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

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

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 $|\cdot|$ 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 $z \mapsto x$ ($x \in K$) is denoted $X$. The $K$-valued characteristic function of a subset $Y$ of $K$ is written $\chi_Y$. For a set $Z$, a function $f : Z \to K$ and a set $W \subset Z$ 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 $Y \subset K$, $n \in \mathbb{N}$ we set $\nabla^n Y := \{(y_1, y_2, \ldots, y_n) \in Y^n : i \neq j \Rightarrow y_i \neq y_j\}$. 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 $C(Y \to K)$.

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

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

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) $C^0(X \to K) \supset C^1(X \to K) \supset \ldots$
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(iii) If \( f \in C^n(X \to K) \) then \( f \) is \( n \) times differentiable and \( \partial_j^i f = f^{(i)} \) for each \( j \in \{0,1,\ldots,n\} \). More generally, if \( i,j \in \{0,1,\ldots,n\} \), \( i+j \leq n \) then \( \binom{i+j}{i} \partial_i^j f = \partial_{i+j} f \).

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

\[
f(x) = f(y) + (x-y)D_i f(y) + \cdots + (x-y)^{n-1} D_{n-1} f(y) + (x-y)^n \rho_i f(x,y),
\]

where \( \rho_i f(x,y) = \Phi_i f(x,y,y,\ldots,y) \).

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

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

Then \( \| f \|_{0,X} = \| f \|_X \). We quote the following from [2] and [3]. Recall that a function \( f : X \to K \) 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

\[
f \mapsto \| f \|_{n,X} := \max_{0 \leq i \leq n-1} \| \partial_i f \|_X \vee \| \rho_i f \|_X^2
\]

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

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

**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).
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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,

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

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

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

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

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 $z_{\sigma,s} \in \nabla^{j_{\sigma,s}+1}X$ for each $s \in \{1, \ldots, N\}$. (In fact, $z_{\sigma,1} = (x_1, \ldots, x_{j_1+1})$, $z_{\sigma,2} = (x_{j_1+1}, \ldots, x_{j_1+j_2+1}), \ldots, z_{\sigma,N} = (x_{j_1+\cdots+j_{N-1}+1}, \ldots, x_{j_1+\cdots+j_N+1})$)

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

Lemma 1.2. Let $0 < \delta < 1$, $0 < \epsilon < 1$, 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 $\|P - \xi_{B_0}\|_{n,B} \leq \epsilon$.

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

$$\left|\begin{array}{cccc}
\frac{ct_1}{c_1} & \frac{ct_2}{c_2} & \cdots & \frac{ct_m}{c_{t-1}} \\
|c_1| & |c_2| & \cdots & |c_{t-1}|
\end{array}\right| \leq \epsilon \delta^n$$
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(It is easily seen that such $k$, $t_1, \ldots, t_m$ exist since $\delta/|c_1| < 1$.) Then the formula

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

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

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

So it remains to be shown that

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

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),

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

So this reduces the proof of (3) to the case where $|x_i - x_j| \leq \delta$ for all $i, j \in \{1, \ldots, n+1\}$; 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

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

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

$$\|\Phi_j(1 - \left(\frac{x}{c_i}\right)^k)\|_{\nabla^{j+1}B_\ell} \leq \begin{cases} 
1 & \text{if } \ell = 0, j = 0 \\
\delta^{-j} (|\delta/|c_1|)^k & \text{if } \ell = 0, j > 0 \\
\delta^{-j} M_i & \text{if } \ell > 0, j = 0
\end{cases}$$
\textbf{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 \( |1 - (\frac{x}{c_i})^k| = |\frac{x}{c_i}|^k = |\frac{c_i}{c_i}|^k \) \\
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 \( \prod_{s=1}^{k}(\Phi_j, X)(z_s) \). Such a term is 0 if one of the \( j_s \) is \( > 1 \), so we only have to deal with \( j_s = 0 \) (then \( \Phi_j, X = X \)) or \( j_s = 1 \) (then \( \Phi_j, X = 1 \)). The latter case occurs \( j \) times (as \( \sum j_s = j \)) and it follows that \\
\[ \prod_{s=1}^{k}(\Phi_j, X)(z_s) \] is a product of \( k-j \) distinct terms taken from \( \{x_1, \ldots, x_{j+1}\} \) (observe that, indeed, \( j \leq k \) since \( j \leq n < k \)), so its absolute value is \( \leq |c_{\ell}|^{k-j} \). It follows that \( \|\Phi_j(1 - (\frac{X}{c_i})^k)\|_{\nabla^{j+1} B_{\ell}} \leq |c_{\ell}|^{k-j}/|c_i|^k \) from which we conclude \\
- if \( \ell = 0 : |c_{\ell}|^{k-j}/|c_i|^k \leq \delta^{k-j}/|c_i|^k \leq \delta^{-j}(\delta/|c_i|)^k \), \\
- if \( \ell > 0 : |c_i|^{k-j}/|c_{\ell}|^k \leq |c_{\ell}-j| < \delta^{-j} = \delta^{-j}M_i \) \\
- if \( \ell = 0 : |c_{\ell}|^{k-j}/|c_{\ell}|^k \leq |c_i|^{k-j} \leq |c_i-1| = \delta^{-j}(\delta/|c_i|)^j \leq \delta^{-j}M_i \) \\
- if \( \ell < j : |c_{\ell}|^{k-j}/|c_{\ell}|^k \leq |c_{\ell}-j| \leq |c_{\ell}|^{k-j}/|c_i|^k \leq \delta^{-j}M_i \) \\
and step 1 is proved. \\

\textbf{Step 2.} For each \( j \in \{0, 1, \ldots, n\}, i \in \{1, \ldots, n\} \) we have \\
\[ \|\Phi_j(1 - (\frac{X}{c_i})^k)\|_{\nabla^{j+1} B_{\ell}} \leq \begin{cases} 1 & \text{if } \ell = 0, j = 0 \\ \delta^{-j}(\frac{\delta}{|c_i|})^k & \text{if } \ell = 0, j > 0 \\ \delta^{-j}M_i^{|j|} & \text{if } \ell > 0 \end{cases} \]

\textbf{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 \( s \in \{1, \ldots, t_i\} \) we have for \( (x_1, \ldots, x_{j+1}) \in \nabla^{j+1} B_{\ell} \) that \( \Phi_j(1 - (\frac{X}{c_i})^k)(x_1, \ldots, x_{j+1}) \) is a sum of terms of the form \\
\[ \prod_{s=1}^{t_i}(\Phi_j, X)(z_s) \]
where $j_1 + \cdots + j_s = j$. If $\ell = 0$ it follows from Step 1 that the absolute value of (5) is 
\[ \leq \prod \delta^{-j_s} \left( \frac{\delta}{|c_i|} \right)^k \] 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 
\[ \leq \delta^{-j} \left( \frac{\delta}{|c_i|} \right)^k \leq \delta^{-j} \left( \frac{\delta}{|c_i|} \right)^k. \] If $\ell > 0$ it follows from Step 1 that the absolute value of (5) is 
\[ \leq \prod_{s=1}^{t_i} \delta^{-j_s} M_i = \delta^{-j} M^i. \] The statement of Step 2 follows.

**Step 3. Proof of (4).** Again, the Product Rule 1.1, now applied to $h_i = (1 - \left( \frac{x}{c_i} \right)^k)^t$ for $i \in \{1, \ldots, m\}$ tells us that for $(x_1, \ldots, x_{n+1}) \in V^{n+1} B_\ell$ the expression 
\[ \Phi_n P(x_1, \ldots, x_{n+1}) \] is a sum of terms of the form 
\[ (6) \quad \prod_{i=1}^{m} \Phi_n \left( 1 - \left( \frac{x}{c_i} \right)^k \right)^{t_i}(z_s) \] where $n_1 + \cdots + n_m = n$. If $\ell = 0$ we have by Step 2 that the absolute value of (6) is 
\[ \leq \prod \delta^{-n_i} \left( \frac{\delta}{|c_i|} \right)^{t_i} \] where the product is taken over $i$ in the nonempty set $\Gamma := \{ i : n_i \neq 0 \}$, so the product is 
\[ \leq \delta^{-n} \left( \frac{\delta}{|c_i|} \right)^k \leq \delta^{-n} \cdot \epsilon \delta^n = \epsilon, \] where we used the assumption $(\delta/|c_i|)^k \leq \epsilon \delta^n$. We see that $|\Phi_n P(z_1, \ldots, z_{n+1})| \leq \epsilon$ if $(z_1, \ldots, z_n) \in B_0$.

Now let $\ell > 0$. By Step 2 we have that the absolute value of (6) is 
\[ \leq \prod_{i=1}^{m} \delta^{-n_i} M_i^{t_i} = \delta^{-n} M_1^{t_1} \cdots M_m^{t_m} = \delta^{-n} \left| c_1^{t_1} \cdots c_m^{t_m} \left( \frac{\delta}{|c_i|} \right)^k \right| \] 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 2.2 there exist polynomials $P_1, \ldots, P_m$ such that $\|\xi_{B_i} - P_i\|_{n, X} \leq \epsilon(|\lambda_i| + 1)^{-1}$ 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 $\|h_i - P_i\|_{n, X} \leq \varepsilon(\|Q_i\|_{n, X} + 1)^{-1}$ 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 $X = \mathbb{Z}_p$, $K = \mathbb{Q}_p$ 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 $e_m(x) = \left(\binom{x}{m}\right)$ 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 $C^\infty(X \to K)$.

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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

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

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 $\Delta(h \circ t)(x_1, x_2, \ldots, x_{n+1}) = h(x_2, x_3, \ldots, x_{n+1}) \Delta t(x_1, x_2, \ldots, x_{n+1}) + t(x_1, x_3, \ldots, x_{n+1}) \Delta h(x_1, x_2, \ldots, x_{n+1})$.

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

$$(x_1, \ldots, x_{n+1}) \mapsto \Phi_1 f(x_{i_1}, x_{i_2}) \quad (1 \leq i_1 < i_2 \leq n + 1)$$

$$(x_1, \ldots, x_{n+1}) \mapsto \Phi_2 f(x_{i_1}, x_{i_2}, x_{i_3}) \quad (1 \leq i_1 < i_2 < i_3 \leq n + 1)$$

$$\vdots$$

$$(x_1, \ldots, x_{n+1}) \mapsto \Phi_n f(x_1, \ldots, x_{n+1}).$$

For $k \in \mathbb{N}$, let $R^k_n$ be the additive group generated by $S_n, S^2_n, \ldots, S^k_n$ where, for each $j \in \{1, \ldots, k\}$, $S^j_n$ 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 $k, n \in \mathbb{N}$, $\Delta R^k_n \subset R^{k+1}_n$. 

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**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

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

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

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

and it follows that $\Delta h \in S_{n+1} \subset R_{n+1}^1$. For the induction step assume $\Delta R_{n+1}^{k-1} \subset R_{n+1}^{k-1}$; it suffices to prove that $\Delta S_n^k \subset R_{n+1}^1$. 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

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

$$+ H(x_1, x_3, \ldots, x_{n+2}) \Delta h_1(x_1, x_2, \ldots, x_{n+2}).$$

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 $H \in S_n^{k-1}$, the function

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

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,

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

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

$$(x_1, \ldots, x_{n+1}) \mapsto \Phi_1 g(f(x_{i_1}), f(x_{i_2})) \quad (1 \leq i_1 < i_2 \leq n + 1)$$

$$(x_1, \ldots, x_{n+1}) \mapsto \Phi_2 g(f(x_{i_1}), f(x_{i_2}), f(x_{i_3})) \quad (1 \leq i_1 < i_2 < i_3 \leq n + 1)$$

$$
\vdots
$$

$$(x_1, \ldots, x_{n+1}) \mapsto \Phi_n g(f(x_1), f(x_2), \ldots, f(x_{n+1})).$$
Let $A_n$ be the additive group generated by $B_n R_n^n$. 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 $(x_1, x_2, \ldots, x_{n+2}) \in \nabla^{n+2}X$

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

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) $r \in R_n^n$ so $(x_1, \ldots, x_{n+2}) \mapsto r(x_1, x_3, \ldots, x_{n+1})$ is in $R_{n+1}^n$ (in the previous proof we had $r \in S_n^k \Rightarrow$ the map $(x_1, \ldots, x_{n+2}) \mapsto r(x_1, x_3, \ldots, x_{n+1})$ 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

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

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

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

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

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

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

(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}^n \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, $\Phi_1(g \circ f) \in B_1S_1 \subset B_1R_1 \subset A_1$. 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 $f \in C^n(X \to K)$ and let $g \in C^n(Y \to K)$ where $Y$ has no isolated points, $Y \supset f(X)$. Then $\|g \circ f\|_{n,X} \leq \|g\|_{n,Y} \max_{0 \leq j \leq n} \|f\|_{j,X}$.

**Proof.** We may assume $\|g\|_{n,Y} < \infty$. It suffices to prove $\|\Phi_n(g \circ f)\|_{n+1,X} \leq \|g\|_{n,Y} \|f\|_{n,X}$. Now $\|\Phi_0(g \circ f)\|_{n+1,X} = \max_{x \in X} |g(f(x))| \leq \|g\|_{0,Y} \|f\|_{0,X}$ 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 $B_nS_n$. By the definition of $B_n$ we have

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

Similarly

\begin{equation}
k \in S_n \Rightarrow \|k\|_{n+1,X} \leq \max_{1 \leq i \leq n} \|\Phi_if\|_{n+1,X} \leq \|f\|_{n,X}
\end{equation}

so that

\begin{equation}
(**) \quad k \in S^n_n \Rightarrow \|k\|_{n+1,X} \leq \|f\|_{n,X}.
\end{equation}

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

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 $B_1, \ldots, B_m$ of radius $\delta$ covering $f(X)$ where, say, $B_1, \ldots, B_q$ lie in $U$, and $B_{q+1}, \ldots, B_m$ are in $K \setminus U$. 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 $B := \bigcup_{i=1}^m B_i$. Then $P := \sum_{i=1}^q P_i$ is a polynomial and

\begin{equation}
\|P - \xi U\|_{n,B} = \|P - \xi B^0\|_{n,B} = \sum_{i=1}^q (P_i - \xi B_i)\|_{n,B} < \varepsilon, \text{ where } B^0 := \bigcup_{i=1}^q B_i.
\end{equation}

By Proposition 2.5

\begin{equation}
\|(P - \xi U) \circ f\|_{n,X} \leq \|P - \xi U\|_{n,B} \max_{0 \leq j \leq n} \|f\|_{j,X} \leq \varepsilon \max_{0 \leq j \leq n} \|f\|_{j,X}
\end{equation}

\begin{equation}
\|(P - \xi B^0) \circ f\|_{n,X} \leq \|P - \xi B^0\|_{n,B} \max_{0 \leq j \leq n} \|f\|_{j,X} \leq \varepsilon \max_{0 \leq j \leq n} \|f\|_{j,X}
\end{equation}

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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 
\[ B := \{ V \subset X, \xi_V \in A \}. \]
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 \( x \in X, y \in X, x \neq y \). 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, \( f^{-1}(U) \in B \). But \( x \in f^{-1}(U) \) whereas \( y \notin f^{-1}(U) \). By [1], Exercise 2.H \( B \) 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 
\[ D_j h(a_i) = 0 \text{ and } |\mathcal{F}_{n-j} D_j h(x_1, \ldots, x_{n-j+1})| \leq \varepsilon \] 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 \( \| h \|_{n,X} \leq \varepsilon \) (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 \( x \in X \cap B_i \):
\[
| h(x) | = \frac{1}{n-1} \sum_{i=0}^{n-1} (x - a_i)^j D_j h(a_i) + (x - a_i)^n \rho_1 h(x, a_i) = | x - a_i | \mathcal{F}_n h(x, a_i, a_i, \ldots, a_i) | \leq \delta_i^n \varepsilon.
\]
Similarly we have for \( j \in \{0, \ldots, n-1\} \) and \( x \in X \cap B_i : | D_j h(x) | = \frac{1}{n-1-j} \sum_{i=0}^{n-1-j} (x - a_i)^j D_{j+1} h(a_i) + (x - a_i)^n \rho_1 (D_j h)(x, a_i) | \leq \delta_i^{n-j} \varepsilon.
\]
Now using Proposition 0.3(iii) we see that \( D_j D_j h(a_i) = 0 \) so that 
\[ |D_j h(x)| = | x - a_i | |D_{n-j} h(x, a_i, \ldots, a_i) | \leq \delta_i^{n-j} \varepsilon. \]
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 \( |\rho_1 h(x, y)| = |\mathcal{F}_n h(x, y, \ldots, y) | \leq \varepsilon \) by assumption. If \( x \in B_i, y \in B_i, \) and \( i \neq s \) then \( |x - y| > \delta := \max(\delta_i, \delta_s) \) and by Taylor's formula
\[
h(x) = \sum_{l=0}^{n-1} (x - y)^l D_l h(y) + (x - y)^n \rho_1 h(x, y)
\]
we obtain, using (\( \ast \)),
\[
|\rho_1 h(x, y)| \leq \frac{|h(x) - h(y)|}{|x - y|^{n+1}} \leq \frac{|D_1 h(y)|}{|x - y|^n} \leq \frac{|D_{n-1} h(y)|}{|x - y|} \leq \frac{\delta_i^{n+1} \varepsilon}{\delta_n} \vee \frac{\delta_i^n \varepsilon}{\delta_{n-1}} \vee \frac{\delta_i \varepsilon}{\delta} \leq \varepsilon.
\]
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)

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

To prove, for example, that \( \|D_1 h\|_{n-1, X} \leq \varepsilon \) we observe that by Proposition 0.4(iii)

\[
\|W U, x - V V - V U A J \|_{n, X} \leq \varepsilon
\]

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 \( \|D_2 h\|_{n-2, X} \leq \varepsilon, \ldots, \|D_n h\|_{n, X} \leq \varepsilon \) 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 \( h_a := f_a - g, |\mathfrak{G}_{n-1-j} D_j h_a(x_1, \ldots, x_{n-j})| \leq \varepsilon \) 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

\[
f := \sum_{i=1}^{m} f_{a_i} \in B(a_1, \delta_{a_1}) \cap X
\]

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 \( g \in \mathcal{A} \).

**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

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

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

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**

