PIECEWISE MONOTONE POLYNOMIAL APPROXIMATION

BY

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ABSTRACT. Given a real function \( f \) satisfying a Lipschitz condition of order 1 on \([a, b]\), there exists a sequence of approximating polynomials \( \{P_n\} \) such that the sequence \( E_n = \|P_n - f\| \) (sup norm) has order of magnitude \( 1/n \) (D. Jackson). We investigate the possibility of selecting polynomials \( P_n \) having the same local monotonicity as \( f \) without affecting the order of magnitude of the error. In particular, we establish that if \( f \) has a finite number of maxima and minima on \([a, b]\) and \( S \) is a closed subset of \([a, b]\) not containing any of the extreme points of \( f \), then there is a sequence of polynomials \( P_n \) such that \( E_n \) has order of magnitude \( 1/n \) and such that for \( n \) sufficiently large \( n \) and \( f \) have the same monotonicity at each point of \( S \). The methods are classical.

Let \( C[a, b] = \{f: f \text{ continuous on } [a, b]\} \), with \( \|f\| = \max_{x \in [a, b]} |f(x)| \). \( \omega(f, b) = \omega(b) \) will denote the modulus of continuity of \( f \). \( P_n \) and \( T_n \) are, respectively, the spaces of algebraic and trigonometric polynomials of degree less than or equal to \( n \). \( C, C_1, C_2, \ldots \) denote absolute positive constants.

\( f \in C[a, b] \) will be called piecewise monotone if it has a finite number of maxima and minima on \([a, b]\). \( a, b \) and the local maxima and minima of \( f \) will be called the peaks of \( f \). It follows from a result proved independently by W. Wolibner [6] and S. W. Young [7] that if \( f \) is a piecewise monotone function on \([a, b]\) and \( \epsilon > 0 \), then there exists an algebraic polynomial \( p \) which increases and decreases simultaneously with \( f \) on \([a, b]\) and satisfies \( \|f - p\| < \epsilon \). We are concerned here with the accuracy of this type of approximation as a function of the degree of the approximating polynomial. Jackson’s classic theorem [2, p. 56] states that for any function \( f \in C[a, b] \) there exists \( p \in P_n \) such that \( \|f - p\| < C\omega(f, 1/n) \). O. Shisha [5], J. Roulier [4], and G. G. Lorentz and K. L. Zeller [1] have obtained results on the accuracy of the approximation of an increasing function by increasing polynomials of degree less than or equal to \( n \). Lorentz and Zeller have shown that for each increasing function \( f \) on \([a, b]\) and for each \( n > 0 \) there exists an increasing \( p \in P_n \) such that \( \|f - p\| < C_2 \omega(f, 1/n) \). They have also shown that for any function \( f \), increasing on \([-\pi, 0]\) and even on \([-\pi, \pi]\), there exists an even polynomial \( t \in T_n \), increasing on \([-\pi, 0]\), which satisfies \( \|f - t\| < C_3 \omega(f, 1/n) \). Our main results are Theorem 3 and Theorem 4

Received by the editors September 8, 1971.


Key words and phrases. Monotone approximation, piecewise monotone approximation, Jackson kernel, Jackson’s Theorem.
in which we extend, in some sense, the result of Lorentz and Zeller to piecewise monotone functions.

We will let $J_n(x)$ be the Jackson kernel; i.e.,

$$J_n(x) = \frac{1}{\lambda_n} \left( \frac{\sin nx/2}{\sin x/2} \right)^4,$$

where $\lambda_n = \int_{-\pi}^{\pi} \left( \frac{\sin nx/2}{\sin x/2} \right)^4 \, dx$.

It is known [2, p. 54] that $n^3 \leq \lambda_n \leq 2\pi n^3$.

**Lemma.** $J_n(x)$ has the following properties:

(i) If $n$ is even, $0 < \delta < \pi$, then

$$\int_0^\delta J_n(x) \, dx > C\int_{\pi-\delta}^{\pi} J_n(x) \, dx.$$  

(ii) If $0 < \delta \leq \pi/2$, then

$$\int_{\pi-\delta}^{\pi} J_n(x) \, dx \leq C\delta^3/n^3.$$  

**Proof.** (i) Case 1. $0 < \delta < \pi/2$.

Since $J_n(x)$ is an even periodic function,

$$\int_{\pi-\delta}^{\pi} J_n(x) \, dx = \int_{\pi-\delta}^{\pi} J_n(x) \, dx.$$  

Thus,

$$\int_0^\delta J_n(x) \, dx - \int_{\pi-\delta}^{\pi} J_n(x) \, dx = \int_0^\delta [J_n(x) - J_n(x + \pi)] \, dx.$$  

Now, when $n$ is even,

$$J_n(x) - J_n(x + \pi) = \frac{1}{\lambda_n} \left[ \left( \frac{\sin nx/2}{\sin x/2} \right)^4 - \left( \frac{\sin nx/2}{\cos x/2} \right)^4 \right].$$  

Since $(\tan x/2)^4 \leq 1$ for $0 \leq x \leq \pi/2$, the integrand in (3) is nonnegative, and, hence, (3) is nonnegative for $0 < \delta < \pi/2$.

Case 2. $\pi/2 \leq \delta \leq \pi$.

Here

$$\int_0^\delta J_n(x) \, dx - \int_{\pi-\delta}^{\pi} J_n(x) \, dx = \int_0^\delta J_n(x) \, dx - \int_{\delta}^{\pi} J_n(x) \, dx,$$

and the result follows from Case 1.

(ii) $\int_{\delta}^{\pi} J_n(x) \, dx \leq \frac{1}{n^3} \int_0^\delta \left( \frac{\sin nx/2}{\sin x/2} \right)^4 \, dx \leq \frac{1}{n^3} \int_{\delta}^{\pi} \left( \frac{\sin x/2}{\sin x/2} \right)^4 \, dx.$

Now $\sin(x/2) \geq x/\pi$ for $0 \leq x \leq \pi$. Therefore
Theorem 1. Let \( r(x) = |x|, -\pi \leq x \leq \pi, \) and be defined periodically by \( r(x + 2k\pi) = r(x) \) for \( k = \pm 1, \pm 2, \ldots \). Then there exists \( t \in T_n \) such that

(i) \( \max_{-\pi \leq x \leq \pi} |t(x) - r(x)| < C_5/n. \)

(ii) \( t(x) \) decreases on \([−\pi, 0]\) and increases on \([0, \pi]\).

(iii) \( t'(x) \) increases on \([−\pi/2, \pi/2]\).

(iv) If \( 0 < \delta \leq \pi/2 \), then for all \( x \in [\delta, \pi - \delta] \)

\[
1 - C_6/n^2 \delta^2 \leq t'(x) \leq 1,
\]

and for all \( x \in (−\pi + \delta, −\delta) \), \(-1 \leq t'(x) \leq 1 - C_6/n^2 \delta^2 \).

(v) \( \int_{−\pi}^{\pi} |r(x) - r(x)| \leq 4C_5/n. \)

Proof. For \( n \) even let

\[
t(x) = \int_{-\pi}^{\pi} J_n(u) r(x - u) du.
\]

By Jackson's Theorem, \( t(x) \) satisfies (i). By periodicity,

\[
t(x) = \int_{x-\pi}^{x+\pi} J_n(u) r(x - u) du = \int_{x-\pi}^{x} J_n(u) r(x - u) du - \int_{x}^{x+\pi} J_n(u) r(x - u) du.
\]

Hence

\[
t'(x) = \int_{x-\pi}^{x} J_n(u) du - \pi J_n(x - \pi) - \int_{x}^{x+\pi} J_n(u) du + \pi J_n(x + \pi)
\]

\[
= \int_{x-\pi}^{x} J_n(u) du - \int_{x}^{x+\pi} J_n(u) du.
\]

Let \( x \in [0, \pi] \). By the periodicity and evenness of \( J_n(u) \) we then get

\[
t'(x) = 2\int_{0}^{\pi} J_n(u) du - 2\int_{\pi-x}^{\pi} J_n(u) du.
\]

Applying (1), \( t'(x) \geq 0 \). By a similar argument \( t'(x) \leq 0 \) for \(-\pi \leq x < 0\), proving (ii) for \( n \) even. For \( n \) odd choose

\[
t(x) = \int_{-\pi}^{\pi} J_{n-1}(u) r(x - u) du,
\]

and the proof follows as above. (i) and (ii) are established.

Proof of (iii). Differentiating in (7),

\[
t''(x) = J_n(x) - J_n(x - \pi) - J_n(x + \pi) + J_n(x) = 2[J_n(x) - J_n(x + \pi)].
\]

This quantity is nonnegative for \( 0 \leq x \leq \pi/2 \), as shown in the proof of part (i).
of the Lemma. Then \( t''(x) \geq 0 \) for \(-\pi/2 \leq x \leq \pi/2\) by evenness and periodicity of \( f_n(x) \).

**Proof of (iv).** Let \( x \in [\delta, \pi - \delta] \). We use (7) to obtain the desired estimates. Since \( \int_{-\pi}^{\pi} f_n(u) \, du = 1 \) and \( f_n(u) \geq 0 \), \( t'(x) \leq 1 \). Now

\[
t'(x) \geq \int_{-\delta}^{\delta} f_n(u) \, du - \int_{\delta}^{\pi-\delta} f_n(u) \, du
\]

which, by (2), gives

\[
t'(x) \geq 1 - 2C_{4/n^3}\delta^3 - 2C_{4/n^3}\delta^3 = 1 - C_6/n^3\delta^3.
\]

The estimates for \( x \in (-\pi + \delta, -\delta) \) are similarly obtained.

**Proof of (v).** If \( h(x) = t(x) - r(x) \), then \( h'(x) = 0 \) on \([0, \pi]\) by (5). Hence the total variation of \( h(x) \) on \([0, \pi]\) is bounded by

\[
\frac{2C}{\pi} \max_{0 < x < \pi} |t(x) - r(x)| \leq \frac{2C_5}{n}
\]

by (4). Similarly the total variation of \( h(x) \) on \([-\pi, 0]\) is bounded by \( 2C_5/n \).

Since \( \int_{-\pi}^{\pi} |dh(x)| \) is equal to the total variation of \( h(x) \) on \([-\pi, \pi]\), (v) is proved.

**Definition.** Let \( f \) be piecewise monotone on \([a, b]\) with peaks at \( a = x_1 < x_2 < \ldots < x_m = b \). A sequence of polynomials \( \{p_n\} \) is said to be **comonotone with** \( f \) on \([a, b]\) if, for \( n \) sufficiently large, \( p_n \) increases and decreases simultaneously with \( f \) on \([a, b]\). \( \{p_n\} \) is said to be **nearly comonotone with** \( f \) on \([a, b]\) if, for every \( \epsilon \) satisfying \( 0 < \epsilon < \min_{i=1}^{m-1} (x_{i+1} - x_i) \), \( p_n \) is comonotone with \( f \) on \([x_i + \epsilon, x_{i+1} - \epsilon] \), \( i = 1, 2, \ldots, m - 1 \).

Using this terminology, the sequence of polynomials defined by (6) and (8) is comonotone with \( r(x) \) on \([-\pi, \pi]\).

**Definition.** Let \( a = y_0 < y_1 < \ldots < y_k = b \) and let \( L \in C[a, b] \) be linear on \([y_j, y_{j+1}]\), \( j = 0, 1, \ldots, k - 1 \). Then \( L \) will be called **piecewise linear** on \([a, b]\) and \( y_0, y_1, \ldots, y_k \) will be called the **nodes** of \( L \). Let \( S_j \) be the slope of \( L \) on \([y_j, y_{j+1}]\); we let \( M(L) = \max_j |S_j| \) and we let \( m(L) = \min_j |S_j| \). If \( m(L) > 0 \) then \( L \) will be called a **proper piecewise linear function**.

**Theorem 2.** Let \( L \) be a proper piecewise linear function on \([-\pi/2, \pi/2]\). Then there exists a nearly comonotone sequence \( \{t_n\}, t_n \in T_n \), such that

\[
\|L - t_n\| \leq C_7 M(L)/n.
\]

**Proof.** Let \(-\pi/2 = x_1 < \ldots < x_m = \pi/2\) be the peaks of \( L \). We will construct a sequence \( \{t_n\}, t_n \in T_n \), satisfying (9) and such that if \( 0 < \epsilon < \min_{i=1}^{m-1} (x_{i+1} - x_i) \) then \( t_n \) will have the same monotonicity as \( L \) on \([x_i + \epsilon, x_{i+1} - \epsilon]\), \( i = 1, 2, \ldots, m - 1 \) for all \( n \geq \epsilon^{-1} \left[ C_8 M(L)/m(L) \right]^{1/3} \).

Let \(-\pi/2 = y_0 < y_1 < \ldots < y_k = \pi/2\) be the nodes of \( L \). Let
Then

\[ L(x) = A + \sum_{j=0}^{k-1} a_j |x - y_j|, \]

where \( A \) is a constant. Let \( t \) be defined as in Theorem 1 [(6) and (8)] and let

\[ t_n(x) = A + \sum_{j=0}^{k-1} a_j t(x - y_j). \]

Then \( t_n \in T_n \). It follows [3, p. 147] that

\[ |L(x) - t_n(x)| \leq \frac{C_7}{n} \max_i \left| \sum_{j=0}^{i} a_j \right| \leq \frac{C_7}{n} \max_i |S_i| = \frac{C_7 m(L)}{n}, \]

thus establishing (9).

Now let \( x \in [x_i + \epsilon, x_{i+1} - \epsilon] \). We assume, without loss of generality, that \( L \) is increasing on \((x_i, x_{i+1})\). Let \( y_{q'}, y_{q'+1}, \ldots, y_{q'} \) be those consecutive nodes (if any) of \( L(x) \) which are within \( \epsilon \) of \( x \); i.e., such that

\[ |x - y_j| < \epsilon, \quad |x - y_{q'}| < \epsilon, \quad \ldots, \quad |x - y_{q'}| < \epsilon. \]

Now, differentiating in (11), we get

\[ t'_n(x) = \sum_{j=0}^{q-1} a_j r_j + \sum_{q'} a_{q'} r_{q'} + \sum_{q+1}^{k-1} a_j r_j, \]

where \( r_j \) denotes \( t'(x - y_j) \). For \( j = q, \ldots, q' \) we have \( |x - y_j| < \epsilon \), hence, from Theorem 1 (iii), \( r_j \) is decreasing as \( j \) goes from \( q \) to \( q' \). Also, from Theorem 1 (ii) and Theorem 1 (iv), \( 0 \leq r_j \leq 1 \) for \( x - y_j \geq 0 \) and \(-1 \leq r_j \leq 0 \) for \( x - y_j \leq 0 \). Applying the estimates from Theorem 1 (iv) for \( t' \) to the first and third sums in (13), we get

\[ t'_n(x) = \sum_{0}^{q-1} a_j - \sum_{q}^{q'} a_{q'} E_j + \sum_{q+1}^{k-1} a_j r_j, \]

where, from (5), we have \( 0 \leq E_j \leq C_6/n^3 \epsilon^3 \). Now, from the definition of \( \{a_j\} \), rewriting the summands, we obtain

\[ \sum_{0}^{q-1} a_j - \sum_{q}^{q'} a_{q'} + \sum_{q}^{q+1} a_j r_j \]

\[ = \frac{1}{2} \left[ S_{q-1}(1 - r_q) + \sum_{q}^{q'-1} S_j (r_j - r_{j+1}) + S_{q'}(1 + r_{q'}) \right] \geq m(L) \]
by positivity of each term. Since \( 0 \leq E_j \leq C_6/n^3 \varepsilon^3 \), by partial summation we obtain

\[
(16) \quad \left| \sum_{q'}^{q} a_j E_j - \sum_{q'}^{q} a_j E_j \right| \leq \frac{C_8M(L)}{n^3 \varepsilon^3}
\]

Combining (15) and (16) in (14), we get \( t_n'(x) \geq m(L) - \frac{C_8}{n} \frac{M(L)}{\varepsilon^3} \). This quantity is \( \geq 0 \) for \( n \geq \varepsilon^{-1} [C_8 M(L)/\varepsilon^2]^{1/3} \). Q.E.D.

Remark. In the proof of Theorem 2 we showed that \( t_n \) will have the same monotonicity as \( L \) on \([x_i + \varepsilon, x_{i+1} - \varepsilon], \) \( i = 1, 2, \ldots, m, \) for \( n \geq \varepsilon^{-1} [C_8 M(L)/\varepsilon^2]^{1/3} \).

It is not difficult to see that \( t_n \) and \( L \) will have the same monotonicity at a point \( x \in [x_i + \varepsilon, x_{i+1} - \varepsilon] \) for \( n \geq \varepsilon^{-1} [C_8 M(L)/\varepsilon^2]^{1/3} \), where \( m(x, \varepsilon, L) \) denotes the minimum slope of \( L \) in an \( \varepsilon \)-neighborhood of \( x \). Indeed, in view of the choice of \( q, q', \ldots, q', S_2, \ldots, S_n \geq m(x, \varepsilon, L) \); hence, when making a local estimate in (15), \( M(L) \) can be replaced by \( m(x, \varepsilon, L) \). In particular, if \( \varepsilon \) is less than the distance from \( x \) to the nearest node, then \( n \) depends only on the slope at \( x \).

A piecewise monotone function \( f \) will be called proper piecewise monotone if it satisfies the following: for any \( \varepsilon > 0 \) and two successive peaks \( x_i, x_{i+1} \) of \( f \) there exists \( \delta > 0 \) such that

\[
\frac{|f(x) - f(y)|}{x - y} \geq \delta
\]

for all \( x, y \in [x_i + \varepsilon, x_{i+1} - \varepsilon], x \neq y \).

Theorem 3. Let \( f \) be a proper piecewise monotone function on \([- \pi/2, \pi/2]\) such that \( f \in \text{Lip}_M 1 \) (i.e., such that \( f \) satisfies \( \omega(f, h) \leq M h \)). Then there is a nearly commonotone sequence \( \{t_n\}, t_n \in T^n \), such that

\[
(17) \quad \| f - t_n \| \leq C_9M/n.
\]

Proof. Let \( L_n \) be the proper piecewise linear function on \([- \pi/2, \pi/2]\) which has nodes at the peaks of \( f \) and at the points \(- \pi/2 + j\pi/n, j = 0, 1, \ldots, n, \) such that \( L_n(x) = f(x) \) at the nodes. Then \( L_n \) and \( f \) have the same peaks and the same monotonicity for all \( x \in [-\pi/2, \pi/2]. \) Also,

\[
(18) \quad \| f - L_n \| \leq M\pi/n
\]

and \( M(L_n) \leq M/n. \) Hence, by Theorem 2, there is a polynomial \( t_n \in T_n \) such that

\[
(19) \quad \| L_n - t_n \| \leq C_7M/n.
\]
Now $\|f - t_n\| \leq \|f - L_n\| + \|L_n - t_n\| \leq C g M/n$ from (20) and (21), establishing (19).

Since $f$ is proper piecewise monotone, for any $\epsilon > 0$ there exists $\delta(\epsilon) > 0$ such that the slope $S_i$ of $L_n$ in $[y_i, y_{i+1}]$ satisfies $S_i \geq \delta$ whenever $[y_i, y_{i+1}]$ is not within $\epsilon$ of a peak. Let $n \geq \epsilon^{-1} [C g M / \delta(\epsilon)]^{1/3}$. In view of the remark following Theorem 2, $t_n$ has the same monotonicity as $L_n$ (and, hence, as $f$) at all points not within $\epsilon$ of a peak.

Remark. Theorems 2 and 3 were stated for the interval $[-\pi/2, \pi/2]$, but are easily extended to the interval $[a, a + \pi/2]$ for any real number $a$ via the translation $x = u + a + \pi/2$.

Theorem 4. Let $f$ be a proper piecewise monotone function on $[a, b]$ such that $f \in \text{Lip}_M 1$. Then there is a nearly comonotone sequence $\{p_n\}, p_n \in P_n$, such that $\|f - p_n\| \leq C_10 M/n$.

This theorem is proved by use of the standard transformation $x = \cos \theta$, with some modifications.

Note that the class of functions for which Theorem 3 and Theorem 4 are proved includes all $f$ which have a continuous derivative that does not vanish except at the peaks. If we view monotonicity more "locally" and less "globally", we can state our results more precisely, in a sense, than we have in Theorem 3 and Theorem 4. This is done in Theorem 3' and Theorem 4', which are actually corollary (indeed, equivalent) to the results already established.

Theorem 3'. Let $f \in \text{Lip}_M 1$ on $[-\pi/2, \pi/2]$. Then there is a sequence $\{t_n\}, t_n \in T_n$, such that

$$\|f - t_n\| < C g M/n.$$  

Moreover, $f$ and $t_n$ will have the same monotonicity at $x$ for all

$$n \geq \epsilon^{-1} [C g M / \delta(\epsilon)]^{1/3},$$

where $\epsilon$ is the distance from $x$ to the nearest peak of $f$ and

$$\delta(\epsilon) = \inf_{0 < |b| < \epsilon} \left\{ \frac{f(x + b) - f(x)}{b} \right\}.$$

Theorem 4'. Let $f \in \text{Lip}_M 1$ on $[a, b]$. Then there is a sequence $\{p_n\}, p_n \in P_n$, such that

$$\|f - p_n\| \leq C_10 M/n.$$  

Moreover, $f$ and $p_n$ will have the same monotonicity at $x$ for all $n \geq \epsilon^{-1} [C g M / \delta(\epsilon)]^{1/3}$, where $\epsilon$ and $\delta(\epsilon)$ are the same as in Theorem 3'.
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