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THE WEIERSTRASS-STONE APPROXIMATION THEOREM
FOR p-ADIC C^n-FUNCTIONS

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Abstract.
Let K be a non-Archimedean valued field. Then, on compact subsets of K, every K-valued C^n-function can be approximated in the C^n-topology by polynomial functions (Theorem 1.4). This result is extended to a Weierstrass-Stone type theorem (Theorem 2.10).

INTRODUCTION
The non-archimedean version of the classical Weierstrass Approximation Theorem - the case n = 0 of the Abstract - is well known and named after Kaplansky ([1], 5.28). To investigate the case n = 1 first let us return to the Archimedean case and consider a real-valued C^1-function f on the unit interval. To find a polynomial function P such that both |f−P| and |f'−P'| are smaller or equal than a prescribed ε > 0 one simply can apply the standard Weierstrass Theorem to f' obtaining a polynomial function Q for which |f'−Q| ≤ ε. Then x ↦ P(x) := f(0) + ∫₀^x Q(t)dt solves the problem.

Now let f : X → K be a C^1-function where K is a non-archimedean valued field and X ⊆ K is compact.

Lacking an indefinite integral the above method no longer works. There do exist continuous linear antiderivations ([3], §64) but they do not map polynomials into polynomials ([3], Ex. 30.C). A further complicating factor is that the natural norm for C^1-functions on X is given by

\[ f ↦ \max\{|f(x)| : x ∈ X\} ∨ \max\left\{\left|\frac{f(x)−f(y)}{x−y}\right| : x, y ∈ X, x \neq y\right\} \]

rather than the more classical formula

\[ f ↦ \max\{|f(x)| : x ∈ X\} ∨ \max\{|f'(x)| : x ∈ X\}. \]

(Observe that in the real case both formulas lead to the same norm thanks to the Mean Value Theorem, see [3], §§26,27 for further discussions.)
Thus, to obtain non-archimedean $C^n$-Weierstrass-Stone Theorems for $n \in \{1, 2, \ldots\}$ our methods will necessarily deviate from the 'classical' ones.

0. PRELIMINARIES

1. Throughout $K$ is a non-archimedean complete valued field whose valuation $| |$ is not trivial. For $a \in K$, $r > 0$ we write $B(a, r) := \{x \in K : |x-a| \leq r\}$, the 'closed' ball about $a$ with radius $r$. 'Clopen' is an abbreviation for 'closed and open'. The function $x \mapsto x$ ($x \in K$) is denoted $X$. The $K$-valued characteristic function of a subset $Y$ of $K$ is written $\xi_Y$. For a set $Z$, a function $f : Z \to K$ and a set $W \subseteq Z$ we define $\|f\|_W := \sup\{|f(x)| : x \in W\}$ (allowing the value $\infty$). The cardinality of a set $\Gamma$ is $\#\Gamma$. $\mathbb{N}_0 := \{0, 1, 2, \ldots\}$, $\mathbb{N} := \{1, 2, 3, \ldots\}$.

We now recall some facts from [2], [3] on $C^n$-theory.

2. For a set $Y \subseteq K$, $n \in \mathbb{N}$ we set $\nabla^n Y := \{(y_1, y_2, \ldots, y_n) \in Y^n : i \neq j \implies y_i \neq y_j\}$. For $f : Y \to K$, $n \in \mathbb{N}_0$ we define its $n$th difference quotient $\Phi_n f : \nabla^{n+1} Y \to K$ inductively by $\Phi_0 f := f$ and the formula

$$\Phi_n f(y_1, \ldots, y_{n+1}) = \frac{\Phi_{n-1} f(y_1, y_3, \ldots, y_{n+1}) - \Phi_{n-1} f(y_2, y_3, \ldots, y_{n+1})}{y_1 - y_2}$$

$f$ is called a $C^n$-function if $\Phi_n f$ can be extended to a continuous function on $Y^{n+1}$. The set of all $C^n$-functions $Y \to K$ is denoted $C^n(Y \to K)$. The function $f : Y \to K$ is a $C^\infty$-function if it is in $C^\infty(Y \to K) := \bigcap_{n=0}^{\infty} C^n(Y \to K)$. The space $C^0(Y \to K)$, consisting of all continuous functions $Y \to K$ is sometimes written as $C(Y \to K)$.

3. Since $X$ has no isolated points we have for an $f \in C^n(X \to K)$ that the continuous extension of $\Phi_n f$ to $X^n$ is unique; we denote this extension by $\Phi_n f$. Also we write

$$D_n f(a) := \Phi_n f(a, a, \ldots, a) \quad (a \in X)$$

The following facts are proved in [2] and [3].

Proposition 0.3.

(i) For each $n \in \mathbb{N}_0$ the space $C^n(X \to K)$ is a $K$-algebra under pointwise operations.
(ii) $C^0(X \to K) \supset C^1(X \to K) \supset \ldots$
(iii) If \( f \in C^n(X \to K) \) then \( f \) is \( n \) times differentiable and \( j!D_jf = f^{(j)} \) for each \( j \in \{0,1,\ldots,n\} \). More generally, if \( i,j \in \{0,1,\ldots,n\}, \ i+j \leq n \) then \((i+j)!D_iD_jf = D_{i+j}f\).

(iv) If \( f \in C^n(X \to K) \) then for \( x,y \in X \) we have Taylor's formula

\[
f(x) = f(y) + (x-y)D_1f(y) + \cdots + (x-y)^nD_nf(y) + (x-y)^n\rho_1f(x,y),
\]

where \( \rho_1f(x,y) = \Phi_nf(x,y,y,\ldots,y) \).

4. Since \( X \) is compact the difference quotients \( \Phi_if \ (0 \leq i \leq n) \) are bounded if \( f \in C^n(X \to K) \). We set

\[
\|f\|_{n,X} := \max\{\|\Phi_if\|_{\sigma^{i+1}X} : 0 \leq i \leq n\}.
\]

Then \( \|f\|_{0,X} = \|f\|_X \). We quote the following from [2] and [3].

**Proposition 0.4.** Let \( n \in \mathbb{N}_0 \).

(i) The function \( \| \|_{n,X} \) is a norm on \( C^n(X \to K) \) making it into a \( K \)-Banach algebra.

(ii) The local polynomials form a dense subset of \( C^n(X \to K) \).

(iii) The function

\[
f \mapsto \|f\|_{n,X} := \max_{0 \leq i \leq n-1} \|D_if\|_X \lor \|\rho_1f\|_X
\]

(see Proposition 0.3 (iv)) also is a norm on \( C^n(X \to K) \). We have

\[
\|f\|_{n,X} = \max\{\|D_if\|_{n-i,X} : 0 \leq i \leq n\} \quad (f \in C^n(X \to K)).
\]

**Remarks**

1. Proposition 0.4 (ii) will also follow from Proposition 2.8.

2. In general \( \| \|_{n,X} \) is not equivalent to \( \| \|_{n,X} \) for \( n \geq 3 \) (see [3], Example 83.2).
1 THE WEIERSTRASS THEOREM FOR $C^n$-FUNCTIONS

The following product rule for difference quotients is easily proved by induction with respect to $j$.

Let $f, g : X \to K$, let $j \in \mathbb{N}_0$. Then for all $(x_1, \ldots, x_{j+1}) \in \nabla^{j+1} X$ we have

$$\Phi_j(fg)(x_1, \ldots, x_{j+1}) = \sum_{k=0}^j \Phi_k f(x_1, \ldots, x_k+1) \Phi_{j-k} g(x_{k+1}, \ldots, x_{j+1}).$$

Or, less precise,

$$\Phi_j(fg)(x_1, \ldots, x_{j+1}) = \sum_{k=0}^j \Phi_k f(z_k) \Phi_{j-k} g(u_{j-k})$$

for certain $z_k \in \nabla^{k+1} X$, $u_{j-k} \in \nabla^{j-k+1} X$.

In the sequel we need an extension of this formula to finite products of functions. The proof is straightforward by induction with respect to $N$.

**Lemma 1.1. (Product Rule)** Let $h_1, \ldots, h_N : X \to K$, let $j \in \mathbb{N}_0$. Then for all $(x_1, \ldots, x_{j+1}) \in \nabla^{j+1} X$ we have

$$\Phi_j \left( \prod_{s=1}^N h_s \right)(x_1, \ldots, x_{j+1}) = \sum_{s=1}^N \Phi_j h_s(z_{\sigma,s})$$

where the sum is taken over all $\sigma := (j_1, \ldots, j_N) \in \mathbb{N}_0^N$ for which $j_1 + \cdots + j_N = j$ and where $z_{\sigma,s} \in \nabla^{j_s+1} X$ for each $s \in \{1, \ldots, N\}$. (In fact, $z_{\sigma,1} = (x_1, \ldots, x_{j_1+1}), z_{\sigma,2} = (x_{j_1+1}, \ldots, x_{j_1+j_2+1}), \ldots, z_{\sigma,N} = (x_{j_1+\cdots+j_{N-1}+1}, \ldots, x_{j+1})$.)

The following key lemma grew out of [1], 5.28.

**Lemma 1.2.** Let $0 < \delta < 1$, $0 < \varepsilon < 1$, let $B = B_0 \cup B_1 \cup \cdots \cup B_m$ where $B_0, \ldots, B_m$ are pairwise disjoint 'closed' balls in $K$ of radius $\delta$. Then, for each $n \in \{0, 1, \ldots\}$ there exists a polynomial function $P : K \to K$ such that $\|P - \xi_{B_0}\|_{n,B} \leq \varepsilon$.

**Proof.** We may assume $0 \in B_0$. Choose $c_1 \in B_1, \ldots, c_m \in B_m$; we may assume that $|c_1| \leq |c_2| \leq \cdots \leq |c_m|$. Then $\delta < |c_1|$. We shall prove the following statement by induction with respect to $n$.

Let $k \in \mathbb{N}$ be such that $(\delta/|c_1|)^k \leq \varepsilon \delta^n$, $k > n$. Let $t_1, t_2, \ldots, t_m \in \mathbb{N}$ be such that for all $\ell \in \{1, \ldots, n\}$

$$\left| \frac{c_{t_\ell}}{c_{t_1}} \right|^{kt_1} \left| \frac{c_{t_\ell}}{c_{t_2}} \right|^{kt_2} \cdots \left| \frac{c_{t_\ell}}{c_{t_{\ell-1}}} \right|^{kt_{\ell-1}} \left( \frac{\delta}{|c_1|} \right)^{kt_\ell} \leq \varepsilon \delta^n$$

(1)
defines a polynomial function $P : K \to K$ for which

$$\|P - \xi_{B_0}\|_{n,B} \leq \varepsilon.$$ 

The case $n = 0$ is proved in [1], 5.28. To prove the step $n - 1 \to n$ we first observe that from the induction hypothesis (with $\varepsilon$ replaced by $\varepsilon \delta$) it follows that

(2) $$\|P - \xi_{B_0}\|_{n-1,B} \leq \varepsilon \delta
$$

So it remains to be shown that

(3) $$|\Phi_n(P - \xi_{B_0})(x_1, \ldots, x_{n+1})| \leq \varepsilon$$

for all $(x_1, \ldots, x_{n+1}) \in \nabla^{n+1} B$. Now, if $|x_i - x_j| > \delta$ for some $i, j \in \{1, \ldots, n + 1\}$ we have, using (2),

$$|\Phi_n(P - \xi_{B_0})(x_1, \ldots, x_{n+1})| = |x_i - x_j|^{-1} |\Phi_{n-1}(P - \xi_{B_0})(x_1, \ldots, x_{j-1}, x_{j+1}, \ldots, x_{n+1}) - \Phi_{n-1}(P - \xi_{B_0})(x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_{n+1})| \leq \delta^{-1} \varepsilon \delta = \varepsilon.$$ 

So this reduces the proof of (3) to the case where $|x_i - x_j| \leq \delta$ for all $i, j \in \{1, \ldots, n + 1\}$; in other words we may assume that $x_1, \ldots, x_{n+1}$ are all in the same $B_{\ell}$ for some $\ell \in \{0, 1, \ldots, m\}$. But then, after observing that $n \geq 1$, we have $\Phi_n \xi_{B_0}(x_1, \ldots, x_{n+1}) = 0$ so it suffices to prove the following.

If $\ell \in \{0, 1, \ldots, m\}$ and $x_1, \ldots, x_{n+1} \in B_{\ell}$ are pairwise distinct then

(4) $$|\Phi_n P(x_1, \ldots, x_{n+1})| \leq \varepsilon$$

To prove it we introduce, with $\ell \in \{1, \ldots, m\}$ fixed, the constants $M_i$ ($i \in \{1, \ldots, n\}$) by

$$M_i := \begin{cases} 1 & \text{if } i > \ell \\ \delta/|c_1| & \text{if } i = \ell \\ |c_\ell/c_i|^k & \text{if } i < \ell \end{cases}$$

and use the following three steps.

**Step 1.** For each $j \in \{0, 1, \ldots, n\}$, $i \in \{1, \ldots, n\}$ we have

$$\|\Phi_j(1 - (\frac{x_i}{c_i})^k)\|_{\nabla^{i+1} B_{\ell}} \leq \begin{cases} 1 & \text{if } \ell = 0, j = 0 \\ \delta^{-j}(\frac{\delta}{|c_1|})^k & \text{if } \ell = 0, j > 0 \\ \delta^{-j} M_i & \text{if } \ell > 0. \end{cases}$$
Proof.

a. The case $j = 0$. Then for $x \in B_{\ell}$ we have
   - if $i > \ell$ then $|1 - (\frac{x}{c_i})^k| = 1$
   - if $i = \ell$ then $|1 - (\frac{x}{c_i})^k| = \frac{|c_i - x|}{|c_i|}^k \leq \frac{\delta^k}{|c_i|^k} \leq \frac{\delta}{|c_i|}$
   - if $i < \ell$ then $|1 - (\frac{x}{c_i})^k| = \frac{|c_i|^k}{|c_i|^k} = 1$

and the statement follows.

b. The case $j > 0$. Then $\Phi_j(1) = 0$ so that

$$\Phi_j(1 - (\frac{x}{c_i})^k) = \frac{1}{c_i^k} \Phi_j(x^k)$$

Let $(x_1, \ldots, x_{j+1}) \in \nabla^{j+1} B_{\ell}$. By the Product Rule 1.1, $\Phi_j(x^k)(x_1, \ldots, x_{j+1})$ is a sum of terms of the form $\prod_{s=1}^{k} (\Phi_j(x^k))(z_s)$. Such a term is 0 if one of the $j_s$ is $> 1$, so we only have to deal with $j_s = 0$ (then $\Phi_j, x^k = x^k$) or $j_s = 1$ (then $\Phi_j, x^k = 1$). The latter case occurs $j$ times (as $\sum_{s=1}^{k} j_s = j$) and it follows that

$$\prod_{s=1}^{k} (\Phi_j(x^k))(z_s)$$

is a product of $k-j$ distinct terms taken from $\{x_1, \ldots, x_{j+1}\}$ (observe that, indeed, $j < k$ since $j \leq n < k$), so its absolute value is $\leq |c_i|^{k-j}$. It follows that $||\Phi_j(1 - (\frac{x}{c_i})^k)||_{\nabla^{j+1} B_{\ell}} \leq |c_i|^{k-j} / |c_i|^k$ from which we conclude

- if $\ell = 0 : |c_i|^{k-j} / |c_i|^k \leq \delta^{k-j} / |c_i|^k = \delta^{-j}\left(\delta / |c_i|\right)^k$,
- if $\ell > 0 : |c_i|^{k-j} / |c_i|^k \leq |c_i|^{-j} < \delta^{-j} = \delta^{-j}M_i$
- if $i = \ell > 0 : |c_i|^{k-j} / |c_i|^k \leq |c_i|^{-j} \leq |c_i|^{-j} = \delta^{-j}\left(\delta / |c_i|\right)^j \leq \delta^{-j}M_i$
- if $i < \ell : |c_i|^{k-j} / |c_i|^k \leq |c_i|^{-j} |c_i|^k \leq \delta^{-j}M_i$

and step 1 is proved.

Step 2. For each $j \in \{0, 1, \ldots, n\}$, $i \in \{1, \ldots, n\}$ we have

$$||\Phi_j(1 - (\frac{x}{c_i})^k)||_{\nabla^{j+1} B_{\ell}} \leq \begin{cases} 1 & \text{if } \ell = 0, j = 0 \\ \delta^{-j}\left(\frac{\delta}{|c_i|}\right)^k & \text{if } \ell = 0, j > 0 \\ \delta^{-j}M_i^{|s_i|} & \text{if } \ell > 0 \end{cases}$$

Proof. The case $j = 0$ follows directly from Step 1, part a, so assume $j > 0$. By the Product Rule 1.1 applied to $h_s = 1 - (\frac{x}{c_i})^k$ for all $s \in \{1, \ldots, t_s\}$ we have for $(x_1, \ldots, x_{j+1}) \in \nabla^{j+1} B_{\ell}$ that $\Phi_j(1 - (\frac{x}{c_i})^k)^{t_i}(x_1, \ldots, x_{j+1})$ is a sum of terms of the form

$$\prod_{s=1}^{t_i} \Phi_{j_s}(1 - (\frac{x}{c_i})^k)(z_s)$$

(5)
where \( j_1 + \cdots + j_s = j \). If \( \ell = 0 \) it follows from Step 1 that the value of (5) is
\[
\leq \prod \delta^{-j_i}(\frac{\delta}{|c_i|})^{k_i}
\]
where the product is taken over all \( s \) in the nonempty set \( \Gamma := \{s \in \{1, \ldots, t_i\} : j_s > 0\} \), so the product is \( \leq \delta^{-j_i}(\frac{\delta}{|c_i|})^{k_i} \leq \delta^{-j_i}(\frac{\delta}{|c_i|})^k \). If \( \ell > 0 \) it follows from Step 1 that the value of (5) is \( \leq \prod_{s=1}^{t_i} \delta^{-j_s} M_i = \delta^{-j} \).

The statement of Step 2 follows.

**Step 3.** Proof of (4). Again, the Product Rule 1.1, now applied to \( h_i = (1 - (\mathcal{A}_i)^k)^{t_i} \) for \( i \in \{1, \ldots, m\} \) tells us that for \( (x_1, \ldots, x_{n+1}) \in \nabla^{n+1} B_\ell \) the expression \( \Phi_n P(x_1, \ldots, x_{n+1}) \) is a sum of terms of the form
\[
\prod_{i=1}^{m} \Phi_{n_i}(1 - (\frac{\mathcal{X}}{c_i})^{t_i})(z_i)
\]
where \( n_1 + \cdots + n_m = n \). If \( \ell = 0 \) we have by Step 2 that the value of (6) is \( \leq \prod \delta^{-n_i}(\frac{\delta}{c_i})^{k_i} \) where the product is taken over \( i \) in the nonempty set \( \Gamma := \{i : n_i \neq 0\} \), so the product is \( \leq \delta^{-n}(\frac{\delta}{c_1})^{k_1} \leq \delta^{-n} \cdot \epsilon \delta^n = \epsilon \), where we used the assumption \( (\delta/c_1)^{k_i} \leq \epsilon \delta^n \). We see that \( |\Phi_n P(x_1, \ldots, x_{n+1})| \leq \epsilon \) if \( (x_1, \ldots, x_n) \in B_0 \).

Now let \( \ell > 0 \). By Step 2 we have that the absolute value of (6) is \( \leq \prod_{i=1}^{m} \delta^{-n_i} M_i^{t_i} = \delta^{-n} M_1^{t_1} \cdots M_m^{t_m} = \delta^{-n} |\frac{\mathcal{X}}{c_1}|^{k_1} \cdots |\frac{\mathcal{X}}{c_{t_i-1}}|^{k_{t_i}}(\frac{\delta}{c_1})^{k_i} \), which is \( \leq \delta^{-n} \epsilon \delta^n \) by (1). This proves (4) and the Lemma.

**Corollary 1.3.** For every locally constant \( f : X \to K \), for every \( n \in \mathbb{N}_0 \) and \( \epsilon > 0 \) there exists a polynomial function \( P : K \to K \) such that \( \|f - P\|_{n,X} \leq \epsilon \).

**Proof.** There exist a \( \delta \in (0,1) \), pairwise disjoint 'closed' balls \( B_1, \ldots, B_m \) of radius \( \delta \) covering \( X \) and \( \lambda_1, \ldots, \lambda_m \in K \) such that
\[
f(x) = \sum_{i=1}^{m} \lambda_i \xi_{B_i}(x) \quad (x \in X)
\]

By Lemma 1.2 there exist polynomials \( P_1, \ldots, P_m \) such that \( \|\xi_{B_i} - P_i\|_{n,X} \leq \frac{\delta}{n,\cup B_i} \leq \epsilon(\|\lambda_i \| + 1)^{-1} \) for each \( i \in \{1, \ldots, m\} \). Then \( P := \sum_{i=1}^{m} \lambda_i P_i \) is a polynomial function and \( \|f - P\|_{n,X} \leq \max_i \|\lambda_i (\xi_{B_i} - P_i)\|_{n,X} \leq \max_i \|\lambda_i \| \epsilon(\|\lambda_i \| + 1)^{-1} \leq \epsilon \).

**Theorem 1.4. (C^n-Weierstrass Theorem)** For each \( n \in \mathbb{N}_0, f \in C^n(X \to K) \) and \( \epsilon > 0 \) there exists a polynomial function \( P : K \to K \) such that \( \|f - P\|_{n,X} \leq \epsilon \).

**Proof.** There is by Proposition 0.4 a local polynomial \( g : K \to K \) with \( \|f - g\|_{n,X} \leq \epsilon \). This \( g \) has the form \( g = \sum_{i=1}^{m} Q_i h_i \) where \( Q_1, \ldots, Q_m \) are polynomials and \( h_1, \ldots, h_m \).
are locally constant. By Corollary 1.3 we can find polynomials $P_1, \ldots, P_m$ for which
\[ \|h_i - P_i\|_{n,X} \leq \varepsilon(\|Q_i\|_{n,X} + 1) \] for each $i$. Then $P := \sum_{i=1}^{m} Q_i P_i$ is a polynomial and
\[ \|g - P\|_{n,X} \leq \varepsilon. \] It follows that $\|f - P\|_{n,X} \leq \max\{\|f - g\|_{n,X}, \|g - P\|_{n,X}\} \leq \varepsilon$.

Remarks.
1. In the case where $X = \mathbb{Z}_p$, $K \supset \mathbb{Q}_p$ the above Theorem 1.4 is not new: The Mahler base $c_0, c_1, \ldots$ of $C(\mathbb{Z}_p \rightarrow K)$ defined by $e_m(x) = \binom{x}{m}$ is proved in [3], §54 to be a Schauder base for $C^n(\mathbb{Z}_p \rightarrow K)$, for each $n$.

2. It follows directly from Theorem 1.4 that the polynomial functions $X \rightarrow K$ form a dense subset of $C^\infty(X \rightarrow K)$.

2. A WEIERSTRASS-STONE THEOREM FOR $C^n$-FUNCTIONS

For this Theorem (2.10) we will need the continuity of $g \mapsto g \circ f$ in the $C^n$-topologies (Proposition 2.5). To prove it we need some technical lemmas that are in the spirit of [3],§77.

Let $n \in \mathbb{N}$. For a function $h : \nabla^n X \rightarrow K$ we define $\Delta h : \nabla^{n+1} X \rightarrow K$ by the formula
\[ \Delta h(x_1, x_2, \ldots, x_{n+1}) = \frac{h(x_1, x_3, x_4, \ldots, x_{n+1}) - h(x_2, x_3, \ldots, x_{n+1})}{x_1 - x_2} \]
We have the following product rule.

**Lemma 2.1. (Product Rule).** Let $n \in \mathbb{N}$, let $h, t : \nabla^n X \rightarrow K$. Then for all
\[ (x_1, x_2, \ldots, x_{n+1}) \in \nabla^{n+1} X \] we have
\[ \Delta(ht)(x_1, x_2, \ldots, x_{n+1}) = h(x_2, x_3, \ldots, x_{n+1}) \Delta t(x_1, x_2, \ldots, x_{n+1}) + t(x_1, x_3, \ldots, x_{n+1}) \Delta h(x_1, x_2, \ldots, x_{n+1}). \]
**Proof.** Straightforward.

**Lemma 2.2.** Let $f : X \rightarrow K$, $n \in \mathbb{N}_0$. Let $S_n$ be the set of the following functions defined on $\nabla^{n+1} X$.
\[ (x_1, \ldots, x_{n+1}) \mapsto \Phi_1 f(x_{i_1}, x_{i_2}) \quad (1 \leq i_1 < i_2 \leq n + 1) \]
\[ (x_1, \ldots, x_{n+1}) \mapsto \Phi_2 f(x_{i_1}, x_{i_2}, x_{i_3}) \quad (1 \leq i_1 < i_2 < i_3 \leq n + 1) \]
\[ : \]
\[ (x_1, \ldots, x_{n+1}) \mapsto \Phi_n f(x_1, \ldots, x_{n+1}). \]

For $k \in \mathbb{N}$, let $R_n^k$ be the additive group generated by $S_n, S_n^2, \ldots, S_n^k$ where, for each $j \in \{1, \ldots, k\}$, $S_n^j$ is the product set $\{h_1 h_2 \ldots h_j : h_i \in S_n \text{ for each } i \in \{1, \ldots, j\}\}$. Then, for all $k, n \in \mathbb{N}$, $\Delta R_n^k \subset R_n^{k+1}$. 

8
Proof. We use induction with respect to \( k \). For the case \( k = 1 \) it suffices to prove \( h \in S_n \Rightarrow \Delta h \in R^1_{n+1} \). Then \( h \) has the form

\[
(x_1, \ldots, x_{n+1}) \mapsto \Phi_j f(x_{i_1}, x_{i_2}, \ldots, x_{i_j+1})
\]

for some \( j \in \{2, 3, \ldots, n+1\} \) and so

\[
\Delta h(x_1, x_2, \ldots, x_{n+1}) = \frac{h(x_1, x_3, \ldots, x_{n+2}) - h(x_2, x_3, \ldots, x_{n+2})}{x_1 - x_2}
\]

vanishes if \( i_1 > 1 \) (and then \( \Delta h \) is the null function), while if \( i_1 = 1 \) it equals

\[
\Phi_j f(x_1, x_{i_2}, \ldots, x_{i_{j+1}+1}) - \Phi_j f(x_2, x_{i_2}, \ldots, x_{i_{j+1}+1}) = \frac{x_1 - x_2}{x_1 - x_2}
\]

and it follows that \( \Delta h \in S_{n+1} \subseteq R^1_{n+1} \). For the induction step assume \( \Delta R^{k-1}_n \subseteq R^{k-1}_n \); it suffices to prove that \( \Delta S^k_n \subseteq R^{k+1}_{n+1} \). So let \( h \in S^k_n \) and write \( h = h_1 H \), where \( h_1 \in S_n \), \( H \in S^{k-1}_n \). By the Product Rule 2.1 we have

\[
\Delta h(x_1, \ldots, x_{n+2}) = h_1(x_2, x_3, \ldots, x_{n+2}) \Delta H(x_1, x_2, \ldots, x_{n+2}) +
+ H(x_1, x_3, \ldots, x_{n+2}) \Delta h_1(x_1, x_2, \ldots, x_{n+2}).
\]

The fact that \( h_1 \in S_n \) makes

\[
(x_1, x_2, \ldots, x_{n+2}) \mapsto h_1(x_1, x_3, \ldots, x_{n+2})
\]

into an element of \( S_{n+1} \). Similarly, since \( H \in S^{k-1}_n \), the function

\[
(x_1, x_2, \ldots, x_{n+2}) \mapsto H(x_2, x_3, \ldots, x_{n+2})
\]

is in \( S^{k-1}_{n+1} \). By our first induction step, \( \Delta h_1 \in R^1_{n+1} \) and by the induction hypothesis \( \Delta H \in R^{k-1}_{n+1} \). Hence,

\[
\Delta h \in S_{n+1} R^{k-1}_{n+1} + S^{k-1}_{n+1} R^1_{n+1} 
\subset R^1_{n+1} R^{k-1}_{n+1} + R^{k-1}_{n+1} R^1_{n+1} \subseteq R^{k+1}_{n+1}.
\]

Lemma 2.3. Let \( f, n, S_n, k, R^n_k \) be as in the previous lemma. Let \( f(X) \subset Y \subset K \) where \( Y \) has no isolated points. Let \( g : Y \to K \) be a \( C^n \)-function. Let \( B_n \) be the set of the following functions defined on \( \nabla^{n+1} X \).

\[
(x_1, \ldots, x_{n+1}) \mapsto \overline{\Phi}_1 g(f(x_{i_1}), f(x_{i_2})) \quad (1 \leq i_1 < i_2 \leq n + 1)
\]

\[
(x_1, \ldots, x_{n+1}) \mapsto \overline{\Phi}_2 g(f(x_{i_1}), f(x_{i_2}), f(x_{i_3})) \quad (1 \leq i_1 < i_2 < i_3 \leq n + 1)
\]

\[
\vdots
\]

\[
(x_1, \ldots, x_{n+1}) \mapsto \overline{\Phi}_n g(f(x_1), f(x_2), \ldots, f(x_{n+1})).
\]
Let $A_n$ be the additive group generated by $B_n R^n$. Then

$$\Delta A_n \subset A_{n+1}.$$ 

Proof. We prove: $h \in B_n R^n \Rightarrow \Delta h \in A_{n+1}$. Write $h = br$ where $b \in B_n$, $r \in R^n$. By the Product Rule 2.1 we have for all $(x_1, x_2, \ldots, x_{n+2}) \in \nabla^{n+2} X$

$$\Delta h(x_1, x_2, \ldots, x_{n+2}) = b(x_2, x_3, \ldots, x_{n+2}) \Delta r(x_1, x_2, \ldots, x_{n+2}) +$$

$$+ r(x_1, x_3, \ldots, x_{n+2}) \Delta b(x_1, x_2, \ldots, x_{n+2}).$$

We have:

(i) $b \in B_n$ so $(x_1, \ldots, x_{n+2}) \mapsto b(x_2, x_3, \ldots, x_{n+1})$ is in $B_{n+1}$.

(ii) $r \in R^n$ so $(x_1, \ldots, x_{n+2}) \mapsto r(x_1, x_3, \ldots, x_{n+2})$ is in $R_{n+1}$ (in the previous proof we had $r \in S^k_n \Rightarrow$ the map $(x_1, \ldots, x_{n+2}) \mapsto r(x_1, x_3, \ldots, x_{n+1})$ is in $S^k_{n+1}$, and (ii) follows from this).

(iii) $r \in R^n$ so $\Delta r \in R_{n+1}$ (Previous Lemma).

(iv) $b$ has the form

$$(x_1, x_2, \ldots, x_{n+1}) \mapsto \Phi_j g(f(x_1), \ldots, f(x_{i_j+1}))$$

for some $j \in \{2, \ldots, n+1\}$ and so

$$\Delta b(x_1, x_2, \ldots, x_{n+2}) = \frac{b(x_1, x_3, x_4, \ldots, x_{n+2}) - b(x_2, x_3, \ldots, x_{n+2})}{x_1 - x_2}$$

vanishes if $i_1 > 1$ (and then $\Delta b$ is the null function), while if $i_1 = 1$ it equals

$$\frac{\Phi_j g(f(x_1), f(x_{i_2+1}), \ldots, f(x_{i_{j+1}+1})) - \Phi_j g(f(x_2), f(x_{i_2+1}), \ldots, f(x_{i_{j+1}+1}))}{x_1 - x_2}$$

$$= \frac{\Phi_{j+1} g(f(x_1), f(x_2), f(x_{i_2+1}), \ldots, f(x_{i_{j+1}+1}))}{x_1 - x_2}$$

$$\Phi_1 f(x_1, x_2).$$

(if $f(x_1) = f(x_2)$ we have 0 at both sides). So we see that $\Delta b \in B_{n+1} R_{n+1}^n$.

Combining (i) - (iv) we get $\Delta h \in B_{n+1} R_{n+1}^n + R_{n+1}^n B_{n+1} R_{n+1}^1 \subset B_{n+1} R_{n+1}^{n+1} + B_{n+1} \cdot R_{n+1}^{n+1} \subset A_{n+1}$.

Corollary 2.4. With the notations as in the previous lemma we have $\Phi_n(g \circ f) \in A_n$ $(n \in \mathbb{N})$.

Proof. We proceed by induction on $n$. For the case $n = 1$ we write, for $(x_1, x_2) \in \nabla^2 X$,

$$\Phi_1 (g \circ f)(x_1, x_2) = (x_1 - x_2)^{-1} \left(g(f(x_1)) - g(f(x_2))\right) = \Phi_1 g(f(x_1), f(x_2)) \Phi_1 f(x_1, x_2).$$
Hence, $\Phi_1(g \circ f) \in B_1 S_1 \subset B_1 R_1 \subset A_1$. To prove the step $n \rightarrow n + 1$ observe that by the induction hypothesis, $\Phi_n(g \circ f) \in A_n$. By Lemma 2.3, $\Phi_{n+1}(g \circ f) = \Delta \Phi_n(g \circ f) \in A_{n+1}$.

**Remark.** From Corollary 2.4 it follows easily that the composition of two $C^n$-functions is again a $C^n$-function, a result that already was obtained in [3], 77.5.

**Proposition 2.5.** (Continuity of $g \mapsto g \circ f$) Let $n \in \mathbb{N}_0$, let $f \in C^n(X \rightarrow K)$ and let $g \in C^n(Y \rightarrow K)$ where $Y$ has no isolated points, $Y \supseteq f(X)$. Then $\|g \circ f\|_{n,X} \leq \|g\|_{n,Y} \max_{0 \leq j \leq n} \|f\|_{j,X}^j$.

**Proof.** We may assume $\|g\|_{n,Y} < \infty$. It suffices to prove $\|\Phi_n(g \circ f)\|_{n+1,X} \leq \|g\|_{n,Y} \|f\|_{n,X}^n$. Now $\Phi_n(g \circ f) = \max_{x \in X} |g(f(x))| \leq \|g\|_{0,Y} \|f\|_{0,X}^0$ which proves the case $n = 0$. For $n \geq 1$ we apply Corollary 2.4 which says that $\Phi_n(g \circ f) \in A_n$, i.e. $\Phi_n(g \circ f)$ is a sum of functions in $B_n S_n^q$. By the definition of $B_n$ we have

\[(*) \quad h \in B_n \Rightarrow \|h\|_{n+1,X} \leq \|g\|_{n,Y}\]

Similarly

\[k \in S_n \Rightarrow \|k\|_{n+1,X} \leq \max_{1 \leq i \leq n} \|\Phi_i f\|_{n+1,X} \leq \|f\|_{n,X}\]

so that

\[k \in S_n^q \Rightarrow \|k\|_{n+1,X} \leq \|f\|_{n,X}\]

Combination of $(*)$ and $(**)$ yields $\|\Phi_n(g \circ f)\|_{n+1,X} \leq \|g\|_{n,Y} \|f\|_{n,X}^n$.

Proposition 2.5 enables us to prove

**Proposition 2.6.** Let $n \in \mathbb{N}_0$ and let $A$ be a closed subalgebra of $C^n(X \rightarrow K)$. Suppose $A$ separates the points of $X$ and contains the constant functions. Then $A$ contains all locally constant functions $X \rightarrow K$.

**Proof.** 1. We first prove that $f \in A$, $U \subset K$, $U$ clopen implies $\xi_{f^{-1}(U)} \in A$. In fact, $f(X)$ is compact so there exist $\delta \in (0,1)$ and finitely many disjoint balls $B_1, \ldots, B_m$ in $U$ of radius $\delta$ covering $f(X)$. Let $\varepsilon > 0$. By the Key Lemma 1.2 there exists, for each $i \in \{1, \ldots, m\}$ a polynomial $P_i$ such that $\|\xi_{B_i} - P_i\|_{n,B} < \varepsilon$, where $B := \bigcup B_i$. Then $P := \Sigma P_i$ is a polynomial and $\|P - \xi_U\|_{n,B} = \|P - \xi_B\|_{n,B} = \|\Sigma (P_i - \xi_{B_i})\| < \varepsilon$.

By Proposition 2.5

\[\|(P - \xi_U) \circ f\|_{n,X} \leq \|P - \xi_U\|_{n,B} \max_{0 \leq j \leq n} \|f\|_{j,X}^j \leq \varepsilon \max_{0 \leq j \leq n} \|f\|_{j,X}^j\]

and we see that there exists a sequence $P_1, P_2, \ldots$ of polynomials such that
\[ \| P_n \circ f - \xi_U \circ f \|_{n,X} \to 0. \] Since \( A \) is an algebra with an identity we have \( P_n \circ f \in A \) for all \( n \). Then \( \xi_{f^{-1}(U)} = \xi_U \circ f = \lim_{n \to \infty} P_n \circ f \in A \).

2. Now consider
\[ B := \{ V \subset X, \xi_V \in A \}. \]

It is very easy to see that \( B \) is a ring of clopen subsets of \( X \) and that \( B \) covers \( X \). To show that \( B \) separates the points of \( X \) let \( x, y \in X \), \( x \neq y \). Then there is an \( f \in A \) for which \( f(x) \neq f(y) \). Set \( U := \{ \lambda \in K : |\lambda - f(x)| < |f(x) - f(y)| \} \). Then \( U \) is clopen in \( K \). By the first part of the proof, \( f^{-1}(U) \in B \). But \( x \in f^{-1}(U) \) whereas \( y \notin f^{-1}(U) \).

By [1], Exercise 2.H \( B \) is the ring of all clopen of \( X \). It follows easily that all locally constant functions are in \( A \).

To arrive at the Weierstrass-Stone Theorem 2.10 we need a final technical lemma.

**Lemma 2.7.** Let \( a_1, \ldots, a_m \in X \), let \( \delta_1, \ldots, \delta_m \) be in \((0, 1)\) such that \( B(a_1, \delta_1), \ldots, B(a_m, \delta_m) \) form a disjoint covering of \( X \). Let \( n \in \mathbb{N}_0 \), \( h \in C^n(X \to K) \) and suppose
\[ D_j h(a_i) = 0 \quad \text{and} \quad \left| \Phi_k \right|_{n-j} D_j h(x_1, \ldots, x_{n-j+1}) \leq \epsilon \quad \text{for all} \quad i \in \{1, \ldots, m\}, \; x_1, \ldots, x_{n+1} \in B(a_i, \delta_i) \cap X, \; j \in \{0, 1, \ldots, n\}. \]

Then \( \| h \|_{n,X} \leq \epsilon. \)

**Proof.** We first prove that \( \| h \|_{n,X} \leq \epsilon \) (see Proposition 0.4(iii)). Let \( i \in \{1, \ldots, m\} \).

By Taylor’s formula (Proposition 0.3(iv)) we have for \( x \in X \cap B_i : |h(x)| =
\[ \left| \sum_{s=0}^{n-1} (x - a_i)^s D_s h(a_i) + (x - a_i)^n \rho_1 h(x, a_i) \right| = \left| x - a_i \right|^n \left| \Phi_n h(x, a_i, a_i, \ldots, a_i) \right| \leq \delta^n \epsilon. \]

Similarly we have for \( j \in \{0, \ldots, n-1\} \) and \( x \in X \cap B_j : |D_j h(x)| =
\[ \left| \sum_{s=0}^{n-1-j} (x - a_i)^s D_{s+j} h(a_i) + (x - a_i)^{n-j} \rho_1 h(x, a_i) \right|. \]

Now using Proposition 0.3(iii) we see that \( D_j D_j h(a_i) = 0 \) so that
\[
|D_j(x)| = \left| x - a_i \right|^{n-j} |\Phi_{n-j} D_j h(x, a_i, \ldots, a_i)| \leq \delta^{n-j} \epsilon.
\]

It follows that \( \| h \|_X, \| D_1 h \|_{X, \ldots, \| D_{n-1} h \|_X \text{ are all } \leq \epsilon. \) Now let \( x, y \in X \). If \( x, y \) are in the same \( B_i \) then \( |\rho_1 h(x, y)| = \left| \Phi_n h(x, y, y, \ldots, y) \right| \leq \epsilon \) by assumption. If \( x \in B_i \), \( y \in B_x \) and \( i \neq s \) then \( |x - y| \geq \delta := \max(\delta_i, \delta_x) \) and by Taylor’s formula
\[ h(x) = \sum_{i=0}^{n-1} (x - y)^i D_i h(y) + (x - y)^n \rho_1 h(x, y) \]

we obtain, using \((*)\),
\[
|\rho_1 h(x, y)| \leq \frac{|h(x) - h(y)|}{|x - y|^n} \vee \frac{|D_1 h(y)|}{|x - y|^n \cdot 1} \vee \ldots \vee \frac{|D_{n-1} h(y)|}{|x - y|^n \cdot 1} \leq \frac{\delta^n \epsilon}{\delta^n} \vee \frac{\delta^{n-1} \epsilon}{\delta^n} \vee \ldots \vee \frac{\delta_x \epsilon}{\delta} \leq \epsilon
\]

12
and we have proved $\|h\|_{n,X} \leq \varepsilon$.
Now to prove that even $\|h\|_{n,X} \leq \varepsilon$ observe that by Proposition 0.4(iii)

$$\|h\|_{n,X} = \|h\|_{n,X} \vee \|D_1 h\|_{n-1,X} \vee \cdots \vee \|D_n h\|_{0,X}.$$

To prove, for example, that $\|D_1 h\|_{n-1,X} \leq \varepsilon$ we observe that $D_1 h \in C^{n-1}(X \to K)$ and that for $i \in \{1, \ldots, m\}$ and $j \in \{0, 1, \ldots, n-2\}$ we have $D_j D_1 h(a_i) = (j+1)D_{j+1} h(a_i) = 0$ and for all $x_1, \ldots, x_n \in B(a_i, \delta_i)$ and $j \in \{0, 1, \ldots, n-2\}$

$$|\Phi_{n-1-j} D_j (D_1 h)(x_1, \ldots, x_{n-j})| = |(j+1)| \Phi_{n-1-j} D_{j+1} h(x_1, \ldots, x_{n-j})| \leq \varepsilon$$

by assumption. So the conditions of our Lemma (with $D_1 h$, $n - 1$ in place of $h$, $n$ respectively) are satisfied and by the first part of the proof we may conclude that $\|D_1 h\|_{n-1,X} \leq \varepsilon$. In a similar way we prove that $\|D_2 h\|_{n-2,X} \leq \varepsilon, \ldots, \|D_n h\|_{0,X} \leq \varepsilon$ and it follows that $\|h\|_{n,X} \leq \varepsilon$.

**Proposition 2.8.** Let $n \in \mathbb{N}_0$ and let $A$ be a closed subalgebra of $C^n(X \to K)$ containing the locally constant functions. Let $g \in C^n(X \to K)$ and suppose for each $a \in X$ there exists an $f_a \in A$ with $D_i g(a) = D_i f_a(a)$ for $i \in \{0, 1, \ldots, n\}$. Then $g \in A$.

**Proof.** Let $\varepsilon > 0$. For each $a \in X$ choose an $f_a \in A$ with $f_a(a) = g(a)$, $D_1 f_a(a) = D_1 g(a), \ldots, D_n f_a(a) = D_n g(a)$. By continuity there exists a $\delta_a > 0$ such that, with $h_a := f_a - g$, $|\Phi_{n-j} D_j h_a(x_1, \ldots, x_{n-j+1})| \leq \varepsilon$ for all $j \in \{0, 1, \ldots, n\}$ and $x_1, \ldots, x_{n-j+1} \in B(a, \delta_a)$. The $B(a, \delta_a)$ cover $X$ and by compactness there exists a finite disjoint subcovering $B(a_1, \delta_{a_1}), \ldots, B(a_m, \delta_{a_m})$. Set

$$f := \sum_{i=1}^m f_{a_i} \cdot 1_{B(a_i, \delta_{a_i}) \cap X}$$

Then, by our assumption on $A, f \in A$. By Lemma 2.7, applied to $h := f - g$ and where $\delta_1, \ldots, \delta_m$ are replaced by $\delta_{a_1}, \ldots, \delta_{a_m}$ respectively, we then have $\|f - g\|_{n,X} \leq \varepsilon$. We see that $g \in \overline{A} = A$.

**Remark.** It follows directly that the local polynomial functions $X \to K$ form a dense subset of $C^n(X \to K)$.

**Proposition 2.9.** Let $n \in \mathbb{N}$ and let $A$ be a $K$-subalgebra of $C^n(X \to K)$ containing the constant functions. Suppose $f'(a) \neq 0$ for some $f \in A, a \in X$. Then there is a $g \in A$ with $g(a) = 0$, $g'(a) = 1$ and $D_2 g(a) = D_3 g(a) = \cdots = D_n g(a) = 0$.

**Proof.** By considering the function $f'(a)^{-1} (f - f(a))$ it follows that we may assume that $f(a) = 0, f'(a) = 1$. Then

$$(*) \quad f = (X - a)h$$

13
where \( h \) is continuous, \( h(a) = 1 \). To obtain the statement by induction with respect to \( n \) we only have to consider the induction step \( n - 1 \to n \) and, to prove that, we may assume that \( D_2 f(a) = \cdots = D_{n-1} f(a) = 0 \). From (*) we obtain

\[
    f^n = (X - a)^n h^n
\]

and by uniqueness of the Taylor expansion of the \( C^n \)-function \( f^n \) we obtain \( f^n(a) = D_1 f^n(a) = \cdots = D_{n-1} f^n(a) = 0 \) and \( D_n f^n(a) = h^n(a) = 1 \). We see that \( g := f - D_n f(a) f^n \) is in \( A \) and that \( g(a) = 0, g'(a) = 1, D_2 g(a) = \cdots = D_{n-1} g(a) = 0 \) and \( D_n g(a) = D_n f(a) - D_n f(a) D_n f^n(a) = 0 \).

**Theorem 2.10. (Weierstrass-Stone Theorem for \( C^n \)-functions).** Let \( n \in \mathbb{N}_0 \) and let \( A \) be a closed subalgebra that separates the points of \( X \) and that contains the constant functions. Suppose also that for each \( a \in X \) there exists an \( f \in A \) with \( f'(a) \neq 0 \). Then \( A = C^n(X \to K) \).

**Proof.** By Proposition 2.9, for each \( a \in X \) there exists an \( f \in A \) with \( f(a) = 0, f'(a) = 1, D_i f(a) = 0 \) for \( i \in \{2, \ldots, n\} \). The function \( g := X \) satisfies \( g(a) = 0, g'(a) = 1, D_i g(a) = 0 \) for \( i \in \{2, \ldots, n\} \) so applying Proposition 2.8 (observe that \( A \) contains the locally constant functions by Proposition 2.6) we obtain that \( X \in A \). But then all polynomials are in \( A \) and \( A = C^n(X \to K) \) by the Weierstrass Theorem 1.4.

**Remarks.**

1. The case \( n = 0 \) yields, at least for those \( X \) that are embeddable into \( K \), the well known Kaplansky Theorem proved in [1], 6.15.

2. We leave it to the reader to establish a \( C^\infty \)-version of Theorem 2.10.

**REFERENCES**

