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Sets of determination for the Nevanlinna class

Stephen J. Gardiner

Abstract

This paper characterizes the subsets \( E \) of the unit disc \( \mathbb{D} \) with the property that \( \sup_E |f| = \sup_{\mathbb{D}} |f| \) for all functions \( f \) in the Nevanlinna class.

1 Introduction

Let \( \mathcal{A} \) be a collection of holomorphic functions on the unit disc \( \mathbb{D} \), and let \( \mathbb{T} \) denote the unit circle. A set \( E \subset \mathbb{D} \) is called a set of determination for \( \mathcal{A} \) if \( \sup_E |f| = \sup_{\mathbb{D}} |f| \) for all \( f \in \mathcal{A} \). Brown, Shields and Zeller [3] have shown that \( E \) is a set of determination for \( H^\infty \), the space of bounded holomorphic functions on \( \mathbb{D} \), if and only if almost every point of \( \mathbb{T} \) can be approached nontangentially by a sequence of points in \( E \). Massaneda and Thomas [6] have observed that the same characterization remains valid when \( \mathcal{A} \) is the Smirnov class \( \mathcal{N}^+ \). However, the situation is more complicated for the Nevanlinna class \( \mathcal{N} \), which consists of all holomorphic functions \( f \) on \( \mathbb{D} \) that satisfy

\[
\sup_{0 < r < 1} \int_0^{2\pi} \log^+ |f(re^{i\theta})| \, d\theta < \infty.
\]

This is the main focus of [6], where a variety of conditions are shown to be either necessary or sufficient for \( E \) to be a set of determination for \( \mathcal{N} \), and some illustrative special cases are examined. (See also Stray [7], p.256.) The purpose of this paper is to give a complete characterization of such sets.

First we recall a related result of Hayman and Lyons [5] for the harmonic Hardy space \( h^1 \), which consists of those functions on \( \mathbb{D} \) that can be expressed as the difference of two positive harmonic functions. For \( n \in \mathbb{N} \) and \( 0 \leq m < 2^{n+4} \) let

\[
z_{m,n} = (1 - 2^{-n}) \exp(2\pi im/2^{n+4})
\]

and

\[
S_{m,n} = \left\{ re^{i\theta} : 2^{-n-1} \leq 1 - r \leq 2^{-n} \quad \text{and} \quad \frac{2\pi m}{2n+4} \leq \theta \leq \frac{2\pi (m+1)}{2n+4} \right\},
\]

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and let \( E_{m,n} = E \cap S_{m,n} \). The Poisson kernel for \( \mathbb{D} \) is given by

\[
P(z, w) = \frac{1 - |z|^2}{|z - w|^2} \quad (z \in \mathbb{D}, w \in \mathbb{T}).
\]

**Theorem A** [5] Let \( E \subset \mathbb{D} \). The following conditions are equivalent:

(a) \( \sup_{E} h = \sup_{\mathbb{D}} h \) for all \( h \in h^1 \);

(b) \( \sum_{m,n \neq 0} 2^{-n} P(z_{m,n}, w) = \infty \) for every \( w \in \mathbb{T} \).

For any set \( A \) which is contained in a disc of radius less than 1, and any \( t \geq 0 \), we define a capacity-related quantity \( Q(A, t) \) as follows. We put \( Q(A, t) = 0 \) if either \( t = 0 \) or \( A = \emptyset \); otherwise,

\[
Q(A, t) = \min\{k \in \mathbb{N} : \exists \xi_1, \ldots, \xi_k \in \mathbb{C} \text{ such that } \sum_{j=1}^{k} \log \frac{1}{|z - \xi_j|} \geq t \ (z \in A)\}.
\]

Clearly \( Q(\cdot, t) \) is translation-invariant and \( Q(\{\zeta\}, \cdot) = \chi(0, \infty) \) for any \( \zeta \in \mathbb{C} \). Also,

\[
Q(\{\zeta_1, \zeta_2\}, t) = \begin{cases} 
0 & \text{if } t = 0 \\
1 & \text{if } |\zeta_1 - \zeta_2| \leq 2e^{-t} \text{ and } t > 0 \\
2 & \text{otherwise}
\end{cases}
\]

and, if \( A \) is a disc of radius of \( r < 1 \), then \( Q(A, t) \) is the least integer \( k \) satisfying \( k \geq t/\log(1/r) \). We use \( \lfloor t \rfloor \) to denote the integer part of a non-negative number \( t \), and \( tA \) to denote the set \( \{tz : z \in A\} \). Our characterization of sets of determination for the Nevanlinna class is as follows.

**Theorem 1** Let \( E \subset \mathbb{D} \). The following conditions are equivalent:

(a) \( \sup_{E} |f| = \sup_{\mathbb{D}} |f| \) for all \( f \in \mathcal{N} \);

(b) \( \sum_{m,n} 2^{-n} Q(2^nE_{m,n}, [P(z_{m,n}, w)]) = \infty \) for every \( w \in \mathbb{T} \).

Since

\[
\log \frac{2^{-n}}{|z - z_{m,n}|} \geq -\frac{1}{2} \log \left( \left( \frac{\pi}{8} \right)^2 + \left( \frac{1}{2} \right)^2 \right) > \frac{1}{3} \quad (z \in S_{m,n}),
\]

we have

\[
3P(z_{m,n}, w) \log \frac{2^{-n}}{|z - z_{m,n}|} \geq P(z_{m,n}, w) \quad (z \in S_{m,n}, w \in \mathbb{T}).
\]

By separate consideration of the cases \( P(z_{m,n}, w) \geq 1 \) and \( P(z_{m,n}, w) < 1 \), we see that

\[
Q(2^nE_{m,n}, [P(z_{m,n}, w)]) \leq 4P(z_{m,n}, w).
\]

(1)
Applying this inequality to terms where $E_{m,n} \neq 0$, it is now clear that condition (b) of Theorem 1 implies the corresponding condition of Theorem A. It is not difficult to check that condition (a) of Theorem 1 is equivalent to the assertion that, if $\log |f| \leq h$ on $E$, where $f \in \mathcal{N}$ and $h \in h^1$, then $\log |f| \leq h$ on all of $\mathbb{D}$ (cf. [6]).

**Examples** Let $U = \{ z : |z - \frac{1}{2}| < \frac{1}{2} \}$ and $F = U \cap \{ z_{m,n} \}$.

(i) The set $E = \mathbb{D} \setminus U$ is not a set of determination (for $\mathcal{N}$) because the series in condition (b) of Theorem A then converges when $w = 1$ (cf. Example 6.2 in [5]).

(ii) Further, even $E \cup F$ is not a set of determination because each of the sets $F_{m,n}$ contains at most 5 points and so

$$
\sum_{m,n} 2^{-n} Q(2^n F_{m,n}, [P(z_{m,n}, 1)]) \leq 5 \sum_{z_{m,n} \in F} 2^{-n} < \infty
$$

(cf. Example 1 in [6]).

(iii) On the other hand, $E \cup [\frac{1}{2}, 1)$ is a set of determination since

$$
Q(2^n [1 - 2^{-n}, 1 - 2^{-n-1}], [P(z_{0,n}, 1)]) = Q\left([0, \frac{1}{2}], 2^n\right)
$$

and $\inf_n 2^{-n} Q\left([0, \frac{1}{2}], 2^n\right) > 0$ because $[0, \frac{1}{2}]$ is non-polar.

### 2 Proof of Theorem 1

Let $G_U(\cdot, \cdot)$ denote the Green function of an open set $U$, let

$$
D_\rho(z) = \{ \zeta : |\zeta - z| < \rho(1 - |z|) \} \quad (z \in \mathbb{D}, 0 < \rho < 1),
$$

and let $A(g, z)$ denote the mean value of a function $g$ over the disc $D_{1/8}(z)$. For potential theoretic background we refer to the book [2].

Suppose firstly that condition (b) of Theorem 1 holds and let $f \in \mathcal{N}$. We will assume that $\sup_{E} |f| < \infty$, for otherwise it is trivially true that $\sup_{E} |f| = \sup_{\mathbb{D}} |f|$. Further, multiplication by a suitable constant enables us to arrange that $\sup_{E} |f| \in [0, 1]$. Now let $a \in (-\infty, 0]$ be such that $a \geq \log \sup_{E} |f|$. We can write

$$
\log |f| = h_1 - h_2 - G_{\mathbb{D}} \mu,
$$

where $h_1$ and $h_2$ are positive harmonic functions and $\mu$ is a sum of unit point masses on $\mathbb{D}$ satisfying

$$
\int (1 - |z|) d\mu(z) < \infty.
$$
Further, by addition to both $h_1$ and $h_2$, we may assume that $h_1 \geq 1$. By the Riesz-Herglotz theorem there is a Borel measure $\nu_1$ on $\mathbb{T}$ such that

$$h_1(z) = \int P(z, w) d\nu_1(w) \quad (z \in \mathbb{D}).$$

We know that

$$h_1 - a \leq h_2 + G_D \mu \quad \text{on } E. \quad (2)$$

Also,

$$G_D(z, \xi) - A(G_D(\cdot, \xi), z) \leq G_{D_{1/8}(z)}(z, \xi) \leq \log \left( \frac{1 - |z|}{|z - \xi|} \right) (\xi \in D_{1/8}(z)) \quad (3)$$

and $G_D(z, \xi) - A(G_D(\cdot, \xi), z) = 0$ otherwise. Let $\varepsilon \in (0, 1)$ and

$$I_{\varepsilon} = \{(m, n) : G_D \mu \geq A(G_D \mu, \cdot) + \varepsilon h_1 \text{ on } E_{m,n}\},$$

and let $I'_{\varepsilon}$ denote the complementary set of pairs $(m, n)$. (We note that $(m, n) \in I_{\varepsilon}$ whenever $E_{m,n} = \emptyset$.) If $(m, n) \in I_{\varepsilon}$, then we see from (3) that

$$\varepsilon h_1(z) \leq G_D \mu(z) - A(G_D \mu, z)$$

$$= \int_{D_{1/8}(z)} (G_D(z, \xi) - A(G_D(\cdot, \xi), z)) d\mu(\xi)$$

$$\leq \int_{A_{m,n}} \log \frac{2^{-n}}{|z - \xi|} d\mu(\xi) \quad (z \in E_{m,n}),$$

where

$$A_{m,n} = \{ \xi : \text{dist}(\xi, S_{m,n}) < 2^{-n-3} \}.$$

(Here we have used the fact that the diameter of $2^n A_{m,n}$ is less than 1.) By Harnack’s inequalities there is an absolute constant $c_1 > 1$ such that $h(\zeta_1) \leq c_1 h(\zeta_2)$ for any positive harmonic function $h$ on $\mathbb{D}$, any points $\zeta_1, \zeta_2 \in S_{m,n}$, and any choice of $(m, n)$. For any $w \in \mathbb{T}$ we thus have

$$P(z_{m,n}, w) \leq \frac{c_1}{\varepsilon h_1(z_{m,n})} P(z_{m,n}, w) \int_{A_{m,n}} \log \frac{2^{-n}}{|z - \xi|} d\mu(\xi) \quad (z \in E_{m,n}),$$

and so

$$Q(2^n E_{m,n}, [P(z_{m,n}, w)]) \leq \left( \frac{c_1}{\varepsilon h_1(z_{m,n})} P(z_{m,n}, w) + 1 \right) \mu(A_{m,n}).$$

Integration of the above inequality with respect to $d\nu_1(w)$ yields

$$\int Q(2^n E_{m,n}, [P(z_{m,n}, w)]) d\nu_1(w) \leq \left( \frac{c_1}{\varepsilon} + h_1(0) \right) \mu(A_{m,n}).$$
Since no point of \( \mathbb{D} \) can lie in more than 4 of the sets \( A_{m,n} \), and \( 1-|z| < 2^{-n-2} \) when \( z \in A_{m,n} \), we see that

\[
\int \sum_{(m,n) \in I_\varepsilon} 2^{-n} \mathcal{Q}(2^n E_{m,n}, [P(z_{m,n}, w)]) \, d\nu_1(w) \\
\leq 2^4 \left( \frac{c_1}{\varepsilon} + h_1(0) \right) \int (1 - |z|) d\mu(z) < \infty,
\]

so

\[
\sum_{(m,n) \in I_\varepsilon} 2^{-n} \mathcal{Q}(2^n E_{m,n}, [P(z_{m,n}, w)]) < \infty \quad \text{for } \nu_1\text{-almost every } w \in \mathbb{T},
\]

and hence, by hypothesis,

\[
\sum_{(m,n) \in I_\varepsilon'} 2^{-n} \mathcal{Q}(2^n E_{m,n}, [P(z_{m,n}, w)]) = \infty \quad \text{for } \nu_1\text{-almost every } w \in \mathbb{T}.
\]

In view of (1) we now see that

\[
\sum_{(m,n) \in I_\varepsilon'} 2^{-2n} |w - z_{m,n}|^{-2} = \infty \quad \text{for } \nu_1\text{-almost every } w \in \mathbb{T}. \quad (4)
\]

For each \( (m,n) \in I_\varepsilon' \) we can find \( \zeta_{m,n} \in E_{m,n} \) such that

\[
G_{\mathbb{D} \mu}(\zeta_{m,n}) < \mathcal{A}(G_{\mathbb{D} \mu}, \zeta_{m,n}) + \varepsilon h_1(\zeta_{m,n}).
\]

Let \( F = \{ \zeta_{m,n} : (m,n) \in I_\varepsilon' \} \). Then

\[
(1 - \varepsilon) h_1 - a \leq h_2 + \mathcal{A}(G_{\mathbb{D} \mu}, \cdot) \quad \text{on } F, \quad (5)
\]

in view of (2). Also, by (4),

\[
\int_{F_\rho} |w - z|^{-2} d\lambda(z) = \infty \quad (0 < \rho < 1) \quad (6)
\]

for \( \nu_1\text{-almost every } w \in \mathbb{T} \), where \( F_\rho = \cup_{\zeta \in F} D_\rho(\zeta) \) and \( \lambda \) denotes area measure. At this point we could invoke Theorem 2 of [4], but for the sake of completeness we will extract the relevant reasoning in the next paragraph.

Let \( 0 < \rho < 1/8 \). If \( z' \in D_\rho(z) \), then by the mean value inequality

\[
G_{\mathbb{D} \mu}(z') \geq \frac{1}{\pi(\rho + 1/8)^2(1 - |z|)^2} \int_{\{\zeta : |\zeta - z'| < (\rho + 1/8)(1 - |z|)\}} G_{\mathbb{D} \mu}(\zeta) \, d\lambda(\zeta) \\
geq \frac{(1/8)^2}{(\rho + 1/8)^2} \mathcal{A}(G_{\mathbb{D} \mu}, z),
\]

and by Harnack’s inequalities

\[
\frac{1 - \rho}{1 + \rho} h_j(z) \leq h_j(z') \leq \frac{1 + \rho}{1 - \rho} h_j(z) \quad (j = 1, 2),
\]

In view of (1) we now see that

\[
\sum_{(m,n) \in I_\varepsilon'} 2^{-2n} |w - z_{m,n}|^{-2} = \infty \quad \text{for } \nu_1\text{-almost every } w \in \mathbb{T}. \quad (4)
\]

For each \( (m,n) \in I_\varepsilon' \) we can find \( \zeta_{m,n} \in E_{m,n} \) such that

\[
G_{\mathbb{D} \mu}(\zeta_{m,n}) < \mathcal{A}(G_{\mathbb{D} \mu}, \zeta_{m,n}) + \varepsilon h_1(\zeta_{m,n}).
\]

Let \( F = \{ \zeta_{m,n} : (m,n) \in I_\varepsilon' \} \). Then

\[
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geq \frac{(1/8)^2}{(\rho + 1/8)^2} \mathcal{A}(G_{\mathbb{D} \mu}, z),
\]

and by Harnack’s inequalities

\[
\frac{1 - \rho}{1 + \rho} h_j(z) \leq h_j(z') \leq \frac{1 + \rho}{1 - \rho} h_j(z) \quad (j = 1, 2),
\]

In view of (1) we now see that

\[
\sum_{(m,n) \in I_\varepsilon'} 2^{-2n} |w - z_{m,n}|^{-2} = \infty \quad \text{for } \nu_1\text{-almost every } w \in \mathbb{T}. \quad (4)
\]

For each \( (m,n) \in I_\varepsilon' \) we can find \( \zeta_{m,n} \in E_{m,n} \) such that

\[
G_{\mathbb{D} \mu}(\zeta_{m,n}) < \mathcal{A}(G_{\mathbb{D} \mu}, \zeta_{m,n}) + \varepsilon h_1(\zeta_{m,n}).
\]

Let \( F = \{ \zeta_{m,n} : (m,n) \in I_\varepsilon' \} \). Then

\[
(1 - \varepsilon) h_1 - a \leq h_2 + \mathcal{A}(G_{\mathbb{D} \mu}, \cdot) \quad \text{on } F, \quad (5)
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in view of (2). Also, by (4),

\[
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\]

for \( \nu_1\text{-almost every } w \in \mathbb{T} \), where \( F_\rho = \cup_{\zeta \in F} D_\rho(\zeta) \) and \( \lambda \) denotes area measure. At this point we could invoke Theorem 2 of [4], but for the sake of completeness we will extract the relevant reasoning in the next paragraph.

Let \( 0 < \rho < 1/8 \). If \( z' \in D_\rho(z) \), then by the mean value inequality

\[
G_{\mathbb{D} \mu}(z') \geq \frac{1}{\pi(\rho + 1/8)^2(1 - |z|)^2} \int_{\{\zeta : |\zeta - z'| < (\rho + 1/8)(1 - |z|)\}} G_{\mathbb{D} \mu}(\zeta) \, d\lambda(\zeta) \\
geq \frac{(1/8)^2}{(\rho + 1/8)^2} \mathcal{A}(G_{\mathbb{D} \mu}, z),
\]

and by Harnack’s inequalities

\[
\frac{1 - \rho}{1 + \rho} h_j(z) \leq h_j(z') \leq \frac{1 + \rho}{1 - \rho} h_j(z) \quad (j = 1, 2),
\]
so (5) yields

\[(1 - \varepsilon) \frac{1 - \rho}{1 + \rho} h_1 - a \leq \frac{1 + \rho}{1 - \rho} h_2 + (8\rho + 1)^2 G_D \mu \quad \text{on } F_\rho.\]  

(7)

Condition (6) is known to ensure that the reduced function \(R_{P(\cdot, w)}^F\), where \(R_{P(\cdot, w)}^F = \inf \{v : v \text{ is positive and superharmonic on } \mathbb{D} \text{ and } v \geq u \text{ on } F_\rho\}\), coincides with \(P(\cdot, w)\) (see Corollary 7.4.6 in [1]). Since this condition holds \(\nu_1\)-almost everywhere on \(\mathbb{T}\), we have

\[R_{h_1}^F = \int R_{P(\cdot, w)}^F \, d\nu_1(w) = \int P(\cdot, w) \, d\nu_1(w) = h_1.\]

Also, \(h_1 \geq 1\), so \(\nu_1\) majorizes normalized arclength measure on \(\mathbb{T}\), and we similarly have \(R_1^F \equiv 1\). Hence, on taking reductions over \(F_\rho\), we see that the inequality in (7) extends to all of \(\mathbb{D}\). (Recall that \(a \leq 0\).) We can now let \(\rho \to 0^+\) and \(\varepsilon \to 0^+\) to see that \(\log |f| \leq a\) on \(\mathbb{D}\). It is now clear that (b) implies (a).

Next suppose that condition (b) of Theorem 1 fails. Then there exists \(w_0 \in \mathbb{T}\) such that

\[\sum_{m,n} 2^{-n} q_{m,n} < \infty, \quad \text{where } q_{m,n} = Q(2^n E_{m,n}, [P(z_{m,n}, w_0)]).\]  

(8)

For each \(m,n\) we can choose points \(\xi_{k,m,n}\) \((k = 1, \ldots, q_{m,n})\) such that

\[\sum_{k=1}^{q_{m,n}} \log \frac{2^{-n}}{|z - \xi_{k,m,n}|} \geq P(z_{m,n}, w_0) - 1 \quad (z \in E_{m,n}),\]  

(9)

and without loss of generality we can assume that \(\xi_{k,m,n}\) lies in the convex hull \(\text{conv}(S_{m,n})\) of \(S_{m,n}\). In view of (8), the Blaschke product

\[B(z) = \prod_{k,m,n} \frac{|\xi_{k,m,n}|}{\xi_{k,m,n}} \left(\frac{\xi_{k,m,n} - z}{1 - z \overline{\xi_{k,m,n}}}\right)\]

converges on \(\mathbb{D}\). There is an absolute constant \(c_2 > 0\) such that

\[G_D(z, \xi) \geq c_2 \log \frac{2^{-n}}{|\xi - z|} \quad (z, \xi \in \text{conv}(S_{m,n}))\]

for any pair \((m, n)\). For a given pair \((m_0, n_0)\) we thus have

\[- \log |B(z)| = \sum_{k,m,n} G_D(z, \xi_{k,m,n}) \geq \sum_{k=1}^{q_{m_0,n_0}} G_D(z, \xi_{k,m_0,n_0}) \]

\[\geq c_2 \sum_{k=1}^{q_{m_0,n_0}} \log \frac{2^{-n_0}}{|\xi_{k,m_0,n_0} - z|} \quad (z \in S_{m_0,n_0})\]
so, by (9),

\[ c_2 - \log |B(z)| \geq c_2 P(z_{m_0,n_0}, w_0) \geq \frac{c_2}{c_1} P(z, w_0) \quad (z \in E_{m_0,n_0}). \] (10)

Let

\[ f(z) = B(z) \exp \left( \frac{c_2}{c_1} \left( \frac{w_0 + z}{w_0 - z} \right) \right) \quad (z \in \mathbb{D}). \]

Then \( |f(z)| \leq (c_2/c_1)P(z, w_0) \), so \( f \in \mathcal{N} \), and certainly \( f \) is unbounded on \( \mathbb{D} \). However, \( |f| \leq e^{c_2} \) on \( E \), by (10). Hence condition (a) of Theorem 1 also fails.

References


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