$.

What could go wrong? One issue is whether $f$ is differentiable at all, and why its derivative is $g$. 

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By the fundamental theorem of calculus, for any index $i$, since $f_i$ is continuous,

$$f_i(x) - f_i(a) = \int_a^x f'_i(t) \, dt$$

Interchanging limit and integral shows that the limit of the right-hand side is

$$\lim_i \int_a^x f'_i(t) \, dt = \int_a^x \lim_i f'_i(t) \, dt = \int_a^x g(t) \, dt$$

Thus, the limit of the left-hand side is

$$f(x) - f(a) = \int_a^x g(t) \, dt$$

from which $f' = g$. That the derivative $f'$ of the limit $f$ is the limit of the derivatives is not a surprise, since if $f$ is differentiable, what else could its derivative be? The point is that $f$ is differentiable, ascertained by computing its derivative, which happens to be $g$. ///

[4.12] Remark: Again, the differentiation map $C^1(T) \to C^0(T)$ is continuous by design. Thus, if a limit of $C^1$ functions $f_n$ is differentiable, its derivative must be the obvious thing, namely, the limit of the derivatives $f'_n$. The issue was whether the limit of the $f_n$ is differentiable. The proof shows that it is differentiable by computing its derivative via the Mean Value Theorem.

By construction, and from the corresponding result for $C^0$,

[4.13] Claim: With the $C^k$-topology, for $x \in T$ and integer $0 \leq i \leq k$, the evaluation functional $C^k(T) \to \mathbb{C}$ by

$$f \mapsto f^{(i)}(x)$$

is continuous. ///

This applies to Fourier series, without any claim about what functions are representable as Fourier series. With $\psi_n(x) = e^{2\pi inx}$,

[4.14] Claim: For complex numbers $c_n$, when

$$\sum_n |c_n| \cdot |n|^k < +\infty$$

the Fourier series $\sum c_n \psi_n$ converges to a function in $C^k(T)$, and its derivative is computed by termwise differentiation

$$\frac{d}{dx} \sum c_n \psi_n = \sum (in) c_n \psi_n \in C^{k-1}(T)$$

Proof: The $C^0(T)$ norm of a Fourier series is easily estimated, by

$$\left| \sum_{|n| \leq N} c_n \psi_n(x) \right| \leq \sum_{|n| \leq N} |c_n| \quad \text{(for all $x \in T$)}$$

[12] The fundamental theorem of calculus for integrals of continuous functions needs only the simplest notion of an integral, for example, Riemann integrals.

[13] For example, interchange of limit and integral is justified by the simplest form of Lebesgue’s Dominated Convergence Theorem. Also, for uniform pointwise limits of continuous functions, this can be proven directly.
The right-hand side is independent of \( x \in T \), so bounds the sup over \( x \in T \). Similarly, estimate derivatives (of partial sums) by

\[
\left| \left( \sum_{|n| \leq N} c_n \psi_n \right)^{(k)} \right| \leq \sum_{|n| \leq N} |c_n| n^k
\]

Thus, the hypothesis of the claim implies that the partial sums form a Cauchy sequence in \( C^k \). The partial sums of a Fourier series are finite sums, so can be differentiated term-by-term. Thus, we have a Cauchy sequence of \( C^k \) functions, which converges to a \( C^k \) function, by the completeness of \( C^k \). That is, the given estimate assures that the Fourier series converges to a \( C^k \) function.

Further, since differentiation is a continuous map \( C^k \rightarrow C^{k-1} \), it maps Cauchy sequences to Cauchy sequences. In particular, the Cauchy sequence of derivatives of partial sums converges to the derivative of the limit of the original Cauchy sequence.

We want the following to hold. Unsurprisingly, it does:

\[\text{[4.15] Claim: The inclusion } C^k(T) \subset C^{k-1}(T) \text{ is continuous.}\]

\[\text{Proof: The point is that, for } f \in C^k(T) \text{ the obvious inequality}
\]

\[|f|_{C^{k-1}} \leq |f|_{C^k}\]

\[\text{gives an explicit estimate for the continuity.} \]

\\[///\]

### 5. Topology on \( C^\infty(T) \)

Next, we care about infinitely differentiable\(^\text{[15]}\) functions, that is, smooth functions, denoted \( C^\infty(T) \). At least as sets (or vector spaces),

\[C^\infty(T) = \bigcap_k C^k(T)\]

However, this space \( C^\infty(T) \) of smooth functions provably does not have a structure of Banach space. Observing that a descending intersection is a (projective) limit we should declare that

\[C^\infty(T) = \lim_k C^k(T)\]

That is, for every topological vector space \( V \) and compatible\(^\text{[16]}\) family of continuous linear maps \( f_k : V \rightarrow C^k(T) \), there is a unique \( f : V \rightarrow C^\infty(T) \) such that all triangles commute in the diagram

\[
\begin{array}{ccc}
C^\infty(T) & \rightarrow & C^1(T) \\
\downarrow & & \downarrow \\
C^0(T) & \rightarrow & \cdots
\end{array}
\]

\[
\begin{array}{ccc}
V & \rightarrow & C^\infty(T) \\
\downarrow & & \downarrow f \\
\end{array}
\]

\[
\begin{array}{ccc}
C^\infty(T) & \rightarrow & C^1(T) \\
\downarrow & & \downarrow \\
C^0(T) & \rightarrow & \cdots
\end{array}
\]

\[
\begin{array}{ccc}
V & \rightarrow & C^\infty(T) \\
\downarrow & & \downarrow f \\
\end{array}
\]

\[\text{[14] In fact, the image of } C^k \text{ in } C^{k-1} \text{ is dense, but, we will prove this later as a side-effect of sharper results.}\]

\[\text{[15] Use of } \text{infinitely} \text{ here is potentially misleading, but is standard. Sometimes the phrase } \text{indefinitely differentiable}\text{ is used, but this also offers its own potential for confusion. A better (and standard) contemporary usage is } \text{smooth}.\]

\[\text{[16] As earlier, for the maps } f_k \text{ to be } \text{compatible} \text{ means that, naming the inclusion } i_k : C^k(\mathbb{R}) \rightarrow C^{k-1}(\mathbb{R}), \]

\[i_k \circ f_k = f_{k-1}. \text{ That is, all the triangles in the relevant diagram commute.}\]
Unfortunately, we may be temporarily insufﬁciently sophisticated about what kind of object this limit might be. In particular, we do not know what kind of auxiliary objects to use in the very deﬁnition of limit.

Too optimistic speculation about what the limit might be leads to trouble: as it happens, this limit is provably not a Banach space (nor Hilbert space). As we have seen, a limit of topological spaces has a unique topology, whatever it may be, by the categorical characterization of this topology.

[5.1] Remark: There is also the disquieting question of what test objects \( V \) we should consider in the diagrammatic characterization, with compatible mappings \( V \to C^k(\mathbb{T}) \) to characterize the limit.

The broadest necessary class of vector spaces with topologies is the following. A topological vector space is what one would reasonably imagine, namely, a (complex) vector space \( V \) with a topology such that

\[
V \times V \to V \quad \text{by} \quad v \times w \to v + w \quad \text{is continuous}
\]

and such that

\[
\mathbb{C} \times V \to V \quad \text{by} \quad \alpha \times v \to \alpha \cdot v \quad \text{is continuous}
\]

and such that the topology is Hausdorff. We require that the topological vector spaces be locally convex in the sense that there is a local basis at 0 consisting of convex sets. It is easy to prove that Hilbert and Banach spaces are locally convex, which is why the issue is invisible in that context. Dismayingly, there are easily constructed complete (invariantly) metrized topological vector spaces which are not locally convex.

Returning to the discussion of limits of topological vector spaces: since the continuity requirements for a topological vector space are of the form \( A \times B \to C \) (rather than having the arrow going the other direction), there is a diagrammatic argument that the continuous algebraic operations on the limitands induce continuous algebraic operations on the limit, in the limit topology (as limit of topological spaces).

[5.2] Claim: Products and limits of topological vector spaces exist. Products and limits of locally convex spaces are locally convex. (Proof in appendix.)

[5.3] Remark: As usual, if they exist at all, then products and limits are unique up to unique isomorphism.

[17] The non-Banach-ness of \( C^\infty(\mathbb{T}) \) is not the main point, but it is reasonable to wonder how this is proven. Briefly, with a deﬁnition of topological vector space, we will prove that a topological vector space is normable if and only if there is a local basis at 0 consisting of bounded opens. This is independent of completeness. The relevant sense of bounded cannot be the usual metric sense. Instead, a set \( E \) in a topological vector space is bounded when, for every open neighborhood \( U \) of 0, there is \( t > 0 \) such that \( E \subset z \cdot U \) for all complex \( z \) with \( |z| \geq t \). That is, sufﬁciently large dilates of opens eventually contain \( E \). But we will eventually that open balls in \( C^k(\mathbb{T}) \) are not contained in any dilate of any open ball in \( C^{k+1}(\mathbb{T}) \). The deﬁnition of the limit topology then shows that \( C^\infty(\mathbb{T}) \) is not normable. A more detailed discussion will be given later.

[18] In fact, soon after giving the deﬁnition, one can show that the weaker condition that points are closed, implies the Hausdorff condition in topological spaces which are vector spaces with continuous vector addition and scalar multiplication. Indeed, the inverse image of \( \{0\} \) under \( x \times y \to x - y \) is the diagonal.

[19] This sense of convexity is the usual: a set \( X \) in a vector space is convex when, for all tuples \( x_1, \ldots, x_n \) of points in \( X \) and all tuples \( t_1, \ldots, t_n \) of non-negative reals with \( \Sigma t_i = 1 \), the sum \( \Sigma t_i x_i \) is again in \( X \).

[20] The simplest examples of complete metric topological vector spaces which are not locally convex are spaces \( \ell^p \) with \( 0 < p < 1 \). The metric comes from a norm-like function which is not a norm: \( |(c_n)|_p = \sum_n |c_n|^p \). No, there is no \( p^{th} \) root taken, unlike the spaces \( \ell^p \) with \( p \geq 1 \), and this causes the function \( | \cdot |_p \) to lose the homogeneity it would need to be a norm. Nevertheless, such a space is complete. It is an amusing exercise to prove that it is not locally convex.
Thus, $C^\infty(T)$ has a (limit) topology for general reasons. As proven earlier for such spaces on intervals $[a,b]$,

**[5.4] Claim:** Differentiation $f \to f'$ is a continuous map $C^\infty(T) \to C^\infty(T)$.

**[5.5] Remark:** Of course differentiation maps the smooth functions to themselves. Continuity of differentiation in the limit topology is less clear.

**Proof:** Differentiation $d/dx$ gives a continuous map $C^k(T) \to C^{k-1}(T)$. Differentiation is compatible with the inclusions among the $C^k(T)$. Thus, we have a commutative diagram

\[
\begin{array}{c}
C^\infty(T) & \ldots & C^k(T) & \longrightarrow & C^{k-1}(T) & \longrightarrow & \ldots \\
\downarrow & & & \downarrow & & & \\
C^\infty(T) & \ldots & C^k(T) & \longrightarrow & C^{k-1}(T) & \longrightarrow & \ldots
\end{array}
\]

Composing the projections with $d/dx$ gives (dashed) induced maps from $C^\infty(T)$ to the limitands, inducing a unique (dotted) map to the limit, as in

\[
\begin{array}{c}
C^\infty(T) & \ldots & C^k(T) & \longrightarrow & C^{k-1}(T) & \longrightarrow & \ldots \\
\downarrow & & & \downarrow & & & \\
C^\infty(T) & \ldots & C^k(T) & \longrightarrow & C^{k-1}(T) & \longrightarrow & \ldots
\end{array}
\]

This proves the continuity of differentiation, in the limit topology. ///

**[5.6] Corollary:** When a Fourier series $\sum_n c_n \psi_n$ satisfies

\[
\sum_m |c_n| |n|^N < +\infty \quad \text{(for every } N)\]

the series is a smooth function, which can be differentiated term-by-term, and its derivative is

\[
\sum_m c_n \cdot in \cdot \psi_n
\]

**Proof:** The hypothesis assures that the Fourier series lies in $C^k$ for every $k$. Differentiation is continuous in the limit topology on $C^\infty$. ///

**[5.7] Remark:** This continuity is necessary to define differentiation of distributions below.
6. Distributions: generalized functions

Although much amplification is needed, having an appropriate topology on $C^\infty(T)$ allows the bare definition: a distribution or generalized function\[21\] on $T$ is a continuous linear functional\[22\]

$$ u : C^\infty(T) \to \mathbb{C} $$

Why a dual space? Unsurprisingly, especially with a precise intrinsic notion of integral on $T$ in the next section, a function $\varphi \in C^\infty(T)$ gives rise to a distribution $u_\varphi$ by integration against $\varphi$,

$$ u_\varphi(f) = \int_T f(x) \varphi(x) \, dx \quad (f \in C^\infty(T)) $$

Thus, we relax our notion of function, no longer requiring pointwise values, but only that a function can be integrated against. Then it may make sense to declare functionals in a dual space to be generalized functions. The vector space of distributions is denoted

$$ \text{distributions} = \text{continuous dual of } C^\infty(T) = \text{Hom}_C^0(C^\infty(T), \mathbb{C}) = C^\infty(T)^* $$

That is, given a reasonable notion of integral, we have a continuous imbedding

$$ C^0(T) \subset C^\infty(T)^* \quad \text{by } \varphi \mapsto u_\varphi \quad \text{where (again) } u_\varphi(f) = \int_T f(x) \varphi(x) \, dx \quad (f \in C^\infty(T)) $$

Typically, the dual of a limit of topological vector spaces is not the colimit of the duals of the limitands. Duals of colimits do behave well, in the sense that in reasonable situations

$$ \text{Hom}(\text{colim}_i X_i, Z) \approx \lim_i \text{Hom}(X_i, Z) $$

But $C^\infty(T)$ is a limit, not a colimit. Luckily, the dual of a limit of Banach spaces is the colimit of the duals:

**[6.1] Theorem:** Let $X = \lim_i B_i$ be a limit of Banach spaces $B_i$ with projections $p_i : X \to B_i$. Any $\lambda \in X^* = \text{Hom}_C^0(X, \mathbb{C})$ factors through some $B_i$. That is, there is $\lambda_j : B_j \to \mathbb{C}$ such that

$$ \lambda = \lambda_j \circ p_j : X \to \mathbb{C} $$

Therefore,

$$ (\lim_i B_i)^* \approx \text{colim}_i B_i^* $$

**Proof:** Without loss of generality, each $B_i$ is the closure of the image of $X$, since otherwise replace of each $B_i$ by that closure.

\[21\] What’s in a name? In this case, generalized function expresses the intention to think of distributions as extensions of ordinary functions, not as abstract things in a dual space.

\[22\] The standard usage is that a functional on a complex vector space $V$ is a $\mathbb{C}$-linear map from $V$ to $\mathbb{C}$. Continuity may or may not be required, and the topology in which continuity is required may vary. It is in this sense that there is a subject functional analysis.
Let $U$ be an open neighborhood of 0 in $X = \lim_i B_i$ such that $\lambda(U)$ is inside the open unit ball at 0 in $\mathbb{C}$, by the continuity at 0. By properties of the limit topology\[^{[23]}\] there are finitely-many indices $i_1, \ldots, i_n$ and open neighborhoods $V_{i_t}$ of 0 in $B_i$, such that

$$\bigcap_{t=1}^n p_{i_t}^{-1}V_{i_t} \subset U \quad \text{(projections $p_i$ from the limit $X$)}$$

To have $\lambda$ factor (continuously) through a limitand $B_j$, we need a single condition to replace the conditions from $i_1, \ldots, i_n$. Let $j$ be any index\[^{[24]}\] with $j \geq i_t$ for all $t$, and

$$V'_j = \bigcap_{t=1}^n p_{i_t,j}^{-1}V_{i_t} \subset B_j$$

By the compatibility

$$p_{i_t}^{-1} = p_j^{-1} \circ p_{i_t,j}^{-1}$$

we have a single sufficient condition, namely $p_j^{-1}V'_j \subset U$. By the linearity of $\lambda$, for $\varepsilon > 0$

$$\lambda(\varepsilon \cdot p_j^{-1}V_j') = \varepsilon \cdot \lambda(p_j^{-1}V_j') \subset \varepsilon\text{-ball in } \mathbb{C}$$

By continuity\[^{[25]}\] of scalar multiplication on $B_j$, $\varepsilon \cdot V'_j$ is an open containing 0 in $B_j$.

We claim that $\lambda$ factors through $p_j X$ with the subspace topology from $B_j$. This makes $p_j X$ a normed space, if not Banach.\[^{[26]}\] Simplifying notation, let $\lambda : X \to \mathbb{C}$ and $p : X \to N$ be continuous linear to a normed space $N$, with

$$\lambda(p^{-1}V) \subset \text{unit ball in } \mathbb{C} \quad \text{(for some neighborhood $V$ of 0 in $N$)}$$

We claim that $\lambda$ factors through $p : X \to N$ as a (continuous) linear map. Indeed, by the linearity of $\lambda$,

$$\lambda\left(\frac{1}{n} \cdot p^{-1}V\right) \subset \frac{1}{n}\text{-ball in } \mathbb{C}$$

so

$$\lambda\left(\bigcap_{n=1}^\infty \frac{1}{n} \cdot p^{-1}V\right) \subset \frac{1}{m}\text{-ball} \quad \text{(for all $m$)}$$

Then

$$\lambda\left(\bigcap_{n=1}^\infty \frac{1}{n} \cdot p^{-1}V\right) \subset \bigcap_{m=1}^\infty \frac{1}{m}\text{-ball} = \{0\}$$

\[^{[23]}\] Recall that $X = \lim_i B_i$ is the closed subspace (with the subspace topology) of the product $Y = \Pi_i B_i$ of all tuples $\{b_i\}$ in which $p_{ij} : b_i \to b_j$ for $i > j$ under the transition maps $p_{ij} : B_i \to B_j$. A local basis at 0 in the product consists of products $V = \Pi_i V_i$ of opens $V_i$ in $B_i$ with $V_i = B_i$ for all but finitely-many $i$, say $i_1, \ldots, i_n$.

\[^{[24]}\] The index set need not be the positive integers, but must be a poset (partially ordered set), directed, in the sense that for any two indices $i, j$ there is an index $k$ such that $k > i$ and $k > j$.

\[^{[25]}\] Multiplication by a non-zero scalar is a homeomorphism: scalar multiplication by $\varepsilon \neq 0$ is continuous, scalar multiplication by $\varepsilon^{-1}$ is continuous, and these are mutual inverses, so these scalar multiplications are homeomorphisms.

\[^{[26]}\] Recall that a normed space is a topological vector with topology given by a norm $| |$ as in a Banach space, but without the requirement that the space is complete with respect to the metric $d(x, y) = |x - y|$. This slightly complicated assertion is correct: in most useful situations $p_j X$ is rarely all of $B_j$, even when $B_j$ is a completion of $p_j X$. 

15
Thus,
\[
\bigcap_n p^{-1}\left(\frac{1}{n} \cdot V\right) = \bigcap_n \frac{1}{n} \cdot p^{-1} V \subset \ker \lambda
\]
For \(x, x'\) in \(X\) with \(px = px'\), certainly \(px - px' \in \frac{1}{n} V\) for all \(n = 1, 2, \ldots\). Therefore,
\[
x - x' \in \bigcap_n p^{-1}\left(\frac{1}{n} \cdot V\right) \subset \ker \lambda
\]
and \(\lambda x = \lambda x'\). This proves the subordinate claim that \(\lambda\) factors through \(p : X \to N\) via a (not necessarily continuous) linear map \(\mu : N \to C\). For the continuity of \(\mu\), by its linearity:
\[
\mu(\varepsilon \cdot V) = \varepsilon \cdot \mu V \subset \varepsilon\text{-ball in } C
\]
proving the continuity of \(\mu : N \to C\). This proves the claim.

The claim gives continuous linear \(\lambda_j : p_j X \to C\) through which \(\lambda\) factors.

Then \(\lambda_j : p_j X \to C\) extends by continuity to the closure of \(p_j X\) in \(B_j\), which is \(B_j\), giving the desired map.

\[6.2\] Remark: The same proof shows that a continuous linear map from a limit of Banach spaces to a normed space factors through a limitand, when the images of projections are dense in the limitands.

\[6.3\] Corollary: The space of distributions on \(\mathbb{T}\) is the ascending union (colimit)
\[
C^\infty(\mathbb{T})^* = (\lim_k C^k(\mathbb{T}))^* = \colim_k C^k(\mathbb{T})^* = \bigcup_k C^k(\mathbb{T})^*
\]
of duals of the Banach spaces \(C^k(\mathbb{T})\).

The order of a distribution \(u\) is the smallest \(k\) such that \(u \in C^k(\mathbb{T})^*\). Since for the circle the space of all distributions is exactly this colimit, the order of a distribution is well-defined.

Distributions as generalized functions should be differentiable, compatibly with the differentiation of functions. The idea is that differentiation of distributions should be compatible with integration by parts for distributions given by integration against \(C^1\) functions. Assuming an integral on \(\mathbb{T}\) as in the next section, for functions \(f, g\), by integration by parts,
\[
\int_\mathbb{T} f(x) g'(x) \, dx = - \int_\mathbb{T} f'(x) g(x) \, dx
\]

[27] Here we need \(V\) to be open, not merely a set containing 0. Continuity at 0 is all that is needed for continuity of linear maps, since \(|\lambda(x)| < \varepsilon\) for \(|x| < \delta\) gives \(|\lambda(x - x')| < \varepsilon\) for \(|x - x'| < \delta\).

[28] The extension by continuity is unambiguous, since \(\lambda_j\) is linear. In more detail: for \(\lambda\) a continuous linear function on a dense subspace \(Y\) of a topological vector space \(X\), given \(\varepsilon > 0\), take convex neighborhood \(U\) of 0 in \(X\) such that \(|\lambda y| < \varepsilon\) for \(y \in U\). We may suppose \(U = -U\) by replacing \(U\) by \(-U \cap U\). Let \(y_i\) a Cauchy net approaching \(x \in X\). For \(y_i, y_j\) inside \(x + \frac{1}{2} U\), \(|\lambda y_i - \lambda y_j| = |\lambda(y_i - y_j)|\), using the linearity. By the symmetry \(U = -U\), since \(y_i - y_j \in \frac{1}{2} \cdot 2U = U\), this gives \(|\lambda y_i - \lambda y_j| < \varepsilon\). Then unambiguously define \(\lambda x\) to be the limit of the \(\lambda y_i\).

[29] The Riesz representation theorem asserts that the dual of \(C^0(\mathbb{T})\) is Borel measures on \(\mathbb{T}\), so order-zero distributions are Borel measures. For example, elements \(\eta\) of \(L^2(\mathbb{T})\) are Borel measures, by giving integrals \(f \to \int_\mathbb{T} f(x) \eta(x) \, dx\) for \(f \in C^0(\mathbb{T})\). Thus, integrating continuous functions against Borel measures is a semi-classical instance of generalizing functions in our present style, integrating against measures. However, the duals of the higher \(C^k(\mathbb{T})\)'s don't have such a classical interpretation. The fact that \(C^0(\mathbb{T})\) can be construed as distributional derivatives of Borel measures is not strongly related to Radon-Nikodym derivatives of measures, because, for example, the distributional derivative of a point-mass measure is not a measure.
with no boundary terms because $\mathbb{T}$ has empty boundary. Note the negative sign. Motivated by this, define the distributional derivative $u'$ of $u \in C^\infty(\mathbb{T})^*$ to be another distribution defined by

$$u'(f) = -u(f') \quad \text{(for any } f \in C^\infty(\mathbb{T}))$$

The continuity of differentiation $\frac{d}{dx} : C^\infty(\mathbb{T}) \to C^\infty(\mathbb{T})$ assures that $u'$ is a distribution, since $u' = -(u \circ \frac{d}{dx}) : C^\infty(\mathbb{T}) \to \mathbb{C}$

7. Invariant integration, periodicization

We an (invariant) integral on the circle $\mathbb{T} = \mathbb{R}/2\pi\mathbb{Z}$. The main property required is translation invariance, meaning that, for a (for example) continuous function $f$ on $\mathbb{T}$,

$$\int_\mathbb{T} f(x + y) \, dx = \int_\mathbb{T} f(x) \, dx \quad \text{(for all } y \in \mathbb{T})$$

This invariance is sufficient to prove that various important integrals vanish.

For example, let $\psi_m(x) = e^{imx}$. As an instance of an important idea, without explicit calculus-like computations,

[7.1] Claim: (Cancellation Lemma) For $m \neq n$, for any reasonable translation-invariant integral on $\mathbb{T}$

$$\int_\mathbb{T} \psi_m(x) \overline{\psi}_n(x) \, dx = 0$$

Proof: For $m \neq n$, the function $f(x) = \psi_m(x)\overline{\psi}_n(x)$ is a non-trivial (not identically 1) continuous group homomorphism $\mathbb{T} \to \mathbb{C}^\times$, meaning that there is $y \in \mathbb{T}$ such that $f(y) \neq 1$. The change of variables $x \to x + y$ in the integral does not change the overall value of the integral, so

$$\int_\mathbb{T} f(x) \, dx = \int_\mathbb{T} f(x + y) \, dx = \int_\mathbb{T} f(x) \cdot f(y) \, dx = f(y) \int_\mathbb{T} f(x) \, dx$$

Thus, the integral $I$ has the property that $I = t \cdot I$ where $t \neq 1$. This gives $(1 - t) \cdot I = 0$, so $I = 0$ since $t \neq 1$.

[7.2] Remark: This vanishing trick is impressive, since nothing specific about the continuous group homomorphism $f$ or topological group ($\mathbb{T}$ here) is used, apart from the finiteness of the total measure of the group, which comes from its compactness. That is, the same proof would show that integrals over compact groups of non-trivial group homomorphisms are 0. However, a notion of invariant measure for general groups requires effort. Nevertheless, with an invariant measure, the same argument succeeds.

Less critically than the invariance, we want a normalization

$$\int_\mathbb{T} 1 \, dx = \text{vol}(\mathbb{T}) = \text{vol}(\mathbb{R}/\mathbb{Z}) = 1$$

[30] Translation-invariant measures on topological groups are called Haar measures. General proof of their existence takes a little work, and invokes the Riesz representation theorem. Uniqueness can be made to be an example of a more general argument about uniqueness of invariant functionals.
Then
\[ \int_T |\psi_n(x)|^2 \, dx = \int_T 1 \, dx = 1 \]
Thus, without any explicit presentation of the integral or measure, we have proven that the distinct exponentials are an orthonormal set with respect to the inner product
\[ \langle f, g \rangle = \int_T f(x) \overline{g}(x) \, dx \]
An integration by parts formula should be expected, with no boundary terms since \( \mathbb{T} = \mathbb{R}/\mathbb{Z} \) has empty boundary. Indeed, without constructing the invariant integral, we prove what we want from its properties:

[7.3] Claim: Let \( f \to \int_T f(x) \, dx \) be an invariant integral on \( \mathbb{T} \), for \( f \in C^o(\mathbb{T}) \). Then for \( f \in C^1(\mathbb{T}) \)
\[ \int_T f'(x) \, dx = 0 \]
and we have the integration by parts formula for \( f, g \in C^1(\mathbb{T}) \)
\[ \int_T f(x) g'(x) \, dx = - \int_T f'(x) g(x) \, dx \]

[7.4] Remark: Vanishing of integrals of derivatives does not depend on the particulars of the situation. The same argument succeeds on an arbitrary group possessing (translation) invariant differentiation(s) and an invariant integral. Thus, the specific geometry of the circle is not needed to argue that \( \int_T f'(x) \, dx = \int_0^1 f(x) \, dx = f(2\pi) - f(0) = 0 \) because \( f \) is periodic. The latter classical argument is valid, but fails to show a generally applicable mechanism. The same independence of particulars applies to the integration by parts rule.

Proof: The translation invariance of the integral makes the integral of a derivative 0, by direct computation, as follows. We interchange a differentiation and an integral [31]
\[ \int_T f'(x) \, dx = \int_T \frac{d}{dt} |_{t=0} f(x+t) \, dx = \frac{d}{dt} |_{t=0} \int_T f(x+t) \, dx = \frac{d}{dt} |_{t=0} \int_T f(x) \, dx = 0 \]
by changing variables in the integral. Then apply this to the function \( (f \cdot g)' = f'g + fg' \) to obtain
\[ \int_T f'(x) g(x) \, dx + \int_T f(x) g'(x) \, dx = 0 \]
which gives the integration by parts formula. \( \/// \)

The usual (Lebesgue) integral on the uniformizing \( \mathbb{R} \) has the corresponding property of translation invariance. Since we present the circle as a quotient \( \mathbb{R} \to \mathbb{R}/\mathbb{Z} = \mathbb{T} \) of \( \mathbb{R} \) we expect a compatibility [32]
\[ \int_\mathbb{R} F(x) \, dx = \int_{\mathbb{R}/\mathbb{Z}} \left( \sum_{n \in \mathbb{Z}} F(x+n) \right) \, dx \]

[31] The argument bluntly demands this interchange of limit and differentiation, so justification of it is secondary to the act itself. In the near future this and many other necessary interchanges are definitively justified via Gelfand-Pettis (also called weak) integrals. In the present concrete situation elementary (but opaque) arguments could be invoked, but we do not do this.

[32] In contrast to many sources, this compatibility is not about choosing representatives in \([0, 1)\) or anywhere else for \( \setminus \mathbb{T} \). Rather, this compatibility would be required for a topological group \( G \) (here \( \mathbb{R} \)), a discrete subgroup \( \Gamma \) (here \( \mathbb{Z} \)), and the quotient \( G/\Gamma \) (here \( \mathbb{T} \)), whether or not that quotient is otherwise identifiable. This compatibility is a sort of Fubini theorem. The usual Fubini theorem applies to products \( X \times Y \), whose quotients \( (X \times Y)/X \approx Y \) are simply the factors, but another version applies to quotients that are not necessarily factors.
for at least *compactly-supported* continuous functions $F$ on $\mathbb{R}$.

Indeed, we can *define* integrals of functions on $T$ by this compatibility relation, by expressing a continuous function $f$ on $T$ as a *periodicization* (or *automorphization*)

$$f(x) = \sum_{n \in \mathbb{Z}} F(x + n)$$

of a compactly supported continuous function $F$ on $\mathbb{R}$, and *define*

$$\int_T f(x) \, dx = \int_{\mathbb{R}} F(x) \, dx$$

We still need to prove that this value is independent of the choice of $F$ for given $f$.

The properties required of an integral on $T$ are clear. Sadly, we are not in a good position (yet) either to prove *uniqueness* or to give a *construction* as gracefully as these ideas deserve.

Postponing a systematic approach, we neglect any proof of uniqueness, and for a construction revert to an ugly-but-tangible reduction of the problem to integration on an interval. That is, note that in the quotient $q : \mathbb{R} \to \mathbb{R}/\mathbb{Z} = T$ the interval $[0, 1]$ maps surjectively, with the endpoints being identified (and no other points identified). In traditional terminology, $[0, 1]$ is a *fundamental domain*\(^{[33]}\) for the action of $\mathbb{Z}$ on $\mathbb{R}$. Then define the integral of $f$ on $T$ by

$$\int_T f(x) \, dx = \int_0^1 (f \circ q)(x) \, dx$$

with usual (Lebesgue) measure on the unit interval. Verification of the *compatibility* with integration on $\mathbb{R}$ is silly, from this viewpoint.

This (bad) definition does allow explicit computations, but makes *translation invariance* harder to prove, since the unit interval gets pushed off itself by translation. But we can still manage the verification. \(^{[34]}\)

Take $y \in \mathbb{R}$, and compute

$$\int_T f(x + y) \, dx = \int_0^1 (f \circ q)(x + y) \, dx = \int_{-y}^{1-y} (f \circ q)(x) \, dx$$

$$= \int_{-y}^0 (f \circ q)(x) \, dx + \int_0^{1-y} (f \circ q)(x) \, dx = \int_{-y}^0 (f \circ q)(x - 1) \, dx + \int_0^{1-y} (f \circ q)(x) \, dx$$

since $(f \circ q)(x) = (f \circ q)(x - 1)$ by periodicity. Then, replacing $x$ by $x + 1$ in the first integral, this is

$$\int_{-y}^{1-y} (f \circ q)(x) \, dx + \int_0^{1-y} (f \circ q)(x) \, dx = \int_0^1 (f \circ q)(x) \, dx$$

\(^{[33]}\) The notion of *fundamental domain* for the action of a group $\Gamma$ on a set $X$ has an obvious appeal, at least that it is more concrete than the notion of *quotient* $\Gamma \setminus X$. However, it is rarely possible to determine an exact fundamental domain, and one eventually discovers that the details are seldom useful even if this is possible. Instead, the *quotient* should be treated directly.

\(^{[34]}\) While suppressing our disgust.
8. **Levi-Sobolev inequalities, Levi-Sobolev imbeddings**

The simplest $L^2$ theory of Fourier series addresses neither continuity nor differentiability.\(^{[35]}\) Yet it would be advantageous on general principles to be able to talk about differentiability in the context of Hilbert spaces, since Hilbert spaces have easily understood dual spaces. Beppo Levi, Frobenius, and Sobolev made useful comparisons. The idea is to compare $C^k$ norms to norms coming from Hilbert spaces whose inner products refer to derivatives, the Levi-Sobolev spaces.

### [8.1] Levi-Sobolev inequalities

First, we have an easy estimate for a variant $C^k$ norm:

$$
\sum_{|n| \leq N} c_n e^{2\pi i n x} = \frac{1}{2^k} \sup_{0 \leq j \leq k} \sup \left| \sum_{|n| \leq N} c_n (2\pi i n)^j e^{2\pi i n x} \right| \leq \sum_{|n| \leq N} \left| c_n \right| \cdot (1 + 4\pi^2 n^2)^{k/2}
$$

all for elementary reasons.\(^{[36]}\) Perhaps surprisingly, rather try to directly obtain a sup norm estimate on this sum, Cauchy-Schwarz-Bunyakowsky is invoked: for any $s \in \mathbb{R}$

$$
\sum_{|n| \leq N} c_n e^{2\pi i n x} \leq \sum_{|n| \leq N} \left| c_n \right| \cdot (1 + 4\pi^2 n^2)^{s/2} \cdot \frac{1}{(1 + 4\pi^2 n^2)^{(s-k)/2}}
$$

$$
\leq \left( \sum_{|n| \leq N} \left| c_n \right|^2 \cdot (1 + 4\pi^2 n^2)^{s} \right)^{1/2} \cdot \left( \sum_{|n| \leq N} \frac{1}{(1 + 4\pi^2 n^2)^{(s-k)}} \right)^{1/2}
$$

Convergence of the elementary sum is easy to understand:

$$
\sum_{n \in \mathbb{Z}} \frac{1}{(1 + 4\pi^2 n^2)^{s-k}} < +\infty \quad \text{for } s > k + \frac{1}{2}
$$

Thus, for any $s > k + \frac{1}{2}$ we have a **Levi-Sobolev inequality**

$$
\left\| \sum_{|n| \leq N} c_n \psi_n \right\|_{C^k} \leq \left( \sum_{n \in \mathbb{Z}} \frac{1}{(1 + 4\pi^2 n^2)^{s-k}} \right)^{1/2} \cdot \left( \sum_{|n| \leq N} \left| c_n \right|^2 \cdot (1 + 4\pi^2 n^2)^{s} \right)^{1/2}
$$

$$
\leq \left( \sum_{n \in \mathbb{Z}} \frac{1}{(1 + 4\pi^2 n^2)^{s-k}} \right)^{1/2} \cdot \left( \sum_{n \in \mathbb{Z}} \left| c_n \right|^2 \cdot (1 + 4\pi^2 n^2)^{s} \right)^{1/2}
$$

which is summarized as

$$
\left\| \sum_{n \in \mathbb{Z}} c_n \psi_n \right\|_{C^k} \leq \left( \sum_{n \in \mathbb{Z}} \frac{1}{(1 + 4\pi^2 n^2)^{s-k}} \right)^{1/2} \cdot \left( \sum_{n \in \mathbb{Z}} \left| c_n \right|^2 \cdot (1 + 4\pi^2 n^2)^{s} \right)^{1/2} \quad \text{for } s > k + \frac{1}{2}
$$

\(^{[35]}\) It was not until the mid-20th century that L. Carleson showed, in L. Carleson, *On convergence and growth of partial sums of Fourier series*, Acta Math. 116 (1966), 135-157, that Fourier series of $L^2$ functions do converge pointwise almost everywhere. But this is a fragile sort of result.

\(^{[36]}\) The awkward expression $(1 + 4\pi^2 n^2)^{1/2}$ is essentially a uniform constant multiple of $n$. However, for $n = 0$ we cannot divide by $n$, and replacing $n$ by $(1 + 4\pi^2 n^2)^{1/2}$ is one traditional device stunt to avoid this annoyance.
Existence of this comparison makes the right side interesting. Taking away from the right-hand side the uniform constant

$$\omega_{s-k} = \left( \sum_{n \in \mathbb{Z}} \frac{1}{(1 + 4\pi^2 n^2)^s} \right)^{1/2}$$

gives the $s^{th}$ Levi-Sobolev norm

$$s^{th} \text{ Levi-Sobolev norm} = \left| \sum_{n \in \mathbb{Z}} c_n \psi_n \right|_{H^s} = \left( \sum_{n \in \mathbb{Z}} |c_n|^2 \cdot (1 + 4\pi^2 n^2)^s \right)^{1/2}$$

Paraphrasing, we have proven the dominance relation

$$|c_k| \leq \omega_{s-k} \cdot |c_s| \quad \text{(for any } s > k + \frac{1}{2})$$

[8.2] Levi-Sobolev imbeddings

For $s \geq 0$, the $s^{th}$ Levi-Sobolev space is \cite{37}

$$H^s(T) = \{ f \in L^2(T) : \sum_n |\hat{f}(n)|^2 \cdot (1 + 4\pi^2 n^2)^s < +\infty \}$$

The inner product on $H^s(T)$ is

$$\langle \sum_n a_n \psi_n, \sum_n b_n \psi_n \rangle = 2\pi \sum_n a_n \overline{b_n} (1 + 4\pi^2 n^2)^s$$

The factor $4\pi^2$ plays no significant role, and is often normalized away.

[8.3] Remark: This definition of $H^s(T)$ defines a useful space of functions or generalized functions only for $s \geq 0$, since for $s < 0$ the constraint $f \in L^2(T)$ is stronger (from the Plancherel theorem) than the condition defining $H^s(T)$ in the previous display.

[8.4] Remark: The $0^{th}$ Levi-Sobolev space is just $L^2(T)$.

[8.5] Corollary: For $s > k + \frac{1}{2}$ there is a continuous inclusion

$$H^s(T) \subset C^k(T)$$

Proof: For $s > k + \frac{1}{2}$, whenever a Fourier series has a finite Levi-Sobolev norm

$$\left| \sum_n c_n \psi_n \right|_{H^s} = \left( \sum_{n \in \mathbb{Z}} |c_n|^2 \cdot (1 + 4\pi^2 n^2)^s \right)^{1/2} < +\infty$$

the partial sums of the Fourier series are Cauchy in $H^s$, hence Cauchy in $C^k$, so converge in the Banach space $C^k$:

$$\sum_n c_n \psi_n = C^k \text{ function on } T$$

\cite{37} This definition is fine for $s \geq 0$, but not sufficient for $s < 0$. We will give the broader definition below. Keep in mind that $L^2(T)$ contains $C^0(T)$ and all the $C^k(T)$'s.
Proof: Apply the Levi-Sobolev inequality \(|f|_{C^k} \leq \omega \cdot |f|_{H^s}\) to finite linear combinations \(f\) of exponentials. Such finite linear combinations are \(C^k\), and the inequality implies that an infinite sum of such, convergent in \(H^s(\mathbb{T})\), has sequence of partial sums convergent in \(C^k(\mathbb{T})\). That is, by the completeness of \(C^k(\mathbb{T})\), the limit is still \(k\) times continuously differentiable. Thus, we have the containment. Given the containment, the inequality of norms implies the continuity of the inclusion.

[8.6] Levi-Sobolev Hilbert spaces

[8.7] Claim: The \(s\)th Levi-Sobolev space \(H^s(\mathbb{T})\) (with \(0 \leq s \in \mathbb{R}\)) is a Hilbert space. In particular, the sequences of Fourier coefficients of functions in \(H^s(\mathbb{T})\) are all two-sided sequences \(\{c_n : n \in \mathbb{Z}\}\) of complex numbers meeting the condition

\[
\sum_n |c_n|^2 \cdot (1 + 4\pi^2 n^2)^s < +\infty
\]

[8.8] Remark: It is clear that the exponentials \(\psi_n\) are an orthogonal basis for \(H^s(\mathbb{T})\), although their norms depend on the index \(s\). In particular, the collection of finite linear combinations of exponentials is dense in \(H^s(\mathbb{T})\).

[8.9] Remark: Again, we do want to define these positively-indexed Levi-Sobolev spaces as subspaces of genuine spaces of functions, not as sequences of Fourier coefficients meeting the condition, and then prove the second assertion of the claim. This does leave open, for the moment, the question of how to define negatively-indexed Levi-Sobolev spaces.

Proof: In effect, this is the space of \(L^2\) functions on which the \(H^s\)-norm is finite. If we prove the second assertion of the claim, then invoke the usual proof that \(L^2\) spaces are complete to know that \(H^s(\mathbb{T})\) is complete, since it is simply a weighted \(L^2\)-space. Given a two-sided sequence \(\{c_n\}\) of complex numbers such that

\[
\sum_n |c_n|^2 \cdot (1 + 4\pi^2 n^2)^s < +\infty
\]

since \(s \geq 0\),

\[
\sum_n |c_n|^2 < +\infty
\]

and, by Plancherel,

\[
\sum_n c_n \psi_n \in L^2(\mathbb{T})
\]

This shows that \(H^s(\mathbb{T})\) is a Hilbert space for \(s \geq 0\).

[8.10] Remark: Insisting on viewing \(L^2(\mathbb{T})\) as equivalence classes of functions may mislead us into making a needlessly complicated assertion about Levi-Sobolev imbeddings \(H^s(\mathbb{T}) \subset C^k(\mathbb{T})\) for \(s > k + \frac{1}{2}\), by insisting that \(H^s(\mathbb{T})\) consists of almost-everywhere equivalence classes of \(L^2(\mathbb{T})\) functions, only one of which is in \(C^k(\mathbb{T})\). This is not a genuine issue.

[8.11] Levi-Sobolev norms in terms of derivatives

[8.12] Remark: Apart from having the virtue of giving inner-product structures, the expressions appearing in these Levi-Sobolev norms are natural because they have meaning in terms of \(L^2\)-norms of derivatives. For \(f = \sum c_n \psi_n \in C^k(\mathbb{T})\), by Plancherel

\[
\text{(norm via derivatives)} = |f|^2 + |f'|^2 + |f''|^2 + \ldots + |f^{(k)}|^2
\]

\[
= \sum_n |c_n|^2 \cdot (1 + (2\pi n)^2 + (2\pi n)^4 + \ldots + (2\pi n)^{2k}) \leq \sum_n |c_n|^2 \cdot (1 + 4\pi^2 n^2)^k
\]
Conversely,
\[(1 + 4\pi^2 n^2)^k \leq C_k \cdot (1 + (2\pi n)^2 + (2\pi n)^4 + (2\pi n)^6 + \ldots + (2\pi n)^{2k})\]
(for some constant $C_k$)
so
\[(\text{norm via Fourier coefficients}) = \sum_n |c_n|^2 \cdot (1 + 4\pi^2 n^2)^k \leq C_k \cdot \left( |f|^2 + |f'|^2 + |f''|^2 + \ldots + |f^{(k)}|^2 \right)\]

Thus, the two definitions of Levi-Sobolev norms, in terms of weighted $L^2$ norms of Fourier series, or in terms of $L^2$ norms of derivatives, give comparable Hilbert space structures. In particular, the topologies are identical.

**[8.13 Corollary]**: For $k \geq 0$,
\[C^k(\mathbb{T}) \subset H^k(\mathbb{T})\]

**Proof**: For $k = 0$, the assertion is that $C^0(\mathbb{T}) \subset L^2(\mathbb{T})$, which holds because $\mathbb{T}$ is compact. Similarly, the relevant derivatives of $f \in C^k(\mathbb{T})$ are in $L^2(\mathbb{T})$, so $f \in H^k(\mathbb{T})$. 

**[8.14 Remark]**: One can work out the corresponding inequalities for Fourier series in several variables, proving that $(k + \frac{n}{2} + \varepsilon)$-fold $L^2$ differentiability (for any $\varepsilon > 0$) in dimension $n$ is needed to assure $k$-fold continuous differentiability. This is $L^2$ Levi-Sobolev theory.

**[8.15 Uniform pointwise convergence, convergence in $C^k(\mathbb{T})$]**

At this moment it is very easy to give a straightforward, if not sharp, result about convergence of $C^k$ functions on $\mathbb{T}$, via the Levi-Sobolev spaces:

**[8.16 Corollary]**: The Fourier series of $f \in C^k(\mathbb{T})$ converges to $f$ in $C^{k-1}(\mathbb{T})$.

**Proof**: A function in $C^k(\mathbb{T})$ is in the Hilbert space $H^k(\mathbb{T})$, meaning that the finite partial sums of the Fourier expansion converge to $f$ in $H^k(\mathbb{T})$. The $H^k(\mathbb{T})$ norm dominates that of $C^{k-1}(\mathbb{T})$, so the Fourier series converges to $f$ in $C^{k-1}(\mathbb{T})$. 

**[8.17 Remark]**: It may seem mildly peculiar that the Fourier series of a $C^k$ function can converge to it only in $C^{k-1}$.

**[8.18 $L^2$-differentiation]**

**[8.19 Claim]**: For every $s \geq 0$, the differentiation map
\[
\frac{d}{dx} : \text{finite Fourier series} \longrightarrow \text{finite Fourier series}
\]
is continuous when the source is given the $H^s(\mathbb{T})$ topology and the target is given the $H^{s-1}(\mathbb{T})$ topology.

**Proof**: This continuity is by design:
\[
\left| \frac{d}{dx} \sum_{|n| \leq N} c_n e^{2\pi inx} \right|_{H^{s-1}}^2 = \sum_{|n| \leq N} c_n^2 \left| 2\pi in e^{2\pi inx} \right|_{H^{s-1}}^2 \leq \sum_{|n| \leq N} |2\pi n c_n|^2 \cdot (1 + 4\pi^2 n^2)^{s-1} \leq \sum_{|n| \leq N} |c_n|^2 \cdot (1 + 4\pi^2 n^2)^s = \sum_{|n| \leq N} c_n e^{2\pi inx} \right|_{H^s}^2
\]
proving the continuity on finite Fourier series.

Therefore, we can extend $\frac{d}{dx}$ by continuity to obtain continuous linear maps

\[
(L^2\text{-differentiation}) = (\text{extension by continuity of}) \frac{d}{dx} : H^s(\mathbb{T}) \rightarrow H^{s-1}(\mathbb{T})
\]

[8.20] **Remark:** In these terms, extra $L^2$-differentiability is needed to assure comparable classical continuous differentiability. Specifically, $(k + \frac{1}{2} + \varepsilon)$-fold $L^2$-differentiability (for any $\varepsilon > 0$) suffices for $k$-fold continuous differentiability, in this one-dimensional example. The comparable computations on $(\mathbb{T})^n$ show that the gap widens as the dimension grows.

9. $C^\infty = \lim C^k = \lim H^s = H^\infty$

For larger purposes, the specific comparisons of indices in the containments

\[
H^s(\mathbb{T}) \subset C^k(\mathbb{T}) \quad (\text{for } s > k + \frac{1}{2})
\]

\[
C^k(\mathbb{T}) \subset H^s(\mathbb{T}) \quad (\text{for } k \geq s)
\]

are secondary, since we are more interested in smooth functions $C^\infty(\mathbb{T})$ than functions with limited continuous differentiability.

Thus, the point is that the Levi-Sobolev spaces and $C^k(\mathbb{T})$ spaces are cofinal under taking descending intersections. That is, letting $H^\infty(\mathbb{T})$ be the intersection of all the $H^s(\mathbb{T})$, as sets we have

\[
C^\infty(\mathbb{T}) = \bigcap_k C^k(\mathbb{T}) = \bigcap_{s \geq 0} H^s(\mathbb{T}) = H^\infty(\mathbb{T})
\]

Since descending nested intersections are limits, the topologies behave well for trivial reasons:

[9.1] **Theorem:** As topological vector spaces

\[
C^\infty(\mathbb{T}) = \lim_k C^k(\mathbb{T}) = \lim_{s \geq 0} H^s(\mathbb{T}) = H^\infty(\mathbb{T})
\]

*Proof:* The cofinality of the $C^k$’s and the $H^s$’s gives a natural isomorphism of the two limits, since they can be combined in a larger limit in which each is cofinal. ///

Again, in general duals of limits are not colimits, but we did show earlier that the dual of a limit of Banach spaces is the colimit of the duals of the Banach spaces. Thus,

[9.2] **Corollary:** The space of distributions on $\mathbb{T}$ is

\[
C^\infty(\mathbb{T})^* = \colim_k C^k(\mathbb{T})^* = \colim_{s \geq 0} H^s(\mathbb{T})^* = H^\infty(\mathbb{T})^*
\]

(and the duals $H^s(\mathbb{T})^*$ admit further explication, below). ///

Expressing $C^\infty(\mathbb{T})$ as a limit of the Hilbert spaces $H^s(\mathbb{T})$, as opposed to its more natural expression as a limit of the Banach spaces $C^k(\mathbb{T})$, is convenient when taking duals, since by the Riesz-Fischer theorem\[^{[38]}\] we have explicit expressions for Hilbert space duals. We exploit this possibility below.

\[^{[38]}\] The Riesz-Fischer theorem asserts that the (continuous) dual $V^*$ of a Hilbert space $V$ is $C$-conjugate linearly isomorphic to $V$. The isomorphism from $V$ to $V^*$ attaches the linear functional $v \mapsto \langle v, w \rangle$ to an element $w \in V$. Since our hermitian inner products $(\cdot, \cdot)$ are conjugate-linear in the second argument, the map $w \mapsto (\cdot, w)$ is conjugate linear.
10. Distributions, generalized functions, again

We will see that distributions on $\mathbb{T}$ have Fourier expansions, greatly facilitating their study.\[39\]

The exponential functions $\psi_n$ are in $C^\infty(\mathbb{T})$, so for any distribution $u$ we can compute Fourier coefficients of $u$ by

$$(n^{\text{th}} \text{ Fourier coefficient of } u) = \hat{u}(n) = \cdot u(\psi_{-n})$$

Write

$$u \sim \sum_n \hat{u}(n) \cdot \psi_n$$

even though pointwise convergence of the indicated sum is certainly not expected. Define Levi-Sobolev spaces for all $s \in \mathbb{R}$ by

$$H^s(\mathbb{T}) = \{ u \in C^\infty(\mathbb{T})^*: \sum_n |u(\psi_{-n})|^2 \cdot (1 + 4\pi^2 n^2)^s < \infty \}$$

and the $s^{\text{th}}$ Levi-Sobolev norm $|u|_{H^s}$ is

$$|u|_{H^s}^2 = \sum_n |u(\psi_{-n})|^2 \cdot (1 + 4\pi^2 n^2)^s$$

For $0 \leq s \in \mathbb{Z}$, this definition is visibly compatible with the previous definition via derivatives.

[10.1] **Remark:** The formation of the Levi-Sobolev spaces of both positive and negative indices portrays the classical functions of various degrees of (continuous) differentiability together with distributions of various orders as fitting together as comparable objects. By contrast, thinking only in terms of the spaces $C^k(\mathbb{T})$ does not immediately suggest a comparison with distributions.

For convenience, define a weighted version $\ell^{2,s}$ of (a two-sided version of) the classical Hilbert space $\ell^2$ by

$$\ell^{2,s} = \{ \{c_n: n \in \mathbb{Z}\} : \sum_{n \in \mathbb{Z}} |c_n|^2 \cdot (1 + 4\pi^2 n^2)^s < \infty \}$$

with the weighted version of the usual hermitian inner product, namely,

$$\langle \{c_n\}, \{d_n\} \rangle = \sum_{n \in \mathbb{Z}} c_n \overline{d_n} \cdot (1 + 4\pi^2 n^2)^s$$

[10.2] **Claim:** The complex bilinear pairing

$$\langle \cdot, \cdot \rangle : \ell^{2,s} \times \ell^{2,-s} \rightarrow \mathbb{C}$$

by

$$\langle \{c_n\}, \{d_n\} \rangle = \sum_n c_n d_{-n}$$

identifies these two Hilbert spaces as mutual duals, where

$$\ell^{2,-s} \rightarrow (\ell^{2,s})^* \quad \text{by} \quad \{d_n\} \rightarrow \lambda_{\{d_n\}} \quad \text{where} \quad \lambda_{\{d_n\}}(\{c_n\}) = \sum_n c_n d_{-n}$$

[39] In contrast, discussion of distributions on the real line $\mathbb{R}$ is more complicated, due to the non-compactness of $\mathbb{R}$. Not every distribution on $\mathbb{R}$ is the Fourier transform of a function. Distributions which admit Fourier transforms, tempered distributions, constitute a proper subset of all distributions on $\mathbb{R}$.
[10.3] **Remark:** The minus sign in the subscript in the last formula is not the main point, but is a necessary artifact of our change from a hermitian form to a complex bilinear form. It is (thus) necessary to maintain compatibility with the Plancherel theorem for ordinary functions.

**Proof:** The Cauchy-Schwarz-Bunyakowsky inequality gives the continuity of the functional attached to \( \{d_n\} \) in \( \ell^{2,-s} \) by

\[
\left| \sum_n c_n \cdot d_{-n} \right| \leq \sum_n |c_n| \left(1 + 4\pi^2n^2\right)^{s/2} \cdot |d_{-n}| \left(1 + 4\pi^2n^2\right)^{-s/2} \\
\leq \left( \sum_n |c_n|^2 \left(1 + 4\pi^2n^2\right)^s \right)^{1/2} \cdot \left( \sum_n |d_n|^2 \left(1 + 4\pi^2n^2\right)^{-s} \right)^{1/2} = |\{c_n\}|_{\ell^{2,s}} \cdot |\{d_n\}|_{\ell^{2,-s}}
\]

proving the continuity. To prove the surjectivity we adapt the Riesz-Fischer theorem by a renormalization. That is, given a continuous linear functional \( \lambda \) on \( \ell^{2,s} \), by Riesz-Fischer there is \( \{a_n\} \in \ell^{2,s} \) such that

\[
\lambda(\{c_n\}) = \langle \{c_n\}, \{a_n\} \rangle_{\ell^{2,s}} = \sum_n c_n \cdot a_n \cdot (1 + 4\pi^2n^2)^s
\]

Take

\[
d_n = a_{-n} \cdot (1 + 4\pi^2n^2)^s
\]

Check that this sequence of complex numbers is in \( \ell^{2,-s} \), by direct computation, using the fact that \( \{a_n\} \in \ell^{2,s} \),

\[
\sum_n |d_n|^2 \cdot (1 + 4\pi^2n^2)^{-s} = \sum_n |a_{-n} \cdot (1 + 4\pi^2n^2)^s|^2 \cdot (1 + 4\pi^2n^2)^{-s} = \sum_n |a_n|^2 \cdot (1 + 4\pi^2n^2)^s < +\infty
\]

Thus, \( \ell^{2,-s} \) is (isomorphic to) the dual of \( \ell^{2,s} \). ///

[10.4] **Claim:** The map \( u \to \{\hat{u}(n)\} \) on \( H^s(\mathbb{T}) \) by taking Fourier coefficients is a Hilbert-space isomorphism

\[
H^s(\mathbb{T}) \cong \ell^{2,s}
\]

**Proof:** That the two-sided sequence of Fourier coefficients \( u(\psi_{-n}) \) is in \( \ell^{2,s} \) is part of the definition of \( H^s(\mathbb{T}) \). The more serious question is surjectivity.

Let \( \{c_n\} \in \ell^{2,s} \). For \( s \geq 0 \), the \( s^{th} \) Levi-Sobolev norm dominates the \( 0^{th} \), so distributions in \( H^s(\mathbb{T}) \) are at least \( L^2(\mathbb{T}) \)-functions. The definition of \( H^s(\mathbb{T}) \) in this case makes \( H^s(\mathbb{T}) \) a Hilbert space, and we directly invoke the Plancherel theorem, using the orthonormal basis \( \frac{e^{inx}}{\sqrt{2\pi}} \cdot (1 + 4\pi^2n^2)^{-s/2} \) for \( H^s(\mathbb{T}) \). This gives the surjectivity \( H^s(\mathbb{T}) \to \ell^{2,s} \) for \( s \geq 0 \).

For \( s < 0 \), to prove the surjectivity, for \( \{c_n\} \in \ell^{2,s} \) we will define a distribution \( u \) lying in \( H^s(\mathbb{T}) \), by

\[
u(f) = \sum_n \hat{\nu}(n) \cdot c_{-n} \quad (f \in C^\infty(\mathbb{T}))
\]

By Cauchy-Schwarz-Bunyakowsky,

\[
|\sum_n \hat{\nu}(n) \cdot c_{-n}| \leq \sum_n |\hat{\nu}(n)| \left(1 + 4\pi^2n^2\right)^{-s/2} \cdot |c_n| \left(1 + 4\pi^2n^2\right)^{s/2} \\
\leq \left( \sum_n |\hat{\nu}(n)|^2 \left(1 + 4\pi^2n^2\right)^{-s} \right)^{1/2} \cdot \left( \sum_n |c_n|^2 \left(1 + 4\pi^2n^2\right)^s \right)^{1/2} = |\nu|_{H^{-s}} \cdot |\{c_n\}|_{\ell^{2,s}}
\]

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This shows that $u$ is a continuous linear functional on $H^{-s}(T)$. For $s < 0$, the test functions $C^\infty(T)$ imbed continuously into $H^{-s}(T)$, so $u$ gives a continuous functional on $C^\infty(T)$, so is a distribution. This proves that the Fourier coefficient map is a surjection to $\ell^2,s$ for $s < 0$.

[10.5] Remark: After this preparation, the remainder of this section is completely unsurprising. The following corollary is the conceptual point of this story.

[10.6] Corollary: For any $s \in \mathbb{R}$, the complex bilinear pairing $\langle , \rangle : H^s \times H^{-s} \to \mathbb{C}$ by $f \times u \to \langle f, u \rangle = \sum_n \hat{f}(n) \cdot \hat{u}(-n)$ gives an isomorphism $H^{-s} \approx (H^s)^*$ by sending $u \in H^{-s}$ to $\lambda_u \in (H^s)^*$ defined by $\lambda_u(f) = \langle f, u \rangle$ (for $f \in H^s(T)$).

[10.7] Remark: The pairing of this last claim is unsymmetrical: the left argument is from $H^s$ while the right argument is from $H^{-s}$.

Proof: This pairing via Fourier coefficients is simply the composition of the maps $H^s(T) \approx \ell^2,s$ and $H^{-s}(T) \approx \ell^2,-s$ with the pairing of $\ell^2,s$ and $\ell^2,-s$ given just above.

[10.8] Corollary: The space of all distributions on $T$ is

\[
\text{distributions} = C^\infty(T)^* = \bigcup_{s \geq 0} H^s(T)^* = \bigcup_{s \geq 0} H^{-s}(T) = \text{colim}_{s \geq 0} H^{-s}(T)
\]

thus expressing $C^\infty(T)^*$ as an ascending union of Hilbert spaces.

[10.9] Corollary: A distribution $u \sim \sum_n c_n \psi_n$ can be evaluated on $f \in C^\infty(T)$ by

$\quad u(f) = \sum_n \hat{f}(n) \cdot \hat{u}(-n)$

Proof: Since $u$ lies in some $H^{-s}(T)$, it gives a continuous functional on $H^s(T)$, which contains $C^\infty(T)$. The Plancherel-like evaluation formula above gives the equality.

A collection of Fourier coefficients $\{c_n\}$ is of moderate growth when there is a constant $C$ and an exponent $N$ such that

$\quad |c_n| \leq C \cdot (1 + 4\pi^2 n^2)^N$ (for all $n \in \mathbb{Z}$)

[10.10] Corollary: Let $\{c_n\}$ be a collection of complex numbers of moderate growth. Then there is a distribution $u$ with those as Fourier coefficients, that is, there is $u$ with

$\quad u(\psi_{-n}) = c_n$

Proof: For constant $C$ and exponent $N$ such that $|c_n| \leq C \cdot (1 + n^2)^N$,

$\quad \sum_n |c_n|^2 \cdot (1 + 4\pi^2 n^2)^{-2(N+1)} \leq \sum_n C^2 \cdot (1 + 4\pi^2 n^2)^{2N} \cdot (1 + 4\pi^2 n^2)^{-2(N+1)} = C^2 \cdot \sum_n (1 + 4\pi^2 n^2)^{-1} < \infty$
That is, from the previous discussion, the sequence gives an element of $H^{-2(N+1)}(T) \subset C^\infty(T)^*$.

[10.11] Corollary: For $u \sim \sum_n c_n \psi_n \in H^s(T)$ the derivative (for any $s \in \mathbb{R}$) is

$$u' \sim \sum_n 2\pi i n \cdot c_n \cdot \psi_n \in H^{s-1}$$

Proof: Invoke the definition (compatible with integration by parts) of the derivative of distributions, and integrating by parts to see that

$$\hat{f}'(n) = 2\pi i n \cdot \hat{f}(n)$$

for $f \in C^\infty(T) = H^\infty(T)$, as claimed. The Fourier coefficients $-in \cdot \hat{u}(n)$ do satisfy

$$\sum_n |2\pi i n \cdot \hat{u}(n)|^2 \cdot (1 + 4\pi^2 n^2)^{s-1} \ll \sum_n (1 + 4\pi^2 n^2)^s |\hat{u}(n)|^2 \cdot (1 + 4\pi^2 n^2)^{s-1}$$

$$= \sum_n |\hat{u}(n)|^2 \cdot (1 + 4\pi^2 n^2)^s = |u|_{H^s}^2 < \infty$$

which proves that the differentiation maps $H^s$ to $H^{s-1}$ continuously.

[10.12] Remark: In the latter proof the sign in the subscript in the definition of the pairing $\ell^{2,s} \times \ell^{2,-s}$ was essential.

[10.13] Corollary: The collection of finite linear combinations of exponentials $\psi_n$ is dense in every $H^s(T)$, for $s \in \mathbb{R}$. In particular, $C^\infty(T)$ is dense in every $H^s(T)$, for $s \in \mathbb{R}$.

Proof: The exponentials are an orthogonal basis for every Levi-Sobolev space.

[10.14] Remark: The topology of colimit of Hilbert spaces is the finest of several reasonable topologies on distributions. Density in a finer topology is a stronger assertion than density in a coarser topology.

11. The provocative example explained

The classically confusing example of the sawtooth function is clarified in the context we’ve developed. By now, we know that Fourier series whose coefficients satisfy sufficient decay conditions are classically differentiable. Even when the coefficients do not decay, but only grow moderately, the Fourier series is that of a generalized function. In other words, we can always differentiate Fourier series term by term, if the coefficients are of at worst polynomial growth, if we can tolerate the outcome being a generalized function, rather than necessarily a classical function.

Again, $s(x)$ is the sawtooth function

$$s(x) = x - \frac{1}{2} \quad \text{ (for } 0 \leq x < 1)$$

made periodic by demanding $s(x + n) = s(x)$ for all $n \in \mathbb{Z}$. Away from $\mathbb{Z}$, this function is infinitely differentiable, with derivative 1. At integers it jumps down from value $\frac{1}{2}$ to value $-\frac{1}{2}$. We do not attempt to define a value at points in $\mathbb{Z}$.

We want to differentiate this function compatibly with integration by parts, and compatibly with term-by-term differentiation of Fourier series.
The sawtooth function is well-enough behaved to give a distribution by integrating against it, over \( \mathbb{R}/\mathbb{Z} \). Therefore, as we saw above, it can be differentiated as a distribution, and be correctly differentiated as (as a distribution) by differentiating its Fourier expansion termwise.

A earlier, Fourier coefficients are computed by integrating against \( e^{-2\pi inx} \)

\[
\int_0^1 s(x) \cdot e^{-2\pi inx} \, dx = \begin{cases} \frac{1}{-2\pi in} & \text{(for } n \neq 0) \\ 0 & \text{(for } n = 0) \end{cases}
\]

Thus, at least as a distribution, its Fourier expansion is

\[
s(x) = \frac{1}{-2\pi i} \sum_{n \neq 0} \frac{1}{n} \cdot e^{2\pi inx}
\]

The series does converge pointwise to \( s(x) \) for \( x \) away from (images of) integers, as we proved happens at left and right differentiable points for piecewise \( C^0 \) functions, following Fourier and Dirichlet.

We are entitled to differentiate, at worst within the class of distributions, within which we are assured of a reasonable sense to our computations. Further, we are entitled (for any distribution) to differentiate the Fourier series term-by-term. That is, as distributions,

\[
s'(x) = -\sum_{n \neq 0} e^{2\pi inx}
\]

\[
s''(x) = -\sum_{n \neq 0} 2\pi in \cdot e^{2\pi inx}
\]

\[
\cdots
\]

\[
s^{(k)}(x) = -\sum_{n \neq 0} (2\pi in)^{k-1} \cdot e^{2\pi inx}
\]

and so on, just as successive derivatives of smooth functions \( f(x) = \sum_n c_n e^{2\pi inx} \) are obtained by termwise differentiation

\[
f^{(k)}(x) = \sum_{n \neq 0} (2\pi in)^k c_n \cdot e^{2\pi inx}
\]

The difficulty of interpreting the right-hand side of the Fourier series for \( s^{(k)} \) as having pointwise values is irrelevant.

More to the point, these Fourier series are things to integrate smooth functions against, by an extension of the Plancherel formula for inner products of \( L^2 \) functions. Namely, for any smooth function \( f(x) \sim \sum_n c_n e^{2\pi inx} \), the imagined integral of \( f \) against \( s^{(k)} \) should be expressible as the sum of products of Fourier coefficients

\[
\text{imagined } \langle f, s^{(k)} \rangle = \sum_{n \neq 0} c_n \cdot \left( \frac{(2\pi in)^k}{-2\pi in} \right) \cdot \text{conj}
\]

(where \( \alpha \to \alpha^{\text{conj}} \) is complex conjugation) and the latter expression should behave well when rewritten in a form that refers to the literal function \( s \). Indeed,

\[
\sum_{n \neq 0} c_n \cdot \left( \frac{(2\pi in)^k}{-2\pi in} \right) \cdot \text{conj} = (-1)^k \sum_{n \neq 0} (2\pi in)^k c_n \cdot \left( \frac{1}{-2\pi in} \right) \cdot \text{conj} = (-1)^k \int_{\mathbb{T}} f^{(k)}(x) \overline{s}(x) \, dx
\]

by the Plancherel theorem applied to the \( L^2 \) functions \( f^{(k)} \) and \( s \). Let \( u \) be the distribution given by integration against \( s \). Then, by the definition of differentiation of distributions, we have computed that

\[
(-1)^k \int_{\mathbb{T}} f^{(k)}(x) \overline{s}(x) \, dx = (-1)^k u(f^{(k)}) = u^{(k)}(f)
\]
It is in this sense that the sum $\sum_{n \neq 0} c_n \cdot \frac{(2\pi in)^k}{2\pi n}$ is integration of $s$ against $f$.

Further, for $f$ a smooth function with support away from the discontinuities of $s$, it is true that $u''(f) = 0$, giving $s''$ a vague pointwise sense of being 0 away from the discontinuities of $s$. This was clear at the outset, but now is given precise meaning.

Thus, as claimed at the outset of the discussion of functions on the circle, we can differentiate $s(x)$ legitimately, and the differentiation of the Fourier series of the sawtooth function $s(x)$ correctly represents this differentiation, viewing $s(x)$ and its derivatives as distributions.

12. Appendix: products and limits of topological vector spaces

Here we recall the diagrammatical proof that products and limits of topological vector spaces exist, and are locally convex when the factors or limitands are locally convex. Nothing surprising happens.

[12.1] Claim: Products and limits of topological vector spaces exist. In particular, limits are closed (linear) subspaces of the corresponding products. When the factors or limitands are locally convex, so is the product or limit.

[12.2] Remark: Part of the point is that products and limits of locally convex topological vector spaces in the larger category of not-necessarily locally convex topological vector spaces are nevertheless locally convex. That is, enlarging the category in which we take test objects does not change the outcome, in this case. By contrast, coproducts and colimits in general are sensitive to local convexity of the test objects.\[40\]

Proof: After we construct products, limits are constructed as closed subspaces of them.

Let $V_i$ be topological vector spaces. We claim that the topological-space product $V = \Pi_i V_i$ (with projections $p_i$) (with the product topology) is a topological vector space product. Let $\alpha_i : V_i \times V_i \to V_i$ be the addition on $V_i$. The family of composites $\alpha_i \circ (p_i \times p_i) : V \times V \to V_i$ induces a map $\alpha : V \times V \to V$ as in

$$
\begin{array}{ccc}
V \times V & \xrightarrow{\alpha} & V \\
p_i \times p_i \downarrow & & \downarrow p_i \\
V_i \times V_i & \xrightarrow{\alpha_i} & V_i
\end{array}
$$

This defines what we will show to be a vector addition on $V$. Similarly, the scalar multiplications $s_i : \mathbb{C} \times V_i \to V_i$ composed with the projections $p_i : V \to V_i$ give a family of maps

$$s_i \circ (1 \times p_i) : \mathbb{C} \times V \to V_i$$

which induce a map $s : \mathbb{C} \times V \to V$ which we will show to be a scalar multiplication on $V$. That these maps are continuous is given us by starting with the topological-space product.

That is, we must prove that vector addition is commutative and associative, that scalar multiplication is associative, and that the two have the usual distributivity. All these proofs are the same in form. For

\[40\] For example, there are problems with uncountable coproducts in the category of not-necessarily locally convex topological vector spaces, essentially because the not-locally-convex spaces $\ell^p$ with $0 < p < 1$ exist.
commutativity of vector addition, consider the diagram

\[
\begin{array}{ccc}
V \times V & \xrightarrow{v \times w \rightarrow v + w} & V \\
\downarrow & & \downarrow \\
V \times V & \xrightarrow{w \times v \rightarrow w + v} & V \\
\end{array}
\]

The upper half of the diagram is the induced-map definition of vector addition on \( V \), and the lower half is the induced map definition of the reversed-order vector addition. The commutativity of addition on each \( V \) implies that going around the top of the diagram from \( V \times V \) to \( V \) yields the same as going around the bottom. Thus, the two induced maps \( V \times V \to V \) must be the same, since induced maps are \emph{unique}.

The proofs of associativity of vector addition, associativity of scalar multiplication, and distributivity, use the same idea. Thus, \emph{products} of topological vector spaces exist.

We should not forget to prove that the product is \textit{Hausdorff}, since we implicitly require this of topological vector spaces. This is immediate, since a (topological space) product of Hausdorff spaces is readily shown to be Hausdorff.

Consider now the case that each \( V \) is locally convex. By definition of the product topology, every neighborhood of 0 in the product is of the form \( \Pi U \), where \( U \) is a neighborhood of 0 in \( V \), and all but finitely many of the \( U \) are the whole \( V \). Since \( V \) is locally convex, we can shrink every \( U \) that is not \( V \) to be a convex open containing 0, while each \emph{whole} \( V \) is convex. Thus, the product is locally convex when every factor is.

To construct limits, reduce to the product.

\textbf{[12.3] Claim:} Let \( V \) be topological vector spaces with transition maps \( \varphi_i : V_i \to V_{i-1} \). The limit \( V = \lim_i V_i \) \emph{exists}, and, in particular, is the closed linear subspace (with subspace topology) of the product \( \Pi_i V_i \) (with projections \( p_i \)) defined by the (closed) conditions

\[
\lim_i V_i = \{ v \in \Pi_i V_i : (\varphi_i \circ p_i)(v) = p_{i-1}(v), \text{ for all } i \}
\]

\textbf{Proof: (of claim)} Constructing the alleged limit as a closed subspace of the product immediately yields the desired properties of vector addition and scalar multiplication, as well as the Hausdorff-ness. What we must show is that the construction does function as a limit.

Given a compatible family of continuous linear maps \( f_i : Z \to V_i \), there is induced a unique continuous linear map \( F : Z \to \Pi_i V_i \) to the product, such that \( p_i \circ f = f_i \) for all \( i \). The \textit{compatibility} requirement on the \( f_i \) exactly asserts that \( f(Z) \) sits inside the subspace of \( \Pi_i V_i \) defined by the conditions \( (\varphi_i \circ p_i)(v) = p_{i-1}(v) \).

Thus, \( f \) maps to this subspace, as desired.

Further, for all limitands locally convex, we have shown that the product is locally convex. The local convexity of a linear subspace (such as the limit) follows immediately.  

\text\( ///\)
13. Appendix: Fréchet spaces and limits of Banach spaces

A class of topological vector spaces arising in practice, larger than the class of Banach spaces, is the class of Fréchet spaces. In the present context, we can give a nice definition: a Fréchet space is a countable limit of Banach spaces.\[41]\] Thus, for example,

\[ C^\infty(\mathbb{T}) = \bigcap_k C^k(\mathbb{T}) = \lim_k C^k(\mathbb{T}) \]

is a Fréchet space, by (this) definition.

Despite its advantages, the present definition is not the usual one.\[42]\] We make a comparison, and elaborate on the features of Fréchet spaces.

Recall that a metric \( d(, ) \) on a vector space \( V \) is invariant (implicitly, under addition), when

\[ d(x + z, y + z) = d(x, y) \quad \text{(for all } x, y, z \in V) \]

All metrics we’ll care about on topological vector spaces will be invariant in this sense.

**[13.1] Claim:** A Fréchet space (a countable limit of Banach spaces) is locally convex and complete metrizable.\[43]\]

**Proof:** Let \( V = \lim_i B_i \) be a countable limit of Banach spaces \( B_i \), where \( \varphi_i : B_i \to B_{i-1} \) are the transition maps and \( p_i : V \to B_i \) are the projections. From the appendix, the limit is a closed linear subspace of the product, and the product is the cartesian product with the product topology and component-wise vector addition. Recall that a product of a countable collection of metric spaces is metrizable, and is complete if each factor is complete. A closed subspace of a complete metric space is complete metric. Thus, \( \lim_i B_i \) is complete metric.

As in the previous appendix, any product or limit of locally convex spaces is locally convex, whether or not it has a countable cofinal family. Thus, the limit is Fréchet. ///

Addressing the comparison between local convexity and limits of Banach spaces, we have

**[13.2] Theorem:** Every locally convex topological vector space is a subspace of a limit of Banach spaces (and vice-versa).

\[ \text{[41]} \] Of course, it suffices that a limit have a countable cofinal subfamily.

\[ \text{[42]} \] A common definition, with superficial appeal, is that a Fréchet space is a complete (invariantly) metrized space that is locally convex. This has the usual disadvantage that there are many different metrics that can give the same topology. This also ignores the manner in which Fréchet spaces usually arise, as countable limits of Banach spaces. There is another common definition that does halfway acknowledge the latter construction, namely, that a Fréchet space is a complete topological vector space with topology given by a countable collection of seminorms. The latter definition is essentially equivalent to ours, but requires explanation of the suitable notion of completeness in a not-necessarily metric situation, as well as explanation of the notion of seminorm and how topologies are specified by seminorms. We skirt the latter issues for the moment.

\[ \text{[43]} \] As is necessary to prove the equivalence of the various definitions of Fréchet space, the converse of this claim is true, namely, that every locally convex and complete (invariantly) metrizable topological vector space is a countable limit of Banach spaces. Proof of the converse requires work, namely, development of ideas about seminorms. Since we don’t need this converse at the moment, we do not give the argument.
[13.3] **Remark:** This little theorem encapsulates the construction of semi-norms to give a locally convex topology. It can also be used to reduce the general Hahn-Banach theorem for locally convex spaces to the Hahn-Banach theorem for Banach spaces.

**Proof:** In one direction, we already know that a product or limit of Banach spaces is locally convex, since Banach spaces are locally convex.

In the Banach or normed-space situation, the topology comes from a metric $d(v, w) = |v - w|$ defined in terms of a single function $v \to |v|$ with the usual properties

- $|\alpha \cdot v| = |\alpha| |v|$ (homogeneity)
- $|v + w| \leq |v| + |w|$ (triangle inequality)
- $|v| \geq 0$, (equality only for $v = 0$) (definiteness)

By contrast, for more general (but locally convex) situations, we consider a family $\Phi$ of functions $p(v)$ for which the definiteness condition is weakened slightly, so we require

- $p(\alpha \cdot v) = |\alpha| p(v)$ (homogeneity)
- $p(v + w) \leq p(v) + p(w)$ (triangle inequality)
- $p(v) \geq 0$ (semi-definiteness)

Such a function $p(\cdot)$ is a semi-norm. For Hausdorff-ness, we further require that the family $\Phi$ is separating in the sense that, given $v \neq 0$ in $V$, there is $p \in \Phi$ such that $p(v) > 0$.

A separating family $\Phi$ of semi-norms on a complex vector space $V$ gives a locally convex topology by taking as local sub-basis at 0 the sets

$$U_{p, \varepsilon} = \{v \in V : p(v) < \varepsilon\} \quad \text{(for } \varepsilon > 0 \text{ and } p \in \Phi\)$$

Each of these is convex, because of the triangle inequality for the semi-norms.

[13.4] **Remark:** The topology obtained from a (separating) family of seminorms may appear to be a random or frivolous generalization of the notion of topology obtained from a norm. However, it is the correct extension to encompass all locally convex topological vector spaces, as we see now. [45]

For a locally convex topological vector space $V$, for every open $U$ in a local basis $B$ at 0 of convex opens, try to define a seminorm

$$p_U(v) = \inf \{t > 0 : t \cdot U \ni v\}$$

We discover some necessary adjustments, and then verify the semi-norm properties.

First, we show that for any $v \in V$ the set over which the inf is taken is non-empty. Since scalar multiplication $\mathbb{C} \times V \to V$ is (jointly!) continuous, for given $v \in V$, given a neighborhood $U$ of 0 in $V$, there are neighborhoods $W$ of 0 in $\mathbb{C}$ and $U'$ of $v$ such that

$$\alpha \cdot w \in U \quad \text{(for all } \alpha \in W \text{ and } w \in U')$$

[44] Again, a sub-basis for a topology is a set of opens such that finite intersections form a basis. In other words, arbitrary unions of finite intersections give all opens.

[45] The semi-norms we construct here are sometimes called Minkowski functionals, even though they are not functionals in the sense of being continuous linear maps.
In particular, since $W$ contains a disk $\{ |\alpha| < \varepsilon \}$ for some $\varepsilon > 0$, we have $t \cdot v \in U$ for all $0 < t < \varepsilon$. That is,

$$v \in t \cdot U \quad \text{ (for all } t > \varepsilon^{-1})$$

Semi-definiteness of $p_U$ is built into the definition.

To avoid nagging problems, we should verify that, for convex $U$ containing 0, when $v \in t \cdot U$ then $v \in s \cdot U$ for all $s \geq t$. This follows from the convexity, by

$$s^{-1} \cdot v = \frac{t}{s} \cdot (t^{-1} \cdot v) = \frac{t}{s} \cdot (t^{-1} \cdot v) + \frac{s - t}{s} \cdot 0 \in U$$

since $t^{-1} \cdot v$ and 0 are in $U$.

The homogeneity condition $p(\alpha v) = |\alpha| p(v)$ already presents a minor issue, since convex sets containing 0 need have no special properties regarding multiplication by complex numbers. That is, the problem is that, given $v \in t \cdot U$, while $\alpha v \in \alpha \cdot t \cdot U$, we do not know that this implies $\alpha v \in |\alpha| \cdot t \cdot U$. Indeed, in general, it will not. To repair this, to make semi-norms we must use only convex opens $U$ which are balanced in the sense that

$$\alpha \cdot U = U \quad \text{ (for } \alpha \in \mathbb{C} \text{ with } |\alpha| = 1)$$

Then, given $v \in V$, we have $v \in t \cdot U$ if and only if $\alpha v \in t \cdot \alpha U$, and now

$$t \alpha U = t |\alpha| \frac{\alpha}{|\alpha|} U = t |\alpha| U$$

by the balanced-ness.

Now we have an obligation to show that there is a local basis (at 0) of convex balanced opens. Fortunately, this is easy to see, as follows. Given a convex $U$ containing 0, from the continuity of scalar multiplication, since $0 \cdot v = 0$, there is $\varepsilon > 0$ and a neighborhood $W$ of 0 such that $\alpha \cdot w \in U$ for $|\alpha| < \varepsilon$ and $w \in W$. Let

$$U' = \{ \alpha \cdot w : |\alpha| \leq \frac{\varepsilon}{2}, w \in W \} = \bigcup_{|\alpha| \leq \varepsilon/2} \alpha \cdot W$$

Being a union of the opens $\alpha \cdot W$, this $U'$ is open. It is inside $U$ by arrangement, and is balanced by construction. That is, there is indeed a local basis of convex balanced opens at 0.

For the triangle inequality for $p_U$, given $v, w \in V$, let $t_1, t_2$ be such that $v \in t_1 \cdot U$ for $t \geq t_1$ and $w \in t_2 \cdot U$ for $t \geq t_2$. Then, using the convexity,

$$v + w \in t_1 \cdot U + t_2 \cdot U = (t_1 + t_2) \cdot \left( \frac{t_1}{t_1 + t_2} \cdot U + \frac{t_2}{t_1 + t_2} \cdot U \right) \subset (t_1 + t_2) \cdot U$$

This gives the triangle inequality

$$p_U(v + w) \leq p_U(v) + p_U(w)$$

Finally, we check that the semi-norm topology is the original one. This is unsurprising. It suffices to check at 0. On one hand, given an open $W$ containing 0 in $V$, there is a convex, balanced open $U$ contained in $W$, and

$$\{ v \in V : p_U(v) < 1 \} \subset U \subset W$$

Thus, the semi-norm topology is at least as fine as the original topology. On the other hand, given convex balanced open $U$ containing 0, and given $\varepsilon > 0$,

$$\{ v \in V : p_U(v) < \varepsilon \} \supset \frac{\varepsilon}{2} \cdot U$$
Thus, each sub-basis open for the semi-norm topology contains an open in the original topology. We conclude that the two topologies are the same.

A summary so far: for a locally convex topological vector space, the semi-norms attached to convex balanced neighborhoods of 0 give a topology identical to the original, and vice-versa.

Before completing the proof of the theorem, recall that a completion of a set with respect to a pseudo-metric can be defined much as the completion with respect to a genuine metric. This is relevant because a semi-norm may only give a pseudo-metric, not a genuine metric.

Let $\Phi$ be a (separating) family of seminorms on a vector space $V$. For a finite subset $i$ of $\Phi$, let $X_i$ be the completion of $V$ with respect to the seminorm

$$p_i(v) = \sum_{p \in i} p(v)$$

with natural map $f_i : V \to X_i$. Order subsets of $\Phi$ by $i \geq j$ when $i \supset j$. For $i > j$ we have

$$p_i(v) = \sum_{p \in i} p(v) \geq \sum_{p \in j} p(v) = p_j(v)$$

so we have natural continuous (transition) maps

$$\varphi_{ij} : X_i \to X_j \quad (\text{for } i > j)$$

We claim that each $X_i$ is a Banach space, that $V$ with its semi-norm topology has a natural continuous inclusion to the limit $X = \lim_i X_i$, and that $V$ has the topology given by the subspace topology inherited from the limit.

The maps $f_i$ form a compatible family of maps to the $X_i$, so there is a unique compatible map $f : V \to X$. By the separating property, given $v \neq 0$, there is $p \in \Phi$ such that $p(v) \neq 0$. Then for all $i$ containing $p$, we have $f_i(v) \neq 0 \in X_i$. The subsets $i$ containing $p$ are cofinal in this limit, so $f(v) \neq 0$. Thus, $f$ is an inclusion.

Since the limit is a (closed) subspace of the product of the $X_i$, it suffices to prove that the topology on $V$ (imbedded in $\Pi_i X_i$ via $f$) is the subspace topology from $\Pi_i X_i$. Since the topology on $V$ is at least this fine (since $f$ is continuous), we need only show that the subspace topology is at least as fine as the semi-norm topology. To this end, consider a semi-norm-topology sub-basis set

$$\{v \in V : p_U(v) < \varepsilon\} \quad (\text{for } \varepsilon > 0 \text{ and convex balanced open } U \text{ containing } 0)$$

This is simply the intersection of $f(V)$ with the sub-basis set

$$\prod_{p \neq p_U} X_i \times \{v \in X_{p_U} : p_U(v) < \varepsilon\}$$

with the last factor inside $X_{p_U}$. Thus, by construction, the map $f : V \to X$ is a homeomorphism of $V$ to its image. ///