UNIMODULAR FUNCTIONS
AND INTERPOLATING BLASCHKE PRODUCTS

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Abstract. The result by Bourgain that every unimodular function \( \psi \) on the unit circle can be factored as \( \psi = e^{i\theta} B_1 \overline{B}_2 \) with \( B_1 \) and \( B_2 \) Blaschke products can be improved. We show that the same result holds with \( B_1 \) and \( B_2 \) interpolating Blaschke products. This will at the same time be a refinement of Jones's result that every unimodular function can be approximated in the \( H^\infty \)-norm by a ratio of interpolating Blaschke products.

1. Introduction

A Blaschke product is an \( H^\infty \)-function on the open unit disk \( \mathbb{D} \) of the form

\[
B(z) = z^m \prod_{|z_n| \neq 0} \frac{-z_n}{|z_n|} \frac{\bar{z} - z_n}{1 - \overline{z_n} \bar{z}},
\]

where \( \{z_n\} \) is a set of points in \( \mathbb{D} \) such that

\[
\sum (1 - |z_n|) < \infty
\]

and \( m \) is the number of \( z_n \)'s equal to 0. The set \( \{z_n\} \) is called the zero set of the Blaschke product, as the zeros of \( B(z) \) are precisely the points \( z_n \) counted with multiplicity. We have \( |B(z)| \leq 1 \) in \( \mathbb{D} \) and non-tangential limits \( |B(z)| = 1 \) almost everywhere on the unit circle \( \mathbb{T} \). See [4, pp. 53–57] for further information on Blaschke products. The Blaschke product is called interpolating if the zero set is an interpolating sequence. That is, if every interpolation problem

\[
f(z_j) = a_j, \quad j \in \mathbb{N}, \quad (a_j) \in \ell^\infty,
\]

has a solution \( f \in H^\infty \). A famous result by Carleson shows that, equivalently, a Blaschke product with zero set \( \{z_n\} \) is an interpolating Blaschke product if and only if the following two conditions hold [2]:

i) \( \inf_{n \neq m} d(z_n, z_m) > 0 \).

ii) For all Carleson squares \( Q = \{re^{i\theta} : \theta_0 < \theta < \theta_0 + \ell(Q), 1 - \ell(Q) < r < 1\} \),

\[
\sum_{z_n \in Q} (1 - |z_n|) < Ct(Q)
\]

for some constant \( C \).

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Here $\ell(Q)$ is the base length of $Q$, while $d$ denotes the pseudo-hyperbolic distance
$$d(z, w) = \left| \frac{z - w}{1 - \overline{w}z} \right|.$$

In 1969 Douglas and Rudin asked whether $\int_T \log |f| > -\infty$ was both a sufficient and necessary condition on $f \not\equiv 0$ for $f$ to be of the form $f = gh$ with $g, h \in H^\infty$ [3]. The question was answered affirmatively by Bourgain in 1986 [1]. He proved the following result, from which the answer to Douglas’s and Rudin’s problem follows easily.

**Theorem 1.** Suppose $a \in L^\infty(T)$ with $\|a\|_\infty \leq \pi$. Then there are Blaschke products $B_1$ and $B_2$ such that
$$\|(a - \text{Arg } B_1)\|_\infty < c$$
where $c$ is a constant.

We use $f \mapsto \tilde{f}$ for the conjugation operator. By examining Bourgain’s proof carefully, we may strengthen the theorem. In fact,
$$\|a - \text{Arg } B_1\|_\infty + \|(a - \text{Arg } B_2)\|_\infty < \varepsilon$$
for every $\varepsilon > 0$. Define $v = -(a - \text{Arg } B_2)^\sim$. Then $v \in L^\infty$, and because $|B_j| = 1$ almost everywhere on $T$, Theorem 1 can be reformulated as follows:

**Theorem 1’.** Suppose $\psi$ is a unimodular function on $T$. Then for every $\varepsilon > 0$ there exist Blaschke products $B_1$ and $B_2$ such that
$$\psi = e^{i\tilde{v}} B_1 B_2 = e^{i\tilde{v}} B_1 \overline{B_2}$$
for some $v \in L^\infty$ with $\|v\|_\infty < \varepsilon$ and $\|\tilde{v}\|_\infty < \varepsilon$.

The question of whether an arbitrary Blaschke product (and thus an arbitrary inner function) can be approximated by an interpolating Blaschke product has been investigated for some time. The problem, which is still open, was posed by Peter Jones who in 1981 approximated an arbitrary unimodular function by a ratio of interpolating Blaschke products in the $H^\infty$-norm [6]. In the present paper we do something similar. We approximate a ratio of Blaschke products $B_1/B_2$ by a ratio of interpolating Blaschke products $B_1^*/B_2^*$ in the sense that
$$\frac{B_1}{B_2} = e^{i\tilde{v}} \frac{B_1^*}{B_2^*},$$
with $v \in L^\infty$ and where $\|v\|_\infty$ and $\|\tilde{v}\|_\infty$ are small. By doing so, we show that Bourgain’s result also holds for interpolating Blaschke products.

**Theorem 2.** Suppose $\psi$ is a unimodular function on $T$. Then for every $\varepsilon > 0$ there exist interpolating Blaschke products $B_1^*$ and $B_2^*$ such that
$$\psi = e^{i\tilde{v}} \frac{B_1^*}{B_2^*} = e^{i\tilde{v}} B_1^* \overline{B_2^*}$$
for some $v \in L^\infty$ with $\|v\|_\infty < \varepsilon$ and $\|\tilde{v}\|_\infty < \varepsilon$.

This result can also be viewed as a strengthened version of Jones’s theorem.
2. Unimodular functions on $\mathbb{T}$

To prove Theorem 2 we use a result of Marshall and Stray [7] concerning the product of interpolating Blaschke products, and a result of Garnett and Nicolau [5] showing how a Blaschke product can be approximated by a ratio of interpolating Blaschke products.

Lemma 3. Let $B_1^*$ and $B_2^*$ be interpolating Blaschke products. Then for every $\varepsilon > 0$ there is an interpolating Blaschke product, $B^*$, such that

$$B_1^* B_2^* = B^* e^{i\tilde{v}}$$

on $\mathbb{T}$ for some $v \in L^\infty$ with $\|v\|_\infty < \varepsilon$ and $\|\tilde{v}\|_\infty < \varepsilon$.

Proof. This lemma can, although not stated explicitly, be inferred from [7]. The main part of the argument can also be found in [8, pp. 101–103], so we only sketch it here. Denote the zero sets of $B_1^*$ and $B_2^*$ by $\{a_n\}$ and $\{b_n\}$ respectively. Choose $\delta$ so small that

$$d(a_n, a_m) \geq 2\delta \quad \text{and} \quad d(b_n, b_m) \geq 2\delta \quad \text{for all } n \neq m.$$

By moving zeros from $B_1^*$ to $B_2^*$ if necessary, the closed disks

$$\Delta_j = \{z : d(z, a_j) \leq c\delta\}, \quad c \text{ small},$$

are disjoint and contain exactly one $b_n$ each. See Figure 1. We must show that also the zeros left in $B_1^*$ can be separated from those of $B_2^*$ such that condition i) holds. By Frostman’s theorem [4, p. 79] there is an $\varepsilon_0 \in (c\delta, \frac{4}{3}c\delta)$ such that

$$\tilde{B}_1^*(z) = \frac{B_1^*(z) - \varepsilon_0}{1 - \varepsilon_0 B_1^*(z)}$$

![Figure 1](http://www.ams.org/journal-terms-of-use)

Figure 1. The closed disks $\Delta_j$ and the corresponding pseudohyperbolic annuli $A_j$. The zeros of $B_1^*$ and $\tilde{B}_1^*$ are marked •, while the zeros of $B_2^*$ are marked ×.
is a Blaschke product. It can then be shown that the zeros of $\hat{B}_1$ lie in the pseudo-
hyperbolic annuli

$$A_j = \{ z : \varepsilon_0 < d(z, a_j) < \delta \}.$$ 

Thus they are separated from the zeros of $B_2^\ast$. It follows that $B^\ast = \hat{B}_1 B_2^\ast$ is an
interpolating Blaschke product approximating $B_1^\ast B_2^\ast$. On $T$, $B_1^\ast \overline{B_2} = |B_1^\ast|^2 = 1$
almost everywhere. Hence we can write

$$\hat{B}_1 = B_1^\ast - \varepsilon_0 \left( 1 - \frac{\varepsilon_0}{1 - \varepsilon_0 B_1^\ast} \right) = B_1^\ast \hat{h}$$

where $h = 1 - \varepsilon_0 B_1^\ast$ is an outer function. So $h = e^{u+i\hat{u}}$ with $u \in L^\infty$. This gives
$\hat{B}_1 = e^{-2i\hat{u}} B_1^\ast$ and by taking $\varepsilon_0$ small enough, we can ensure that $\|u\|_\infty$ and $\|\hat{u}\|_\infty$
are less than $\frac{\varepsilon}{2}$.

Observe that this lemma is easily extended to finite products of interpolating
Blaschke products.

The main step in the proof of Theorem 2 is the approximation of Blaschke
products by ratios of interpolating Blaschke products. This is accomplished through
the following lemma, which is a slight modification of a result by Garnett and
Nicolau [3].

Lemma 4. Let $B$ be a Blaschke product. Then for every $\varepsilon > 0$ there exist interpo-
lating Blaschke products $B_1^\ast$ and $B_2^\ast$ such that

$$B = e^{i\hat{u}} \frac{B_1^\ast}{B_2^\ast} = e^{i\hat{u}} B_1^\ast \overline{B_2}$$

on $T$ for some $v \in L^\infty$ with $\|v\|_\infty < \varepsilon$ and $\|\hat{u}\|_\infty < \varepsilon$.

Proof. We follow the same construction as Garnett and Nicolau. Let $0 < \alpha < \beta < 1$,
$M = 2^K > 1$ and $\delta < 1$ be constants whose values will be determined later. Note
that by applying a preliminary conformal mapping we may assume $|B(0)| > \beta$. We
will consider dyadic Carleson squares of the form

$$Q_{n,j} = \{ re^{i\theta} : 2\pi j 2^{-n} \leq \theta < 2\pi (j+1) 2^{-n}, 1 - 2^{-n} \leq r < 1 \}$$

and their top-halves $T(Q_{n,j})$. Let $G_1 = \{ Q_1^{(1)}, Q_2^{(1)}, \ldots \}$ be the set of maximal $Q_{n,j}$
with

$$\inf_{T(Q_{n,j})} |B(z)| < \alpha.$$ 

Write $S_{p,k}^{(1)}$, $1 \leq p \leq M = 2^K$, for the $M$ different $Q_{n+k,j} \subset Q_{n,j} = Q_1^{(1)}$, and let
$H_1 = \{ V_1^{(1)}, V_2^{(1)}, \ldots \}$ be the set of maximal $Q_{n,j}$ for which $V_1^{(1)} \subset Q_1^{(1)}$ for some
$Q_1^{(1)}$ and

$$\inf_{T(V_1^{(1)})} |B(z)| > \beta.$$ 

The function $|B|$ has non-tangential limit 1 almost everywhere, so

$$\sum_{V_1^{(1)} \subset Q_1^{(1)}} \ell(V_1^{(1)}) = \ell(Q_1^{(1)}).$$ 

Let

$$f(z) = \frac{B(z) - w_0}{1 - \overline{w_0}B(z)}$$
with \( w_0 = B(z_0), \ z_0 \in Q^{(1)}_k \) and \( |w_0| = \alpha \). If \( 1 - \beta \) is small, then Schwarz’s Lemma applied to \( f \) implies that
\[
\sup_{T(S^{(1)}_{p,k})} |B(z)| < \beta.
\]
We may also deduce that \( V^{(1)}_l \subset S^{(1)}_{p,k} \) for some \( p, k \).

Next we iterate the construction. Let \( G_2 = \{Q^{(2)}_1, Q^{(2)}_2, \ldots\} \) be the set of maximal \( Q_{n,j} \) such that
\[
Q_{n,j} \subset V^{(1)}_l \in H_1 \quad \text{and} \quad \inf_{T(Q_{n,j})} |B(z)| < \alpha.
\]
The \( Q^{(2)}_k \) are relatively few. In fact, by \[4, \text{p. 334}\], given \( \varepsilon_0 > 0 \) we can take \( (1 - \beta)/(1 - \alpha) \) so small that
\[
\sum_{Q^{(2)}_k \subset V^{(1)}_l} \ell(Q^{(2)}_k) < \varepsilon_0 \ell(V^{(1)}_l).
\]
The sets \( \{S^{(2)}_{p,k}\} \) and \( H_2 = \{V^{(2)}_l\} \) are constructed in the same manner as above.

By repeating the argument we obtain
\[
Q^{(m)}_k \supset S^{(m)}_{p,k} \supset V^{(m)}_l \supset Q^{(m+1)}_k.
\]
Define
\[
R^{(m)}_{p,k} = c^{(m)}_{p,k} \setminus \bigcup_{V^{(m)}_l \subset S^{(m)}_{p,k}} V^{(m)}_l
\]
and observe that the zeros of \( B(z) \) are in
\[
\bigcup_{k,m} \left( Q^{(m)}_k \setminus \bigcup_{V^{(m)}_l \subset Q^{(m)}_k} V^{(m)}_l \right).
\]
By taking \( 1 - \alpha \) small we can make all zeros from \( Q^{(m)}_k \setminus \bigcup V^{(m)}_l \) fall into \( \bigcup_{p=1}^M R^{(m)}_{p,k} \).

Factor \( B = B_1 \cdots B_M \) where \( B_p \) has zeros only in \( \bigcup_{k,m} R^{(m)}_{p,k} \). Fix \( p \) and set
\[
\Gamma^{(m)}_{p,k} = \partial R^{(m)}_{p,k} \setminus \partial S^{(m)}_{p,k}.
\]
See Figure 2. Mark points \( z^*_{\nu} = z^*_{\nu}(k,m,p) \) on \( \Gamma^{(m)}_{p,k} \) such that
\[
d(z^*_\nu, z^*_\nu + 1) = \delta.
\]
Let \( B^*_p \) be the Blaschke product with zeros \( \bigcup_{k,m} z^*_{\nu}(k,m,p) \). Then condition i) holds by (1). From the definition of the \( z^*_{\nu} \)'s there is a constant \( c \) dependent on \( \delta \) such that
\[
\sum_{z^*_{\nu} \in Q^{(m)}_k} (1 - |z^*_{\nu}|) \leq c \sum_{V^{(m)}_l \subset Q^{(m)}_k} \ell(V^{(m)}_l).
\]
Hence by (2) and (3),
\[
\sum_{z^*_{\nu} \in Q^{(m)}_k} (1 - |z^*_{\nu}|) < \frac{c}{1 - \varepsilon_0} \ell(Q^{(m)}_k),
\]
so condition ii) holds for all dyadic Carleson squares, and therefore for all Carleson squares. It follows that \( B^*_p \) is an interpolating Blaschke product. By Lemma 3 there is then an interpolating Blaschke product \( B^* = e^{i\theta} B^*_1 \cdots B^*_M \) on \( T \). To finish
the proof we will need to show the existence of yet another interpolating Blaschke product \( C^* \) such that \( C^* = e^{i\bar{u} B B^*} \).

Before doing so we state three lemmas from [5] which help us with this last part.

**Lemma 5.** Let \( B \) be a Blaschke product and let \( \{z_\nu\} \) be its zeros, counted with their multiplicities. Then \( B \) is a finite product of interpolating Blaschke products if and only if there exist positive constants \( d_0, \delta_0 \) such that for each \( z_\nu \) there is \( w_\nu \) with

\[
d(z_\nu, w_\nu) \leq d_0 \text{ and } (1 - |w_\nu|^2) |B'(w_\nu)| \geq \delta_0.
\]

**Lemma 6.** \( |B_p'| \leq \delta^{1/4} \) on \( \bigcup_{k,m} R^{(m)}_{p,k} \).

**Lemma 7.** There exist \( A = A(\alpha, \beta, \delta, M) \) and \( \eta = \eta(\alpha, \beta, \delta, M) > 0 \) so that if

\[
\inf_{\xi \in \bigcup_{k,m} R^{(m)}_{p,k}} d(z, \xi) > A
\]

and if

\[
|B_p B^*_p(z)| = \delta^{1/8}, \text{ and } (1 - |z|^2) |(B_p B^*_p)'(z)| \geq \eta.
\]

**Proof of Lemma 4 continued.** By Frostman’s theorem there is a constant \( \gamma \) with \( |\gamma| = \delta^{1/8} \) so that

\[
C_p = \frac{B_p B^*_p - \gamma}{1 - \gamma B_p B^*_p}
\]

is a Blaschke product. Let \( z_0 \) be such that \( C_p(z_0) = 0 \). Then \( |(B_p B^*_p)'(z_0)| = \delta^{1/8} \) and

\[
(1 - |z_0|^2) |C_p'(z_0)| \geq \frac{1 - |z_0|^2}{1 - |\gamma|^2} |(B_p B^*_p)'(z_0)|.
\]
If (5) holds, Lemma 7 implies that
\[(1 - |z_0|^2)|C_p'(z_0)| \geq \frac{\eta}{1 - |\gamma|^2} > 0.\]
If, on the other hand, (5) does not hold, there is a \(\xi \in \bigcup_{k,m} R_{p,k}^{(m)}\) with \(d(z_0, \xi) \leq A\).
From Lemma 8 we have \(|(B_p B_p^*)'(\xi)| \leq \delta^1/4\), so somewhere along the hyperbolic geodesic from \(z_0\) to \(\xi\) there is a point \(w\) with
\[(1 - |w|^2)|B_p B_p^*|(w)| > \hat{\gamma} > 0 \quad \text{and} \quad d(z, w) < A.
Then also
\[(1 - |w|^2)|C_p(w)| > 0.\]
So either way Lemma 5 tells us that \(C_p\) is a finite product of interpolating Blaschke products.

Lemma 8 then gives us the existence of \(u_p \in L^\infty\) such that \(C_p^* = e^{-iu_p} C_p\) are interpolating Blaschke products on \(T\). Furthermore,
\[C_p^* = \frac{B_p B_p^*(1 - \gamma B_p B_p^*)}{1 - \gamma B_p B_p^*} e^{-iu_p} = e^{-iu_p} B_p B_p^* \quad \text{or} \quad B_p = e^{iu_p} C_p^* B_p^*,\]
and
\[B = B_1 \cdots B_M = e^{iu} C^* B^* = e^{iu} C^* B^*\]
where \(B^* = B_1^* \cdots B_M^*\) and \(C^* = C_1^* \cdots C_M^*\) are interpolating Blaschke products. Also \(v = v_1 + \cdots + v_M \in L^\infty\) with \(\|v\|_{\infty} < \varepsilon\) and \(\|\hat{v}\|_{\infty} < \varepsilon\). \(\Box\)

**Proof of Theorem 2.** From (1) we have that \(\psi = e^{iu_p B_p}\) for some \(u_p \in L^\infty\) with \(\|u_p\|_{\infty} < \frac{\varepsilon}{5}\) and \(B_1\) and \(B_2\) Blaschke products. Lemma 3 aids us in approximating \(B_1\) and \(B_2\) by interpolating Blaschke products \(B_{i,j}\),
\[\psi = e^{iu_1 B_{1,1}/B^*_{1,1}} e^{iu_2 B_{2,1}/B^*_{2,1}} = e^{i(u_1 + u_2)} B_{1,1}^* B_{2,1}^*/B_{1,2}^* B_{2,2}^*.\]
By Lemma 3 these products may again be approximated by interpolating Blaschke products. Thus,
\[\psi = e^{i(u_1 + u_2 - u_1)} B_{1,1}^*/B_{1,2}^* e^{i(u_1 - u_2)} B_{2,1}^*/B_{2,2}^* = e^{i\hat{u} B_1^* B_2^*},\]
where \(B_1^*\) and \(B_2^*\) are interpolating Blaschke products and \(v = u + u_1 - u_2 - v_1 + v_2 \in L^\infty\). The norms of \(u_1, u_2, v_1\) and \(v_2\) can all be taken less than \(\frac{\varepsilon}{5}\), so also can the norms of \(\hat{u}_1, \hat{u}_2, \hat{v}_1\) and \(\hat{v}_2\). Thus \(\|v\|_{\infty} < \varepsilon\) and \(\|\hat{v}\|_{\infty} < \varepsilon\). \(\Box\)

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