J. ARAUJO

WIM H. SCHIKHOF

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

J. Araujo and Wim H. Schikhof

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 $\varepsilon > 0$ one simply can apply the standard Weierstrass Theorem to f' obtaining a polynomial function Q for which $|f'-Q| \leq \varepsilon$. Then $x \mapsto P(x) := f(0) + \int_0^x Q(t)dt$ solves the problem.

Now let $f : X \rightarrow K$ be a C^1 -function where K is a non-archimedean valued field and $X \subset K$ 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

$$f \mapsto \max\{|f(x)| : x \in X\} \vee \max\left\{\left|\frac{f(x)-f(y)}{x-y}\right| : x, y \in X, x \neq y\right\}$$

rather than the more classical formula

$$f \mapsto \max\{|f(x)| : x \in X\} \vee \max\{|f'(x)| : x \in X\}.$$

(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 $n \in \{1, 2, \dots\}$ our methods will necessarily deviate from the 'classical' ones.

0. PRELIMINARIES

1. Throughout K is a non-archimedean complete valued field whose valuation $|\cdot|$ 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 $\mathcal{X}$. The K -valued characteristic function of a subset Y of K is written ξ_Y . For a set Z , a function $f : Z \rightarrow K$ and a set $W \subset Z$ we define $\|f\|_W := \sup\{|f(z)| : z \in W\}$ (allowing the value ∞). The cardinality of a set Γ is $\#\Gamma$. $\mathbb{N}_0 := \{0, 1, 2, \dots\}$, $\mathbb{N} := \{1, 2, 3, \dots\}$.

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

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

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

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 $Y \rightarrow K$ is denoted $C^n(Y \rightarrow K)$. The function $f : Y \rightarrow K$ is a C^∞ -function if it is in $C^\infty(Y \rightarrow K) := \bigcap_{n=0}^{\infty} C^n(Y \rightarrow K)$. The space $C^0(Y \rightarrow K)$, consisting of all continuous functions $Y \rightarrow K$ is sometimes written as $C(Y \rightarrow K)$.

**FROM NOW ON IN THIS PAPER X IS A NONEMPTY
COMPACT SUBSET OF K WITHOUT ISOLATED POINTS.**

3. Since X has no isolated points we have for an $f \in C^n(X \rightarrow K)$ that the continuous extension of $\Phi_n f$ to X^{n+1} is unique; we denote this extension by $\overline{\Phi}_n f$. Also we write

$$D_n f(a) := \overline{\Phi}_n f(a, a, \dots, a) \quad (a \in X)$$

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

Proposition 0.3.

- (i) For each $n \in \mathbb{N}_0$ the space $C^n(X \rightarrow K)$ is a K -algebra under pointwise operations.
- (ii) $C^0(X \rightarrow K) \supset C^1(X \rightarrow K) \supset \dots$

- (iii) If $f \in C^n(X \rightarrow K)$ then f is n times differentiable and $j!D_j f = f^{(j)}$ for each $j \in \{0, 1, \dots, n\}$. More generally, if $i, j \in \{0, 1, \dots, n\}$, $i+j \leq n$ then $\binom{i+j}{i} D_i D_j f = D_{i+j} f$.
- (iv) If $f \in C^n(X \rightarrow K)$ then for $x, y \in X$ we have Taylor's formula

$$f(x) = f(y) + (x-y)D_1 f(y) + \dots + (x-y)^{n-1} D_{n-1} f(y) + (x-y)^n \rho_1 f(x, y),$$

$$\text{where } \rho_1 f(x, y) = \overline{\Phi}_n f(x, y, y, \dots, y).$$

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

$$\|f\|_{n,X} := \max\{\|\Phi_i f\|_{\nabla^{i+1}X} : 0 \leq i \leq n\}.$$

Then $\|f\|_{0,X} = \|f\|_X$. We quote the following from [2] and [3]. Recall that a function $f : X \rightarrow K$ is a local polynomial if for every $a \in X$ there is a neighbourhood U of a such that $f|_{X \cap U}$ is a polynomial function.

Proposition 0.4. Let $n \in \mathbb{N}_0$.

- (i) The function $\|\cdot\|_{n,X}$ is a norm on $C^n(X \rightarrow K)$ making it into a K -Banach algebra.
- (ii) The local polynomials form a dense subset of $C^n(X \rightarrow K)$.
- (iii) The function

$$f \mapsto \|f\|_{n,X}^{\sim} := \max_{0 \leq i \leq n-1} \|D_i f\|_X \vee \|\rho_1 f\|_X$$

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

$$\|f\|_{n,X} = \max\{\|D_i f\|_{n-i,X}^{\sim} : 0 \leq i \leq n\} \quad (f \in C^n(X \rightarrow K)).$$

Remarks

- Proposition 0.4 (ii) will also follow from Proposition 2.8.
- In general $\|\cdot\|_{n,X}^{\sim}$ is not equivalent to $\|\cdot\|_{n,X}$ 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 $f, g : X \rightarrow K$, let $j \in \mathbb{N}_0$. Then for all $(x_1, \dots, x_{j+1}) \in \nabla^{j+1}X$ we have

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

Or, less precise,

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

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 $h_1, \dots, h_N : X \rightarrow K$, let $j \in \mathbb{N}_0$. Then for all $(x_1, \dots, x_{j+1}) \in \nabla^{j+1}X$ we have*

$$\Phi_j\left(\prod_{s=1}^N h_s\right)(x_1, \dots, x_{j+1}) = \sum \prod_{s=1}^N \Phi_{j_s} h_s(z_{\sigma,s})$$

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

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

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

Proof. We may assume $0 \in B_0$. Choose $c_1 \in B_1, \dots, c_m \in B_m$; we may assume that $|c_1| \leq |c_2| \leq \dots \leq |c_m|$. 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 $t_1, t_2, \dots, t_m \in \mathbb{N}$ be such that for all $\ell \in \{1, \dots, m\}$

$$(1) \quad \left| \frac{c_\ell}{c_1} \right|^{kt_1} \left| \frac{c_\ell}{c_2} \right|^{kt_2} \dots \left| \frac{c_\ell}{c_{\ell-1}} \right|^{kt_{\ell-1}} \left(\frac{\delta}{|c_1|} \right)^{t_\ell} \leq \varepsilon \delta^n$$

(It is easily seen that such $k, t_1, \dots, t_m$ exist since $\delta/|c_1| < 1$.) Then the formula

$$P(x) = \prod_{i=1}^m \left(1 - \left(\frac{x}{c_i}\right)^k\right)^{t_i}$$

defines a polynomial function $P: K \rightarrow K$ for which

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

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

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

So it remains to be shown that

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

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

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

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

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

To prove it we introduce, with $\ell \in \{1, \dots, m\}$ fixed, the constants M_i ($i \in \{1, \dots, n\}$) 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 $j \in \{0, 1, \dots, n\}$, $i \in \{1, \dots, n\}$ we have

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

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 $|1 - (\frac{x}{c_i})^k| = |\frac{x}{c_i}|^k = |\frac{c_\ell}{c_i}|^k$

and the statement follows.

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

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

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

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

- if $\ell = 0$: $|c_\ell|^{k-j}/|c_i|^k \leq \delta^{k-j}/|c_1|^k = \delta^{-j}(\delta/|c_1|)^k$,
- if $i > \ell > 0$: $|c_\ell|^{k-j}/|c_i|^k \leq |c_\ell^{-j}| < \delta^{-j} = \delta^{-j} M_i$
- if $i = \ell > 0$: $|c_\ell|^{k-j}/|c_i|^k \leq |c_\ell^{-j}| \leq |c_1^{-j}| = \delta^{-j}(\frac{\delta}{|c_1|})^j \leq \delta^{-j} M_i$
- if $i < \ell$: $|c_\ell|^{k-j}/|c_i|^k \leq |c_\ell|^{-j} |\frac{c_\ell}{c_i}|^k \leq \delta^{-j} M_i$

and step 1 is proved.

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

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

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

$$(5) \quad \prod_{s=1}^{t_i} \Phi_{j_s}(1 - (\frac{\mathcal{X}}{c_i})^k)(z_s)$$

where $j_1 + \dots + j_s = j$. If $\ell = 0$ it follows from Step 1 that the absolute value of (5) is $\leq \prod \delta^{-j_s} (\frac{\delta}{|c_1|})^k$ where the product is taken over all s in the nonempty set $\Gamma := \{s \in \{1, \dots, t_i\} : j_s > 0\}$, so the product is $\leq \delta^{-j} (\frac{\delta}{|c_1|})^{k \cdot \#\Gamma} \leq \delta^{-j} (\frac{\delta}{|c_1|})^k$. If $\ell > 0$ it follows from Step 1 that the absolute value of (5) is $\leq \prod_{s=1}^{t_i} \delta^{-j_s} M_i = \delta^{-j} M_i^{t_i}$.

The statement of Step 2 follows.

Step 3. Proof of (4). Again, the Product Rule 1.1, now applied to $h_i = (1 - (\frac{\chi}{c_i})^k)^{t_i}$ for $i \in \{1, \dots, m\}$ tells us that for $(x_1, \dots, x_{n+1}) \in \nabla^{n+1} B_\ell$ the expression $\Phi_n P(x_1, \dots, x_{n+1})$ is a sum of terms of the form

$$(6) \quad \prod_{i=1}^m \Phi_{n_i} (1 - (\frac{\chi}{c_i})^k)^{t_i} (z_s)$$

where $n_1 + \dots + n_m = n$. If $\ell = 0$ we have by Step 2 that the absolute value of (6) is $\leq \prod \delta^{-n_i} (\frac{\delta}{|c_1|})^k$ where the product is taken over i in the nonempty set $\Gamma := \{i : n_i \neq 0\}$, so the product is $\leq \delta^{-n} (\frac{\delta}{|c_1|})^{k \cdot \#\Gamma} \leq \delta^{-n} (\frac{\delta}{|c_1|})^k \leq \delta^{-n} \cdot \varepsilon \delta^n = \varepsilon$, where we used the assumption $(\delta/|c_1|)^k \leq \varepsilon \delta^n$. We see that $|\Phi_n P(x_1, \dots, x_{n+1})| \leq \varepsilon$ if $(x_1, \dots, x_n) \in B_0$. Now let $\ell > 0$. By Step 2 we have that the absolute value of (6) is $\leq \prod_{i=1}^m \delta^{-n_i} M_i^{t_i} = \delta^{-n} M_1^{t_1} \dots M_m^{t_m} = \delta^{-n} \cdot |\frac{c_\ell}{c_1}|^{kt_1} \dots |\frac{c_\ell}{c_{t-1}}|^{kt_t} (\frac{\delta}{|c_1|})^{t_\ell}$ which is $\leq \delta^{-n} \varepsilon \delta^n$ by (1). This proves (4) and the Lemma.

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

Proof. There exist a $\delta \in (0, 1)$, pairwise disjoint 'closed' balls $B_1, \dots, B_m$ of radius δ covering X and $\lambda_1, \dots, \lambda_m \in K$ 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 $P_1, \dots, P_m$ such that $\|\xi_{B_i} - P_i\|_{n,X} \leq \|\xi_{B_i} - P_i\|_{n, \cup B_i} \leq \varepsilon(|\lambda_i| + 1)^{-1}$ for each $i \in \{1, \dots, m\}$. Then $P := \sum_{i=1}^m \lambda_i P_i$ is a polynomial function and $\|f - P\|_{n,X} \leq \max_i \|\lambda_i(\xi_{B_i} - P_i)\|_{n,X} \leq \max_i |\lambda_i| \varepsilon(|\lambda_i| + 1)^{-1} \leq \varepsilon$.

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

Proof. There is by Proposition 0.4 a local polynomial $g : K \rightarrow K$ with $\|f - g\|_{n,X} \leq \varepsilon$. This g has the form $g = \sum_{i=1}^m Q_i h_i$ where $Q_1, \dots, Q_m$ are polynomials and $h_1, \dots, h_m$

are locally constant. By Corollary 1.3 we can find polynomials $P_1, \dots, P_m$ for which $\|h_i - P_i\|_{n,X} \leq \varepsilon(\|Q_i\|_{n,X} + 1)^{-1}$ 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 $e_0, e_1, \dots$ 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

$$\Delta h(x_1, x_2, \dots, x_{n+1}) = \frac{h(x_1, x_3, x_4, \dots, x_{n+1}) - h(x_2, x_3, \dots, x_{n+1})}{x_1 - x_2}$$

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 $(x_1, x_2, \dots, x_{n+1}) \in \nabla^{n+1} X$ we have $\Delta(ht)(x_1, x_2, \dots, x_{n+1}) = h(x_2, x_3, \dots, x_{n+1})\Delta t(x_1, x_2, \dots, x_{n+1}) + t(x_1, x_3, \dots, x_{n+1})\Delta h(x_1, x_2, \dots, x_{n+1})$.*

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 $\nabla^{n+1} X$.*

$$\begin{aligned} (x_1, \dots, x_{n+1}) &\mapsto \Phi_1 f(x_{i_1}, x_{i_2}) & (1 \leq i_1 < i_2 \leq n+1) \\ (x_1, \dots, x_{n+1}) &\mapsto \Phi_2 f(x_{i_1}, x_{i_2}, x_{i_3}) & (1 \leq i_1 < i_2 < i_3 \leq n+1) \\ &\vdots \\ (x_1, \dots, x_{n+1}) &\mapsto \Phi_n f(x_1, \dots, x_{n+1}). \end{aligned}$$

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

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

$$(x_1, \dots, x_{n+1}) \mapsto \Phi_j f(x_{i_1}, x_{i_2}, \dots, x_{i_{j+1}})$$

for some $j \in \{2, 3, \dots, n+1\}$ and so

$$\Delta h(x_1, x_2, \dots, x_{n+1}) = \frac{h(x_1, x_3, \dots, x_{n+2}) - h(x_2, x_3, \dots, x_{n+2})}{x_1 - x_2}$$

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

$$\begin{aligned} & \frac{\Phi_j f(x_1, x_{i_2+1}, \dots, x_{i_{j+1}+1}) - \Phi_j f(x_2, x_{i_2+1}, \dots, x_{i_{j+1}+1})}{x_1 - x_2} = \\ & = \Phi_{j+1} f(x_1, x_2, x_{i_2+1}, \dots, x_{i_{j+1}+1}) \end{aligned}$$

and it follows that $\Delta h \in S_{n+1} \subset R_{n+1}^1$. For the induction step assume $\Delta R_n^{k-1} \subset R_{n+1}^{k-1}$; it suffices to prove that $\Delta S_n^k \subset R_{n+1}^k$. So let $h \in S_n^k$ and write $h = h_1 H$, where $h_1 \in S_n$, $H \in S_n^{k-1}$. By the Product Rule 2.1 we have

$$\begin{aligned} \Delta h(x_1, \dots, x_{n+2}) &= h_1(x_2, x_3, \dots, x_{n+2}) \Delta H(x_1, x_2, \dots, x_{n+2}) + \\ &+ H(x_1, x_3, \dots, x_{n+2}) \Delta h_1(x_1, x_2, \dots, x_{n+2}). \end{aligned}$$

The fact that $h_1 \in S_n$ makes

$$(x_1, x_2, \dots, x_{n+2}) \mapsto h_1(x_1, x_3, \dots, x_{n+2})$$

into an element of S_{n+1} . Similarly, since $H \in S_n^{k-1}$, the function

$$(x_1, x_2, \dots, x_{n+2}) \mapsto H(x_2, x_3, \dots, x_{n+2})$$

is in S_{n+1}^{k-1} . By our first induction step, $\Delta h_1 \in R_{n+1}^1$ and by the induction hypothesis $\Delta H \in R_{n+1}^{k-1}$. Hence,

$$\begin{aligned} \Delta h &\in S_{n+1} R_{n+1}^{k-1} + S_{n+1}^{k-1} R_{n+1}^1 \\ &\subset R_{n+1}^1 R_{n+1}^{k-1} + R_{n+1}^{k-1} R_{n+1}^1 \subset R_{n+1}^k. \end{aligned}$$

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 $g : Y \rightarrow K$ be a C^n -function. Let B_n be the set of the following functions defined on $\nabla^{n+1} X$.

$$\begin{aligned} (x_1, \dots, x_{n+1}) &\mapsto \overline{\Phi}_1 g(f(x_{i_1}), f(x_{i_2})) & (1 \leq i_1 < i_2 \leq n+1) \\ (x_1, \dots, x_{n+1}) &\mapsto \overline{\Phi}_2 g(f(x_{i_1}), f(x_{i_2}), f(x_{i_3})) & (1 \leq i_1 < i_2 < i_3 \leq n+1) \\ &\vdots \\ (x_1, \dots, x_{n+1}) &\mapsto \overline{\Phi}_n g(f(x_1), f(x_2), \dots, f(x_{n+1})). \end{aligned}$$

Let A_n be the additive group generated by $B_n R_n^n$. Then

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

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

$$\begin{aligned} \Delta h(x_1, x_2, \dots, x_{n+2}) &= b(x_2, x_3, \dots, x_{n+2}) \Delta r(x_1, x_2, \dots, x_{n+2}) + \\ &\quad + r(x_1, x_3, \dots, x_{n+2}) \Delta b(x_1, x_2, \dots, x_{n+2}). \end{aligned}$$

We have:

- (i) $b \in B_n$ so $(x_1, \dots, x_{n+2}) \mapsto b(x_2, x_3, \dots, x_{n+1})$ is in B_{n+1} .
- (ii) $r \in R_n^n$ so $(x_1, \dots, x_{n+2}) \mapsto r(x_1, x_3, \dots, x_{n+2})$ is in R_{n+1}^n (in the previous proof we had $r \in S_n^k \Rightarrow$ the map $(x_1, \dots, x_{n+2}) \mapsto r(x_1, x_3, \dots, x_{n+1})$ is in S_{n+1}^k , and (ii) follows from this).
- (iii) $r \in R_n^n$ so $\Delta r \in R_{n+1}^n$ (Previous Lemma).
- (iv) b has the form

$$(x_1, x_2, \dots, x_{n+1}) \mapsto \bar{\Phi}_j g(f(x_{i_1}), \dots, f(x_{i_{j+1}}))$$

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

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

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

$$\begin{aligned} &\frac{\bar{\Phi}_j g(f(x_1), f(x_{i_2+1}), \dots, f(x_{i_{j+1}+1})) - \bar{\Phi}_j g(f(x_2), f(x_{i_2+1}), \dots, f(x_{i_{j+1}+1}))}{x_1 - x_2} \\ &= \bar{\Phi}_{j+1} g(f(x_1), f(x_2), f(x_{i_2+1}), \dots, f(x_{i_{j+1}+1})) \bar{\Phi}_1 f(x_1, x_2). \end{aligned}$$

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

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 $(x_1, x_2) \in \nabla^2 X$,

$$\Phi_1(g \circ f)(x_1, x_2) = (x_1 - x_2)^{-1} (g(f(x_1)) - g(f(x_2))) = \bar{\Phi}_1 g(f(x_1), f(x_2)) \bar{\Phi}_1 f(x_1, x_2).$$

Hence, $\bar{\Phi}_1(g \circ f) \in B_1 S_1 \subset B_1 R_1^1 \subset A_1$. 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, $Y \supset f(X)$. 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 $\|\Phi_n(g \circ f)\|_{\nabla^{n+1}X} \leq \|g\|_{n,Y} \|f\|_{n,X}^n$. Now $\|\Phi_0(g \circ f)\|_{\nabla^1 X} = \max_{x \in X} |g(f(x))| \leq \|g\|_{0,Y} = \|g\|_{0,Y} \|f\|_{0,X}^0$ 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 $B_n S_n^n$. By the definition of B_n we have

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

Similarly

$$k \in S_n \Rightarrow \|k\|_{\nabla^{n+1}X} \leq \max_{1 \leq i \leq n} \|\Phi_i f\|_{\nabla^{i+1}X} \leq \|f\|_{n,X}$$

so that

$$(**) \quad k \in S_n^n \Rightarrow \|k\|_{\nabla^{n+1}X} \leq \|f\|_{n,X}^n.$$

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

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 a $\delta \in (0, 1)$ and finitely many disjoint balls $B_1, \dots, B_m$ of radius δ covering $f(X)$ where, say, $B_1, \dots, B_q$ lie in U , and $B_{q+1}, \dots, B_m$ are in $K \setminus U$. Let $\varepsilon > 0$. By the Key Lemma 1.2 there exists, for each $i \in \{1, \dots, m\}$ a polynomial P_i such that $\|\xi_{B_i} - P_i\|_{n,B} < \varepsilon$, where $B := \bigcup_{i=1}^m B_i$. Then $P := \sum_{i=1}^q P_i$ is a polynomial and

$$\|P - \xi_U\|_{n,B} = \|P - \xi_{B^0}\|_{n,B} = \left\| \sum_{i=1}^q (P_i - \xi_{B_i}) \right\|_{n,B} < \varepsilon, \text{ where } B^0 := \bigcup_{i=1}^q B_i.$$

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 $P_1, P_2, \dots$ of polynomials such that $\|P_k \circ f - \xi_U \circ f\|_{n,X} \rightarrow 0$. Since A is an algebra with an identity we have $P_k \circ f \in A$ for all k . Then $\xi_{f^{-1}(U)} = \xi_U \circ f = \lim_{k \rightarrow \infty} P_k \circ f \in A$.

2. Now consider

$$\mathcal{B} := \{V \subset X, \xi_V \in A\}.$$

It is very easy to see that $\mathcal{B}$ is a ring of clopen subsets of X and that $\mathcal{B}$ covers X . To show that $\mathcal{B}$ separates the points of X let $x \in X, y \in X, x \neq y$. 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, $f^{-1}(U) \in \mathcal{B}$. But $x \in f^{-1}(U)$ whereas $y \notin f^{-1}(U)$. By [1], Exercise 2.H $\mathcal{B}$ is the ring of all clopens 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 $a_1, \dots, a_m \in X$, let $\delta_1, \dots, \delta_m$ be in $(0, 1)$ such that $B(a_1, \delta_1), \dots, B(a_m, \delta_m)$ form a disjoint covering of X . Let $n \in \mathbb{N}_0$, $h \in C^n(X \rightarrow K)$ and suppose $D_j h(a_i) = 0$ and $|\overline{\Phi}_{n-j} D_j h(x_1, \dots, x_{n-j+1})| \leq \varepsilon$ for all $i \in \{1, \dots, m\}$, $x_1, \dots, x_{n-j+1} \in B(a_i, \delta_i) \cap X$, $j \in \{0, 1, \dots, n\}$. Then $\|h\|_{n,X} \leq \varepsilon$.*

Proof. We first prove that $\|h\|_{n,X} \leq \varepsilon$ (see Proposition 0.4(iii)). Let $i \in \{1, \dots, m\}$. Set $B_i = B(a_i, \delta_i)$. By Taylor's formula (Proposition 0.3(iv)) we have for $x \in X \cap B_i$:

$$|h(x)| = \left| \sum_{s=0}^{n-1} (x - a_i)^s D_s h(a_i) + (x - a_i)^n \rho_1 h(x, a_i) \right| = |x - a_i|^n |\overline{\Phi}_n h(x, a_i, a_i, \dots, a_i)| \leq \delta_i^n \varepsilon.$$

Similarly we have for $j \in \{0, \dots, n-1\}$ and $x \in X \cap B_i$: $|D_j h(x)| =$

$$\left| \sum_{t=0}^{n-1-j} (x - a_i)^t D_t D_j h(a_i) + (x - a_i)^{n-j} \rho_1(D_j h)(x, a_i) \right|.$$

Now using Proposition 0.3(iii) we see that $D_t D_j h(a_i) = 0$ so that

$$(*) \quad |D_j h(x)| = |x - a_i|^{n-j} |\overline{\Phi}_{n-j} D_j h(x, a_i, \dots, a_i)| \leq \delta_i^{n-j} \varepsilon.$$

It follows that $\|h\|_X, \|D_1 h\|_X, \dots, \|D_{n-1} h\|_X$ are all $\leq \varepsilon$. Now let $x, y \in X$. If x, y are in the same B_i then $|\rho_1 h(x, y)| = |\overline{\Phi}_n h(x, y, y, \dots, y)| \leq \varepsilon$ by assumption. If $x \in B_i, y \in B_s$ and $i \neq s$ then $|x - y| \geq \delta := \max(\delta_i, \delta_s)$ and by Taylor's formula

$$h(x) = \sum_{t=0}^{n-1} (x - y)^t D_t h(y) + (x - y)^n \rho_1 h(x, y)$$

we obtain, using (*),

$$\begin{aligned} |\rho_1 h(x, y)| &\leq \frac{|h(x) - h(y)|}{|(x - y)^n|} \vee \frac{|D_1 h(y)|}{|x - y|^{n-1}} \vee \dots \vee \frac{|D_{n-1} h(y)|}{|x - y|} \\ &\leq \frac{\delta^n \varepsilon}{\delta^n} \vee \frac{\delta_s^{n-1} \varepsilon}{\delta^{n-1}} \vee \dots \vee \frac{\delta_s \varepsilon}{\delta} \leq \varepsilon \end{aligned}$$

and we have proved $\|h\|_{n,X}^{\sim} \leq \varepsilon$.

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

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

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

$$|\bar{\Phi}_{n-1-j} D_j(D_1 h)(x_1, \dots, x_{n-j})| = |(j+1)| |\bar{\Phi}_{n-1-j} D_{j+1} h(x_1, \dots, x_{n-j})| \leq \varepsilon$$

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 $\|D_1 h\|_{n-1,X}^{\sim} \leq \varepsilon$. In a similar way we prove that $\|D_2 h\|_{n-2,X}^{\sim} \leq \varepsilon, \dots, \|D_n h\|_{0,X}^{\sim} \leq \varepsilon$ 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 $C^n(X \rightarrow K)$ containing the locally constant functions. Let $g \in C^n(X \rightarrow K)$ 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 $i \in \{0, 1, \dots, n\}$. Then $g \in A$.*

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

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

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

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

Proposition 2.9. *Let $n \in \mathbb{N}$ and let A be a K -subalgebra of $C^n(X \rightarrow K)$ 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

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

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 $n - 1 \rightarrow n$ and, to prove that, we may assume that $D_2f(a) = \dots = D_{n-1}f(a) = 0$. From (*) we obtain

$$f^n = (\mathcal{X} - a)^n h^n$$

and by uniqueness of the Taylor expansion of the C^n -function f^n we obtain $f^n(a) = D_1f^n(a) = \dots = D_{n-1}f^n(a) = 0$ and $D_nf^n(a) = h^n(a) = 1$. We see that $g := f - D_nf(a)f^n$ is in A and that $g(a) = 0$, $g'(a) = 1$, $D_2g(a) = \dots = D_{n-1}g(a) = 0$ and $D_ng(a) = D_nf(a) - D_nf(a)D_nf^n(a) = 0$.

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 $A = C^n(X \rightarrow K)$.*

Proof. By Proposition 2.9, for each $a \in X$ there exists an $f \in A$ with $f(a) = 0$, $f'(a) = 1$, $D_if(a) = 0$ for $i \in \{2, \dots, n\}$. The function $g := \mathcal{X}$ satisfies $g(a) = 0$, $g'(a) = 1$, $D_ig(a) = 0$ for $i \in \{2, \dots, n\}$ so applying Proposition 2.8 (observe that A contains the locally constant functions by Proposition 2.6) we obtain that $\mathcal{X} \in A$. But then all polynomials are in A and $A = C^n(X \rightarrow K)$ 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^∞ -version of Theorem 2.10.

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Departamento de Matematicas
 Universidad de Cantabria
 Avenida de Los Castros
 39071 SANTANDER
 SPANE

Department of Mathematics
 Catholic University of Nijmegen
 6525 ED NIJMEGEN
 THE NETHERLANDS