NON-ARCHIMEDEAN MONOTONE FUNCTIONS

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Introduction.

In the sequel, $K$ is a non-archimedean, non-trivially valued field, that is complete under the metric induced by the valuation. The residue class field of $K$ is denoted by $k$. $X$ will always be a closed, non empty subset of $K$ without isolated points (except in 2.2, if you want).

Since $K$ admits no ordering in the usual sense it is not possible to define monotone functions $X \rightarrow K$ just by taking over the classical definitions. Thus, our procedure will be to try and find statements for functions $\mathbb{R} \rightarrow \mathbb{R}$ equivalent to monotony, and formulated in terms that are translatable to $K$. This way we will obtain several definitions of "$f : X \rightarrow K$ is monotone", that are, although not equivalent, closely related.

The connections between these various definitions and the properties of the non-archimedean monotone functions can be put together to form a little theory which is interesting in its own right, but of which the relations to the other parts of $p$-adic analysis are yet not very tight.

1. Monotone functions.

For a function $f : \mathbb{R} \rightarrow \mathbb{R}$ the following conditions are equivalent:

(a) $f$ is monotone (in the non-strict sense),
(b) If $C \subseteq \mathbb{R}$ is convex then $f^{-1}(C)$ is convex,
(c) If $x$ is between $y, z$ then $f(x)$ is between $f(y)$ and $f(z)$.

Also, the following conditions are equivalent:

(a) $f$ is strictly monotone,
(b) $f$ is injective. If $C \subseteq \mathbb{R}$ is convex then $f(C)$ is relatively convex in $f(\mathbb{R})$,
(c) If $f(x)$ is between $f(y)$ and $f(z)$ then $x$ is between $y$ and $z$.

Let $x, y \in K$. Then the smallest ball that contains $x, y$ is denoted by $[x, y]$. $z \in K$ is between $x$ and $y$ if $z \in [x, y]$. (If $z \notin [x, y]$, we

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call x, y at the same side of z. A subset \( C \subseteq K \) is called convex if \( x, y \in C, \ z \in [x, y] \) implies \( z \in C \). Each convex subset of \( K \) can be written in at least one of the following forms
\[
\{x : |x - a| < r\}, \ \{x : |x - a| \leq r\}
\]
for some \( a \in K, \ r \in (0, \infty) \).

Let \( Z \subset Y \subset K \). Then \( Z \) is called convex in \( Y \) if \( Z = C \cap Y \), where \( C \) is convex.

With all these definitions we have the following theorem.

**THEOREM 1.1.** Let \( f : X \to K \). Then the following conditions are equivalent:

1. If \( x, y, z \in X \), \( x \) is between \( y \) and \( z \) then \( f(x) \) is between \( f(y) \) and \( f(z) \).
2. If \( C \subseteq K \) is convex, then \( f^{-1}(C) \) is convex in \( X \).

We denote the collection of those \( f : X \to K \) satisfying (1) or (2) by \( M_b(X) \), i.e., \( f \in M_b(X) \) if, and only if, for each \( x, y, z \in X \),
\[
|x - y| \leq |y - z| \text{ implies } |f(x) - f(y)| \leq |f(y) - f(z)|.
\]

Isometries are in \( M_b \) (viz. exp), but also non trivial locally constant functions (e.g., choose a center in each ball of radius \( r > 0 \), and let \( f \) be the map assigning to \( x \in X \) the center of the ball of radius \( r \) to which \( x \) belongs. Then \( f \in M_b(X) \)).

**THEOREM 1.2.** Let \( f : X \to K \). Then the following conditions are equivalent:

1. If \( x, y, z \in X \), \( f(x) \) is between \( f(y) \) and \( f(z) \) then \( x \) is between \( y \) and \( z \).
2. If \( O \subseteq X \) is convex in \( X \) then \( f(O) \) is convex in \( f(X) \). \( f \) is injective.

We denote the collection of those \( f : X \to K \) satisfying (1) or (2) by \( M_s(X) \), i.e., \( f \in M_s(X) \) if, and only if, for each \( x, y, z \in X \),
\[
|x - y| < |y - z| \text{ implies } |f(x) - f(y)| < |f(y) - f(z)|.
\]

The classical situations suggests the question as to whether \( M_s(X) = M_b(X) \) and also whether \( f \in M_b(X), \ f \) injective implies \( f \in M_s(X) \). In general, both statements are false, but we do have the following:

**THEOREM 1.3.** \( f \in M_s(X) \) implies \( f^{-1} \in M_b(f(X)) \). \( f \in M_b(X), \ f \) injective implies \( f^{-1} \in M_s(f(X)) \). If \( k \) is finite and \( X \) is convex, then an injective \( M_b \)-function is in \( M_s(X) \).
So we are led to define \( M_b \cap M_s(X) \) as being the more or less natural translation of "the space of the strictly monotone functions".

The following theorem concerns continuity of monotone functions. For a function \( f : X \to K \), we define its oscillation function, \( \omega_f \), in the usual way:

\[
\omega_f(a) := \lim_{n \to \infty} \sup \{|f(x) - f(y)| : |x - a| \leq \frac{1}{n}, |y - a| \leq \frac{1}{n}\}
\]

\[
= \lim_{n \to \infty} \sup \{|f(x) - f(a)| : |x - a| \leq \frac{1}{n}\} \quad (a \in X).
\]

\( f \) is continuous at \( a \) if, and only if, \( \omega_f(a) = 0 \).

**Theorem 1.4.** Let \( f \) be either in \( M_b(X) \) or in \( M_s(X) \). Then

(i) \( \omega_f(a) = \inf_{z \neq a} |f(z) - f(a)| \quad (a \in X) \)

(ii) \( f \) is bounded on compact subsets of \( X \),

(iii) For each \( a \in X \) we have the following alternative. Either \( f \) is continuous at \( a \), or for each sequence \( x_1, x_2, \ldots \) converging to \( a \), the sequence \( f(x_1), f(x_2), \ldots \) is bounded and has no convergent subsequence.

Let \( g \in M_b(X) \). If \( Y \subset X \) is spherically complete, then so is \( g(Y) \).

Let \( h \in M_s(X) \). If \( Z \subset h(X) \) is spherically complete, then so is \( h^{-1}(Z) \).

**Proof (sketch).** If \( f \in M_b(X) \cup M_s(X) \), then:

\[
|x - y| < |y - z| \implies |f(x) - f(y)| < |f(y) - f(z)|.
\]

So \( f \) is locally bounded, and (ii) follows. Of (i), only the \( \leq \) part is interesting. Choose \( z \neq a \). If \( |x - a| < |z - a| \), then

\[
|f(x) - f(a)| < |f(z) - f(a)| \quad \text{whence} \quad \omega_f(a) < |f(z) - f(a)|.
\]

Let \( \lim x_n = a \) (\( x_n \neq a \) for all \( n \)) and \( \lim f(x_n) = \alpha \). Let \( \lim y_n = a \). It suffices to show that \( \lim f(y_n) = \alpha \). Indeed, let \( \epsilon > 0 \), and choose \( k \) such that \( |f(x_k) - \alpha| < \epsilon \). Then \( |y_n - a| < |x_k - a| \) for large \( n \), so

\[
|y_n - y_m| < |x_k - x_m|
\]

for large \( m \) depending on \( m \). Hence \( |f(y_n) - f(x_n)| < |f(x_k) - f(x_m)| \), so

\[
(m \to \infty) \quad |f(y_n) - \alpha| < |f(x_k) - \alpha| < \epsilon,
\]

and we have (iii). The rest of the proof is straightforward.

**Corollary 1.5.** Let \( f : X \to K \) be in \( M_b(X) \cup M_s(X) \).

(i) If \( K \) is a local field, then \( f \) is continuous.

(ii) If \( |K| \) is discrete, then \( f \in M_s(X) \Rightarrow f \) is a homeomorphism \( X \to f(X) \), and \( f \in M_b(X) \Rightarrow f \) is a closed map.

(iii) The graph of \( f \) is closed in \( K^2 \).

(iv) If \( f(X) \) has no isolated points, then \( f \) is continuous.
An \( M_b \)-function may be everywhere discontinuous on \( K \) (even when \( |K| \) is discrete).

**THEOREM 1.6.** Let \( B \) be the unit ball of \( K \),

(i) If \( K \) is a local field and \( f \in M_b(B) \cup M_s(B) \), then \( f \) has bounded difference quotients (i.e., there is \( C > 0 \) such that \( |f(x) - f(y)| \leq C|x - y| \) for all \( x \in B \)). If, in addition, \( f(B) \) is convex, then \( f \) is a similarity (i.e., a scalar multiple of an isometry).

(ii) If \( K \) has discrete valuation and \( f \in M_b(B) \) is bounded, then \( f \) has bounded difference quotients. If \( f \in M_{bs}(B) \) and if \( f(B) \) is convex, then \( f \) is a similarity.

2. **Monotone functions having a type.**

In this section, we want to translate the usual classification of (strictly) monotone functions \( \mathbb{R} \to \mathbb{R} \) into two types: the increasing and the decreasing functions. The equivalence relation in \( \mathbb{R}^r \): \( x \sim y \) if \( x \) and \( y \) are at the same side of \( 0 \), yields \((-\infty, 0) \) and \((0, \infty) \) as equivalence classes. The relation \( \sim \) is compatible with the canonical group homomorphism \( \mathbb{R}^\times \to \mathbb{R}^*/\mathbb{R}^+ \), the latter group being \([1, -1] \). \( \pi(x) \) (usually called \( \text{sgn}(x) \)) assigns \(+1\) to every positive element and \(-1\) to every negative element. A function \( f: \mathbb{R} \to \mathbb{R} \) is strictly monotone if there exists \( \sigma: \mathbb{R}^*/\mathbb{R}^+ \to \mathbb{R}^*/\mathbb{R}^+ \) such that for all \( x \neq y \)

\[
\pi(f(x) - f(y)) = \sigma(\pi(x - y)).
\]

If \( \sigma \) is the identity then \( f \) is called increasing; if \( \sigma(1) = -1 \), \( \sigma(-1) = 1 \), \( f \) is called decreasing. Other maps \( \sigma: [-1, 1] \to [-1, 1] \) cannot occur (i.e., there is no \( f \) such that, for all \( x \neq y \),

\[
\pi(f(x) - f(y)) = \sigma(\pi(x - y)).
\]

This rather weird description of real monotone functions can be used in the non-archimedean case.

For \( x, y \in K^\times \) define \( x \sim y \) if \( x, y \) are at the same side of \( 0 \). This means: \( 0 \notin [x, y] \), or \( |x - y| > |y| \), or \( |xy^{-1} - 1| < 1 \). Thus \( x \sim y \) if, and only if, \( xy^{-1} \in K^+ \) where

\[
K^+ := \{x \in K; \ |1 - x| < 1 \}.
\]

We call the elements of \( K^+ \) the positive element of \( K \).

The relation \( \sim \) is compatible with the canonical homomorphism of (multiplicative) groups

\[
\pi: K^\times \to K^*/K^+ =: \Sigma.
\]

We call \( \Sigma \) the group of signs and \( \pi(x) \) the sign of an element \( x \in K^\times \) ( \( x \) is
positive if, and only if, \( \pi(x) = 1 \).

If \( K \) is a local field, we can make a group embedding \( \rho : \Sigma \to K^\# \) such that \( \pi \circ \rho \) is the identity on \( \Sigma \). For example, if \( K = \mathbb{Q}_p \), \( \delta \) is a primitive \((p - 1)^{th}\) root of unity, then

\[
\pi \left( \sum_{n \geq 0} a_n p^n \right) = a_k p^k \quad (k \in \mathbb{Z}, \ a_k \neq 0)
\]

(Here \( a_n \in \{0, 1, \delta, \ldots, \delta^{p-2}\} \) for each \( n \)).

**Definition 2.1.** Let \( \sigma : \Sigma \to \Sigma \) be any map. A function \( f : X \to K \) is monotone of type \( \sigma \) if, for all \( x, y \in X, \ x \neq y \),

\[
\pi(f(x) - f(y)) = \sigma(\pi(x - y))
\]

(i.e., if \( x - y \in \sigma \in \Sigma \) then \( f(x) - f(y) \in \sigma(\sigma) \)).

We call \( f \) of type \( \beta \in \Sigma \) if \( f \) is of type \( \sigma \) where \( \sigma \) is the multiplication with \( \beta \), i.e.,

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

We call \( f \) increasing if \( f \) is of type \( \sigma \) where \( \sigma \) is the identity, i.e.,

\[
\frac{f(x) - f(y)}{x - y} \text{ is positive} \quad (x \neq y).
\]

Clearly, if \( f \) is of type \( \beta \), and if \( b \in \beta \), then \( b^{-1} f \) is increasing.

First, we look at increasing functions, then we discuss more general types \( \sigma \).

Notice that increasing functions are isometries hence are in \( K_{bs}(X) \). If \( f \) is increasing then \( f(x) = x + h(x) \), where \( |h(x) - h(y)| < |x - y| \) \((x, y \in X, x \neq y)\). Such \( h \) we call pseudo-contractions.

**Lemma 2.2.** Let \( X \) be an ultrametric space. Then the following are equivalent

(a) \( X \) is spherically complete,

(b) Each pseudocontraction \( X \to X \) has a (unique) fixed point.

**Proof (sketch).** (a) \( \to \) (b). Let \( \sigma : X \to X \) be a pseudocontraction. A convex set \( C \subset X \) is called invariant if \( \sigma(C) \subset C \). It is easily proved that the invariant convex subsets of \( X \) form a nest. Let \( C_0 \) be the smallest invariant convex set. If \( a \in C_0 \) and \( \sigma(a) \neq a \) then

\[
B_0 := \{ x \in X ; \ d(x, \sigma(a)) < d(a, \sigma(a)) \}
\]

is invariant, convex, and does not contain \( a \). Hence \( \sigma(a) = a \) for all \( a \in C_0 \), and \( C_0 \) is a singleton. (b) \( \to \) (a). If \( B_1 \neq B_2 \neq \ldots \) are balls in \( X \) with \( \bigcap B_n = \emptyset \) then choose \( x_n \in B_n \setminus B_{n+1} \) \((n \in \mathbb{N})\). The map \( \sigma : X \to X \) defined by

\[
\sigma(x) = x_{n+1} \quad (x \in B_n \setminus B_{n+1})
\]

is a pseudocontraction without a fixed point.
COROLLARY 2.3. - Let $X$ be convex, let $K$ be spherically complete, and let $f : X \to K$ be increasing. Then $f(X)$ is convex. If $f(X) \subset X$, then $f$ is surjective.

Proof. - Let $f(X) \subset X$. Choose $a \in X$. Then $x \mapsto f(x) + x + a$ is a pseudocontraction mapping $X$ into $X$, hence has a fixed point. So $f(x) = a$ for some $x \in X$.

If $K$ is not spherically complete, we have always increasing $f : K \to K$ that are not surjective. (Let $h : K \to K$ be a pseudocontraction without a fixed point. Let $f(x) = x - h(x) \ (x \in K)$, then $0 \notin f(I)$. The inverse $f^{-1} : f(K) \to K$ can, of course, not be extended to an increasing function $K \to K$.

THEOREM 2.4. - Let $K$ be spherically complete, and let $f : X \to K$ be increasing. Then $f$ can be extended to an increasing function $K \to K$.

Proof. - By Zorn's Lemma, it suffices to extend $f$ to an increasing function on $X \cup \{a\}$, where $a \notin X$. We are done if we can find $a \in K$ such that, for all $x \in X$,

$$\left|\frac{a - f(x)}{a - x} - 1\right| < 1$$

i.e. $a \in B_{f(x)}((a-x))$ for all $x \in X$. These balls form a nest.

Let us call a function $f : X \to K$ positive if $f(X) \subset K^+$.

THEOREM 2.5.

(i) If $f : X \to K$ is increasing then $f'$ is positive,

(ii) If $g : X \to K$ is a positive Baire class one function, then $g$ has an increasing antiderivative,

(iii) If $g : X \to K$ is continuous and positive, then $g$ has a $C^1$-antiderivative,

(iv) If $f \in C^1(X)$ and $f'$ is positive then $f = j + h$ where $j$ is increasing, and $h$ is locally constant.

EXAMPLES.

1° The exponential function (defined on its natural convergence region) is increasing.

2° Let $f \in C(\mathbb{Z}_p)$, and let $e_n = \xi_n$, for $n \in \mathbb{N}_0$,

$$e_n(x) = \begin{cases} 1 & \text{if } |x - n| < \frac{1}{n} \\ 0 & \text{elsewhere} \end{cases} \quad (x \in \mathbb{Z}_p).$$

Then $e_0, e_1, \ldots$ form an orthonormal base of $C(\mathbb{Z}_p)$, so there exist $\lambda_0, \lambda_1, \ldots \in \mathbb{Q}_p$ such that $f = \sum_{n=0}^{\infty} \lambda_n e_n$, uniformly.
f is increasing if, and only if, for all \( n \in \mathbb{N} \),
\[
|\lambda_n - [n]| < [n]
\]
(where, if \( n = a_0 + a_1 p + \ldots + a_k p^k \) (\( a_i \in \{0, 1, \ldots, p - 1\} \) for each \( i \), \( a_k \neq 0 \)), then \( [n]_1 = a_k p^k \).

In other words, \( f = \sum \lambda_n e_n \in C(\mathbb{Z}_p) \) is increasing if, and only if, \( \lambda_n/\{n\} \) is positive for all \( n \in \mathbb{N} \).

Let \( \alpha, \beta \in \Sigma \). If the set theoretic sum \( \alpha + \beta := \{x + y \mid x \in \alpha, \ y \in \beta\} \) does not contain \( 0 \) then \( \alpha + \beta \in \Sigma \), notation \( \alpha \oplus \beta \). It follows that \( \alpha \oplus \beta \) is defined if, and only if, \( \alpha \neq -\beta \).

If \( x, y \in \alpha \in \Sigma \) then \( |x| = |y| \). This defines \( |\alpha| \) in a natural way.

We have the following results.

**THEOREM 2.6.** - Let \( f : K \to K \) be monotone of type \( \sigma : \Sigma \to \Sigma \). Let \( \alpha, \beta \in \Sigma \),

(i) \( \sigma(-\alpha) = -\sigma(\alpha) \),

(ii) If \( \sigma(\alpha) \oplus \sigma(\beta) \) is defined then so is \( \alpha \oplus \beta \) and \( \sigma(\alpha \oplus \beta) = \sigma(\alpha) \oplus \sigma(\beta) \),

(iii) \( |\alpha| < |\beta| \) implies \( |\sigma(\alpha)| < |\sigma(\beta)| \),

(iv) If \( |\beta| = 1 \), \( \beta \) contains an element of the prime field of \( K \) then \( \sigma(\beta \alpha) = \beta \sigma(\alpha) \),

(v) \( f \in \mathcal{M}_b(K) \),

(vi) \( f \) is either nowhere continuous or uniformly continuous.

**THEOREM 2.7.** - Let \( f : K \to K \) be monotone of type \( \sigma : \Sigma \to \Sigma \). Then the following conditions are equivalent,

(\( \alpha \)) \( \sigma \) is injective,

(\( \beta \)) \( f \in \mathcal{M}_b(X) \),

(\( \gamma \)) If for some \( \alpha, \beta \in \Sigma \), \( \alpha \oplus \beta \) is defined, then so is \( \sigma(\alpha) \oplus \sigma(\beta) \),

(\( \delta \)) \( |\sigma(\alpha)| < |\sigma(\beta)| \) implies \( |\alpha| < |\beta| \) \( (\alpha, \beta \in \Sigma) \).

**COROLLARY 2.8.** - Let \( k \) be a prime field, and let \( f : K \to K \) be monotone of type \( \sigma : \Sigma \to \Sigma \). Then \( \sigma \) is injective.

(If \( K = \mathbb{Q}_p(\sqrt{-1}) \), \( p = 3 \mod 4 \), we can find an example of an \( f : K \to K \) monotone of type \( \sigma \), where \( \sigma \) is not injective).

**EXAMPLE 2.9.** - Let \( K = \mathbb{Q}_p \). Then

\[ \{\sigma : \Sigma \to \Sigma : \text{there is } f : \mathbb{Q}_p \to \mathbb{Q}_p, \ f \text{ monotone of type } \sigma\} \]
consists of all $\sigma : \Sigma \to \Sigma$ of the form
$$\phi^i \cdot p^n \mapsto \phi^i \cdot \delta^{(n)} \cdot \lambda(n)$$
where $s : \mathbb{Z} \to \{0, 1, 2, \ldots, p - 2\}$ and $\lambda : \mathbb{Z} \to \mathbb{Z}$ is strictly increasing.

3. Functions of bounded variation.

**Lemma 3.1.** Let $f : X \to K$ have bounded difference quotients. Then $f$ is a linear combination of two increasing functions.

**Proof.** Choose $\lambda \in K$,
$$|\lambda| > \sup \{|f(x) - f(y)| / x - y ; x \neq y\}.$$Then $\lambda^{-1} f$ is a (pseudo-) contraction, so $g(x) := -x + \lambda^{-1} f(x)$ ($x \in X$) is increasing. If $h(x) := x$ ($x \in X$), then $\lambda h + \lambda g = f$.

**Corollary 3.2.** Let $X$ be the unit ball of a local field $K$ and let $f : X \to K$. Then the following are equivalent

(a) $f \in BA(X)$ (i.e., $\sup \{|f(x) - f(y)| / x - y ; x \neq y\} < \infty$),

(b) $f$ is a linear combination of two increasing functions,

(γ) $f \in \| H_\gamma(X) \|$,

(δ) $f \in \| H_\delta(X) \|$.

**Proof.** Use 1.6.

REFERENCES
