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NON - ARCHIMEDEAN DIFFERENTIATION

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by

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§ 1. Introduction.

The subject is part of the so-called non-archimedean (or ultrametric) analysis. Roughly speaking, one may say that this is the analysis that one obtains when replacing in the "classical" analysis IR or C by a non-archimedean valued field K.

A non-archimedean valued field is a (commutative) field K, together with a map \(| \cdot | : K \rightarrow \mathbb{R}\) (the valuation) satisfying

\[
|a| \geq 0 , \quad |a| = 0 \text{ iff } a = 0 \\
|ab| = |a| |b| \\
|a+b| \leq \max(|a|,|b|) \quad \text{(the strong triangle inequality)}
\]

for all \(a,b \in K\).

We have the following remarks.

(1) Apart from IR or C, every complete valued field is non-archimedean.

(2) If \(K\) is a non-archimedean valued field and if \(L \supset K\) is an overfield of \(K\) then the valuation on \(K\) can be extended to a non-archimedean valuation on \(L\).

(3) If \(K\) is a (non-archimedean) valued field then its completion \(\overline{K}\) (with respect to the metric \((x,y) \mapsto |x-y|\)) can, in a natural...
way, be given the structure of a non-archimedean valued field. In the sequel we exclude the so-called **trivial** valuation given by

\[ |x|^o = \begin{cases} 0 & \text{if } x = 0 \\ 1 & \text{if } x \neq 0. \end{cases} \]

The non-archimedean analysis has several branches, similar to the classical analysis. Thus we have non-archimedean **functional analysis**, **harmonic analysis**, **theory of analytic functions in one or several variables**, etc.

In this talk we consider a more elementary subject, namely **infinitesimal calculus** in K. More specifically, we want to see what remains of the so-called **Fundamental Theorem of Calculus** (in \( \mathbb{R} \)) that states that the operations of differentiation and integration are in some sense each others inverses.

§ 2. **Differentiation in K.** Let \( X \subset K \) be a subset without isolated points. A function \( f : X \to K \) is called **differentiable** if for all \( a \in X \)

\[ f'(a) := \lim_{x \to a} \frac{f(x) - f(a)}{x - a} \]

exists. The proof of the well known rules (sum-, product-, chain-rule) can formally be taken over from the classical theory. Thus, a rational function is differentiable if it has no poles on \( X \). An analytic function \( x \to \sum a_n x^n \) is differentiable on

\[ \{ x : |x| < \left( \lim \sqrt[n]{a_n} \right)^{-1} \} \]

Deviations from the classical theory appear when we look at the functions whose derivative vanishes everywhere. For example,
let $\epsilon > 0$, $a \in K$. Then $B(a, \epsilon) := \{x \in K : |x-a| < \epsilon\}$ is an open-
and-closed subset of $K$, hence $\xi_{B(a, \epsilon)}$, defined by

$$\xi_{B(a, \epsilon)}(x) := \begin{cases} 1 & \text{if } x \in B(a, \epsilon) \\ 0 & \text{elsewhere} \end{cases}$$

is differentiable and $\xi'_{B(a, \epsilon)} = 0$.

Locally constant functions all have derivative zero. On the other
hand they form a uniformly dense subset of $C(X)$, the space of all
continuous functions: $X \to K$.

Even worse: let $\mathbb{Q}_p$ the field of the $p$-adic numbers and let

$$\mathbb{Z}_p := \{x \in \mathbb{Q}_p : |x| \leq 1\}.$$  Then the function $f : \mathbb{Z}_p \to \mathbb{Q}_p$ defined by

$$f(\sum_{n} a_n p^n) = \sum_{n} a_n p^{2n} \quad (\sum_{n} a_n p^n \in \mathbb{Z}_p)$$

satisfies $|f(x)-f(y)| = |x-y|^2$ for all $x,y \in \mathbb{Z}_p$. So $f' = 0$ but $f$
is injective, hence not locally constant.

The above example shows also that a Mean Value Theorem is necessa-
ry absent in our theory.

Notice that the difficulties encountered above also appear when we
study differentiability of functions $f : \mathbb{D} \to \mathbb{R}$, where $\mathbb{D} \subset [0,1]$ is the Cantor set. So it is the domain of $f$ that is responsible for the troubles rather than its range.

§ 3. Continuously differentiable functions.

If we follow naively the path of the classical analysis and define

$$C^1(X) := \{f : X \to K, f \text{ is differentiable, } f' \text{ is continuous}\}$$

then we run up against difficulties.

First of all, one can prove that $C^1(\mathbb{Z}_p)$ (with the norm
\( f \mapsto \max(\|f\|_\infty, \|f'\|_\infty) \) is not a Banach space. In fact one shows that for every pair of continuous functions \( f, g : \mathbb{Z}_p \to \mathbb{Q}_p \) there exists a sequence \( f_1, f_2, \ldots \) in \( C^1(\mathbb{Z}_p) \) for which both \( f_n \to f \) and \( f'_n \to g \) uniformly.

What is worse, we have no local invertibility theorem for such \( C^1 \)-functions.

In fact, let \( f : \mathbb{Z}_p \to \mathbb{Q}_p \) be defined by

\[
f(x) = \begin{cases} x-p^{-2n} & \text{if } |x-p^n| < p^{-2n} \\ x & \text{elsewhere} \end{cases} \quad (n \in \mathbb{N})
\]

Then \( f'(x) = 1 \) for all \( x \in \mathbb{Z}_p \). But \( f(p^n) = f(p^n-p^{2n}) \) for all \( n \in \mathbb{N} \), so \( f \) is not even locally injective at 0.

Therefore we are led to define:

Let \( f : X \to K \). Put

\[
\Phi f(x,y) := \frac{f(x)-f(y)}{x-y} \quad (x,y \in X, x \neq y).
\]

We say that \( f \in C^1(X) \) if \( \Phi f \) can continuously be extended to a function \( \Phi f : X \times X \to K \).

Then \( BC^1(X) := \{ f \in C^1(X) : f \text{ and } \Phi f \text{ are bounded} \} \) is a Banach space under \( f \mapsto \|f\|_1 := \max(\|f\|_\infty, \|\Phi f\|_\infty) \).

Further, if \( f \in C^1(X) \), \( f'(a) \neq 0 \) for some \( a \in X \), then \( f \) has a \( C^1 \)-inverse, locally at \( a \).

**Theorem.** Differentiation is a continuous surjection \( BC^1(X) \to BC(X) \).

(here \( BC(X) \) is the space of all bounded continuous functions with the supremum norm)

§ 4. "Integration".

Next, we want to define an "indefinite integral" \( \Phi : BC(X) \to BC^1(X) \)
(an analogue of \((Pf)(x) := \int_0^X f(t)dt\) for real functions) such that
\(DP\) is the identity on \(BC(X)\).

A natural try is first to find an analogue of the Lebesgue
measure in \(K\). But this turns out to be a dead end road. For example
if \(K = \mathbb{Q}_p\) there does not exist a nonzero translation invariant
bounded additive \(\mathbb{Q}_p\)-valued function \(m\) defined on the compact open
subsets of \(K\). (By translation invariance
\(|m(p^n\mathbb{Z}_p)| = p^n|m(\mathbb{Z}_p)| \to \infty\) if \(m(\mathbb{Z}_p) \neq 0\)). For similar reasons it
goes wrong for every local field \(K\).

Following the ideas of Dieudonné, Treiber, we define for
\(f \in BC(X)\)
\[(Pf)(x) := \sum_{n=1}^{\infty} f(x_n)(x_{n+1}-x_n) \quad (x \in X)\]
Here the \(x_n\) are defined as follows. For each \(n \in \mathbb{N}\) the equivalence
relation \(\sim_n\) defined by \(x \sim_n y\) if \(|x-y| < \frac{1}{n}\) yields a partition of \(X\)
into balls. Choose a center in each ball and let \(R_n\) be the set of
these centers.
For each \(x \in X\) and \(n \in \mathbb{N}\), \(x_n\) is defined by \(x_n \in R_n, |x_n-x| < \frac{1}{n}\).

**Theorem.** (A NON-ARCHIMEDEAN FORM OF THE FUNDAMENTAL THEOREM).
\(P\) is a linear isometry of \(BC(X)\) into \(BC^1(X)\). \(DP\) is the identity on
\(BC(X)\), whereas \(PD\) is a projection of \(BC^1(X)\) onto a complement of
\(\{f \in BC^1(X) : f' = 0\}\).

§ 5. Generalizations of the Fundamental Theorem.

We may ask whether there exists some form of the Fundamental
Theorem for functions belonging to spaces, larger than \(BC(X)\), \(BC^1(X)\)
respectively. (For example, compare the classical theorem on $L^1$-functions versus absolutely continuous functions).

We have the following striking fact that has no counterpart in classical analysis. We say that $g : X \to K$ is of the first class of Baire if there exists a sequence $g_1, g_2, \ldots$ of continuous functions $X \to K$ such that $\lim g_n = g$ pointwise.

**THEOREM.** (a) Let $f : X \to K$ be differentiable. Then $f'$ is of the first class of Baire.

(b) Let $g : X \to K$ be of the first class of Baire. Then $g$ has an antiderivative.

Let $B^1(X)$ be the Banach space consisting of all bounded functions $X \to K$ of the first class of Baire with respect to the supremum norm. Let $BD(X)$ be the Banach space of all differentiable $f : X \to K$ for which both $f$ and $\phi f$ are bounded, with respect to the norm $f \to |f|_\infty \lor |\phi f|_\infty$. Then we have

**THEOREM.** Differentiation is a quotient map $BD(X) \to B^1(X)$.

If $K$ has discrete valuation then there exists a continuous linear $P : B^1(X) \to BD(X)$ for which $DP$ is the identity on $B^1(X)$.

**Notes.**

1. The construction of the above $P$ is awful and, contrary to § 4, $P$ does not resemble an indefinite integral in any way.

2. If the valuation of $K$ is dense the existence of such a $P$ is still an open question.
5 6. Restriction of the Fundamental Theorem.

In classical analysis, we have that if \( f \in C^n \) then
\[
\int_0^x f(t) \, dt \text{ is in } C^{n+1}.
\]
In our situation we define for \( f : X \to K \):
\( f \in C^2(X) \) if the function \( \Phi f \), defined by
\[
\Phi f(x,y,z) = \frac{\Phi_1 f(x,z) - \Phi_1 f(y,z)}{x-y} \quad (x,y,z \in X, x \neq y, y \neq z, x \neq z)
\]
can continuously be extended to \( \Phi f : X^3 \to K \). Similarly, we define
\( C^3(X), C^4(X), \ldots \). Let \( C^\infty(X) := \bigcap_{n=1}^{\infty} C^n(X) \).

The map \( P \), defined in § 4, does not always map \( C^1 \)-functions
into \( C^2 \)-functions. But we have (notations as in § 4)

THEOREM. Let the characteristic of \( K \) be unequal to 2. Then the map
\( P_2 \) defined via
\[
(P_2 f)(x) := \sum_{n=1} f(x_n) (x_{n+1} - x_n) + \frac{1}{2} \sum_{n=1} f'(x_n) (x_{n+1} - x_n)^2 \quad (x \in X)
\]
maps \( C^1(X) \) into \( C^2(X) \) and \( (Pf)' = f \) for all \( f \in C^1(X) \).

Similarly, one can define antiderivation maps \( P_n : C^{n-1}(X) \to C^n(X) \)
in case the characteristic of \( K \) is unequal to 2, 3, \ldots, \( n \).

OPEN QUESTION. Let \( K \) have characteristic 0. Does every \( f \in C^\infty(X) \)
have a \( C^\infty \)-antiderivative?

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Reference

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