ANNALES MATHÉMATIQUES BLAISE PASCAL

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Annales mathématiques Blaise Pascal, tome 1, nº 1 (1994), p. 61-74
<http://www.numdam.org/item?id=AMBP_1994__1_1_61_0>

Ann. Math. Blaise Pascal, Vol. 1, N° 1, 1994, pp. 61 - 74

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 $\varepsilon > 0$ 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 $f : X \to K$ 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 $n \in \{1, 2, \ldots\}$ 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 $\mathcal{X}$. The K-valued characteristic function of a subset Y of K is written ξ_Y. For a set Z, a function $f : Z \to K$ 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 $\#\Gamma$. $\mathbb{N}_0 := \{0, 1, 2, \ldots\}$, $\mathbb{N} := \{1, 2, 3, \ldots\}$.

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 $\nabla^n Y := \{(y_1, y_2, \ldots, y_n) \in Y^n : i \neq j \Longrightarrow y_i \neq y_j\}$. For $f : Y \to K$, $n \in \mathbb{N}_0$ we define its nth 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^∞-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 $C(Y \to K)$.

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 $f \in C^n(X \to K)$ 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

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

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* $i,j \in \{0,1,\ldots,n\}$, $i+j \le n$ *then* $\binom{i+j}{i}D_iD_jf = D_{i+j}f$.

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

$$f(x) = f(y) + (x-y)D_if(y) + \cdots + (x-y)^{n-1}D_{n-1}f(y) + (x-y)^n\rho_1f(x,y),$$

where $\rho_1f(x,y) = \overline{\Phi}_nf(x,y,y,\ldots,y)$.

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

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

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

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*

$$f \mapsto \|f\|^{\sim}_{n,X} := \max_{0\le i\le n-1}\|D_if\|_X \vee \|\rho_1f\|_{X^2}$$

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

$$\|f\|_{n,X} = \max\{\|D_if\|^{\sim}_{n-i,X} : 0 \le i \le n\} \qquad (f \in C^n(X \to K)).$$

Remarks

1. Proposition 0.4 (ii) will also follow from Proposition 2.8.
2. In general $\|\ \|^{\sim}_{n,X}$ is not equivalent to $\|\ \|_{n,X}$ for $n \ge 3$ (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*

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

where the sum is taken over all $\sigma := (j_1, \ldots, j_N) \in \mathbb{N}_0^N$ 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 δ. Then, for each $n \in \{0, 1, \ldots\}$ there exists a polynomial function $P : K \to K$ such that $\|P - \xi_{B_0}\|_{n,B} \le \varepsilon$.*

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

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

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

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

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

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

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

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 ε replaced by $\varepsilon\delta$) it follows that

$$\|P - \xi_{B_0}\|_{n-1,B} \le \varepsilon\delta \tag{2}$$

So it remains to be shown that

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

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),
$|\Phi_n(P - \xi_{B_0})(x_1, \ldots, x_{n+1})| = |x_i - x_j|^{-1} \cdot |\Phi_{n-1}(P - \xi_{B_0})(x_1, \ldots, x_{j-1}, x_{j+1}, \ldots, x_{n+1}) - \Phi_{n-1}(P - \xi_{B_0})(x_1, \ldots, x_{i-1}, x_{i+1}, \ldots, x_{n+1})| \le \delta^{-1} \cdot \varepsilon\delta = \varepsilon$. So this reduces the proof of (3) to the case where $|x_i - x_j| \le \delta$ 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_ℓ for some $\ell \in \{0, 1, \ldots, m\}$. But then, after observing that $n \ge 1$, 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

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

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

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

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 $|1 - (\frac{x}{c_i})^k| = |\frac{c_i - x}{c_i}|^k \leq \frac{\delta^k}{|c_i|^k} \leq \frac{\delta}{|c_1|}$
- 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 $(x_1, \ldots, x_{j+1}) \in \nabla^{j+1}B_\ell$. By the Product Rule 1.1, $\Phi_j(\mathcal{X}^k)(x_1, \ldots, x_{j+1})$ 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 $\{x_1, \ldots, x_{j+1}\}$ (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 $j \in \{0, 1, \ldots, n\}$, $i \in \{1, \ldots, n\}$ 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 $s \in \{1, \ldots, t_i\}$ we have for $(x_1, \ldots, x_{j+1}) \in \nabla^{j+1}B_\ell$ that $\Phi_j(1 - (\frac{\mathcal{X}}{c_i})^k)^{t_i}(x_1, \ldots, x_{j+1})$ is a sum of terms of the form

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

where $j_1 + \cdots + j_s = j$. 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 $\Gamma :=$ $\{s \in \{1,\ldots,t_i\} : j_s > 0\}$, 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 $h_i = (1-(\frac{X}{c_i})^k)^{t_i}$ 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

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

where $n_1 + \cdots + n_m = n$. 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 $|\Phi_n P(x_1,\ldots,x_{n+1})| \leq \varepsilon$ 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 $\leq \prod_{i=1}^{m} \delta^{-n_i} M_i^{t_i} = \delta^{-n} M_1^{t_1}\ldots M_m^{t_m} = \delta^{-n}\cdot|\frac{c_\ell}{c_1}|^{kt_1}\cdots|\frac{c_\ell}{c_{\ell-1}}|^{kt_\ell}(\frac{\delta}{|c_1|})^{t_\ell}$ which is $\leq \delta^{-n}\varepsilon\delta^n$ by (1). This proves (4) and the Lemma.

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

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

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

Proof. There is by Proposition 0.4 a local polynomial $g : K \to K$ with $\|f - g\|_{n,X} \leq \varepsilon$. This g has the form $g = \sum_{i=1}^{m} Q_i h_i$ where $Q_1,\ldots,Q_m$ 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 $\|h_i - P_i\|_{n,X} \leq \varepsilon(\|Q_i\|_{n,X} + 1)^{-1}$ 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 $e_0, e_1, \ldots$ of $C(\mathbb{Z}_p \to K)$ defined by $e_m(x) = \binom{x}{m}$ is proved in [3], §54 to be a Schauder base for $C^n(\mathbb{Z}_p \to K)$, for each n.
2. It follows directly from Theorem 1.4 that the polynomial functions $X \to K$ form a dense subset of $C^\infty(X \to K)$.

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 $h : \nabla^n X \to K$ we define $\Delta h : \nabla^{n+1} X \to K$ 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 $h, t : \nabla^n X \to K$. 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 $f : X \to K$, $n \in \mathbb{N}_0$. Let S_n be the set of the following functions defined on $\nabla^{n+1} X$.*

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

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 $k, n \in \mathbb{N}$, $\Delta R_n^k \subset R_{n+1}^k$.

Proof. We use induction with respect to k. For the case $k = 1$ it suffices to prove $h \in S_n \Rightarrow \Delta h \in R^1_{n+1}$. 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 Δh is the null function), while if $i_1 = 1$ it equals

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

and it follows that $\Delta h \in S_{n+1} \subset R^1_{n+1}$. For the induction step assume $\Delta R^{k-1}_n \subset R^{k-1}_{n+1}$; it suffices to prove that $\Delta S^k_n \subset R^k_{n+1}$. 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

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

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,

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

Lemma 2.3. *Let f, n, S_n, k, R^k_n 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 $\nabla^{n+1} X$.*

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

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 $(x_1, x_2, \dots, x_{n+2}) \in \nabla^{n+2} X$

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

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

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

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

$$\frac{\overline{\Phi}_j g\big(f(x_1), f(x_{i_2+1}), \dots, f(x_{i_{j+1}+1})\big) - \overline{\Phi}_j g\big(f(x_2), f(x_{i_2+1}), \dots, f(x_{i_{j+1}+1})\big)}{x_1 - x_2}$$
$$= \overline{\Phi}_{j+1} g\big(f(x_1), f(x_2), f(x_{i_2+1}), \dots, f(x_{i_{j+1}+1})\big) \Phi_1 f(x_1, x_2).$$

(if $f(x_1) = f(x_2)$ we have 0 at both sides). So we see that $\Delta b \in B_{n+1} R_{n+1}^1$. 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 $(x_1, x_2) \in \nabla^2 X$,

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

Hence, $\overline{\Phi}_1(g \circ f) \in B_1 S_1 \subset B_1 R_1^1 \subset A_1$. To prove the step $n \to n+1$ 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 $f \in C^n(X \to K)$ and let $g \in C^n(Y \to K)$ where Y has no isolated points, $Y \supset f(X)$. Then* $\|g \circ f\|_{n,X} \le \|g\|_{n,Y} \max_{0 \le j \le n} \|f\|_{j,X}^j$.

Proof. We may assume $\|g\|_{n,Y} < \infty$. It suffices to prove $\|\Phi_n(g \circ f)\|_{\nabla^{n+1}X} \le \|g\|_{n,Y} \|f\|_{n,X}^n$. Now $\|\Phi_0(g \circ f)\|_{\nabla^1 X} = \max_{x \in X} |g(f(x))| \le \|g\|_{0,Y} = \|g\|_{0,Y} \|f\|_{0,X}^0$ which proves the case $n = 0$. For $n \ge 1$ 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

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

Similarly

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

so that

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

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

Proposition 2.5 enables us to prove

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

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 $K \backslash U$. 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 $\|P - \xi_U\|_{n,B} = \|P - \xi_{B^0}\|_{n,B} = \| \sum_{i=1}^q (P_i - \xi_{B_i})\|_{n,B} < \varepsilon$, where $B^0 := \bigcup_{i=1}^q B_i$.
By Proposition 2.5

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

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

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 $a_1, \ldots, a_m \in X$, 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 $D_j h(a_i) = 0$ and $|\overline{\Phi}_{n-j} D_j h(x_1, \ldots, x_{n-j+1})| \leq \varepsilon$ for all $i \in \{1, \ldots, m\}$, $x_1, \ldots, x_{n+1} \in B(a_i, \delta_i) \cap X$, $j \in \{0, 1, \ldots, n\}$. Then $\|h\|_{n,X} \leq \varepsilon$.*

Proof. We first prove that $\|h\|^{\sim}_{n,X} \leq \varepsilon$ (see Proposition 0.4(iii)). Let $i \in \{1, \ldots, m\}$. Set $B_i = B(a_i, \delta_i)$. By Taylor's formula (Proposition 0.3(iv)) we have for $x \in X \cap B_i$: $|h(x)| =$
$|\sum_{s=0}^{n-1} (x - a_i)^s D_s h(a_i) + (x - a_i)^n \rho_1 h(x, a_i)| = |x - a_i|^n |\overline{\Phi}_n h(x, a_i, a_i, \ldots, a_i)| \leq \delta_i^n \varepsilon$.
Similarly we have for $j \in \{0, \ldots, n-1\}$ and $x \in X \cap B_i : |D_j h(x)| =$
$|\sum_{t=0}^{n-1-j} (x - a_i)^t D_t D_j h(a_i) + (x - a_i)^{n-j} \rho_1 (D_j h)(x, a_i)|$. Now using Proposition 0.3(iii) we see that $D_t D_j h(a_i) = 0$ so that

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

It follows that $\|h\|_X, \|D_1 h\|_X, \ldots, \|D_{n-1} h\|_X$ are all $\leq \varepsilon$. Now let $x, y \in X$. If x, y are in the same B_i then $|\rho_1 h(x, y)| = |\overline{\Phi}_n h(x, y, y, \ldots, y)| \leq \varepsilon$ 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 $(*)$,

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

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

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

To prove, for example, that $\|D_1 h\|^{\sim}_{n-1,X} \le \varepsilon$ 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 $j \in \{0, 1, \ldots, n-2\}$

$$|\overline{\Phi}_{n-1-j} D_j (D_1 h)(x_1, \ldots, x_{n-j})| = |(j+1)|\, |\overline{\Phi}_{n-1-j} D_{j+1} h(x_1, \ldots, x_{n-j})| \le \varepsilon$$

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 $\|D_1 h\|^{\sim}_{n-1,X} \le \varepsilon$. In a similar way we prove that $\|D_2 h\|^{\sim}_{n-2,X} \le \varepsilon, \ldots, \|D_n f\|^{\sim}_{0,X} \le \varepsilon$ and it follows that $\|h\|_{n,X} \le \varepsilon$.

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 $h_a := f_a - g$, $|\overline{\Phi}_{n-j} D_j h_a(x_1, \ldots, x_{n-j+1})| \le \varepsilon$ 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

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

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 $\|f - g\|_{n,X} \le \varepsilon$. 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

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

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 $n-1 \to n$ and, to prove that, we may assume that $D_2 f(a) = \cdots = D_{n-1} f(a) = 0$. From $(*)$ we obtain

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

and by uniqueness of the Taylor expansion of the C^n-function f^n we obtain $f^n(a) = D_1 f^n(a) = \cdots = D_{n-1} f^n(a) = 0$ 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 A 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 $g := \mathcal{X}$ 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 $\mathcal{X} \in A$. 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^∞-version of Theorem 2.10.

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Manuscript received in February 1993