

WANDERING MONTEL THEOREMS FOR HILBERT SPACE VALUED HOLOMORPHIC FUNCTIONS

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ABSTRACT. We prove that if $\{u^k\}$ is a sequence of holomorphic functions that takes values in an infinite dimensional Hilbert space \mathcal{H} , there are unitaries $\{U^k\}$ on \mathcal{H} so that $U^k u^k$ has a subsequence that converges locally uniformly. We also prove a non-commutative version of this result.

1. INTRODUCTION

1.1. Commutative theory. Let Ω be an open set in \mathbb{C}^d and assume that $\{u^k\}$ is a sequence in $\text{Hol}(\Omega)$, the algebra of holomorphic functions on Ω equipped with the topology of uniform convergence on compact subsets. The classical Montel Theorem asserts that if $\{u^k\}$ is locally uniformly bounded on Ω , then there exists a subsequence $\{u^{k_i}\}$ that converges in $\text{Hol}(\Omega)$.

It is well known that if \mathcal{X} is an infinite dimensional Banach space, then Montel's Theorem breaks down for $\text{Hol}_{\mathcal{X}}(\Omega)$, the space of \mathcal{X} -valued holomorphic functions; see e.g. [5, 14]. For example, if $\mathcal{X} = \ell^2$ and $\{f^k\}$ is a locally uniformly bounded sequence of holomorphic functions on Ω , then the sequence

$$\begin{pmatrix} f^1(\lambda) \\ 0 \\ 0 \\ \vdots \end{pmatrix}, \begin{pmatrix} 0 \\ f^2(\lambda) \\ 0 \\ \vdots \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ f^3(\lambda) \\ \vdots \end{pmatrix}, \dots$$

is a locally uniformly bounded sequence that will have a convergent subsequence only if there exists a subsequence $\{f^{k_i}\}$ that converges uniformly to 0 on Ω .

Observe that the problem in the example given above is that while for all $\lambda \in \Omega$, u^k converges weakly to 0, it needn't be the case that $u^k(\lambda)$ converges in norm for any $\lambda \in \Omega$. However, just as in the case of the classical proof of Montel's theorem that uses the Arzela-Ascoli Theorem, if one assumes that $\{u^k\}$ is well behaved pointwise on a large enough set, then one *can* conclude uniform convergence in norm on compact sets. For example, consider the following theorem by Arendt and Nikolski [5, Cor. 2.3].

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Theorem 1.1. *Let Ω be an open connected set in \mathbb{C} , and let u^k be a sequence in $\text{Hol}_X(\Omega)$ that is locally bounded. Assume that*

$$\Omega_0 := \{z \in \Omega : \{u^k(z) : k \in \mathbb{N}\} \text{ is relatively compact in } X\}$$

has an accumulation point in Ω . Then there exists a subsequence which converges to a holomorphic function uniformly on compact subsets of Ω .

Theorem 1.1 deals with the difficulty by making strong additional assumptions about the pointwise behavior of $\{u^k\}$, assumptions that may not hold in desirable applications. The central idea of this paper, for Hilbert space valued functions, is instead to use a sequence of unitaries to push (most of) the range of the functions into a finite dimensional space. Here is our first main result.

Theorem 1.2. *If Ω is an open set in \mathbb{C}^d , \mathcal{H} is a Hilbert space, and $\{u^k\}$ is a locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$, then there exists a sequence $\{U^k\}$ of unitary operators on \mathcal{H} such that $\{U^k u^k\}$ has a subsequence that converges in $\text{Hol}_{\mathcal{H}}(\Omega)$.*

We prove Theorem 1.2 in Section 2. In Sections 3 and 4 we consider versions for non-commutative functions. These functions have been extensively studied recently; see e.g. [4, 6, 8–13, 15, 17]. Before stating our results, we must spend a little time explaining some definitions.

1.2. Non-commutative theory. In commutative analysis, one studies holomorphic functions defined on domains in \mathbb{C}^d . In non-commutative analysis one studies holomorphic functions defined on domains in \mathbb{M}^d , the *d-dimensional nc universe*. For each n we let \mathbb{M}_n^d denote the set of d -tuples of $n \times n$ matrices. We then let

$$\mathbb{M}^d = \bigcup_{n=1}^{\infty} \mathbb{M}_n^d.$$

When E is a subset of \mathbb{M}^d , for each n , we adopt the notation

$$E_n = E \cap \mathbb{M}_n^d.$$

In non-commutative analysis one studies *graded* functions, i.e., functions f defined on subsets E of \mathbb{M}^d , that satisfy

$$(1.3) \quad \forall_n \quad \forall_{\lambda \in E_n} \quad f(\lambda) \in \mathbb{M}_n.$$

\mathbb{M}^d carries a topology, the so-called *finite topology*,¹ wherein a set Ω is deemed to be open precisely when

$$\forall_n \quad \Omega_n \text{ is open in } \mathbb{M}_n^d.$$

With this definition, note that a graded function $f : E \rightarrow \mathbb{M}^1$ is finitely continuous if and only if $f|_{E_n}$ is continuous for each n and also that a set $K \subseteq \mathbb{M}^d$ is finitely compact if and only if there exists n such that $E_m = \emptyset$ when $m > n$ and E_m is compact when $m \leq n$.

If Ω is finitely open in \mathbb{M}^d , then for each n , Ω_n can be identified with an open set in \mathbb{C}^{dn^2} in an obvious way. If, in addition, f is a graded function on Ω , then we say that f is *holomorphic on Ω* if for each n , $f|_{\Omega_n}$ is a holomorphic mapping of Ω_n into \mathbb{M}_n . We let $\text{Hol}(\Omega)$ denote the collection of graded holomorphic functions.

¹Subsequently, we shall consider other topologies as well.

It is also possible to consider \mathcal{H} -valued holomorphic functions in the non-commutative setting. One particularly concrete way to do this is to realize in the scalar case just considered that (1.3) is equivalent to asserting that

$$\forall_n \forall_{\lambda \in E_n} f(\lambda) \in \mathcal{B}(\mathbb{C}^n, \mathbb{C}^n).$$

We therefore replace the former definition (that f be graded) with the requirement that f be a *graded \mathcal{H} -valued function*, i.e., that

$$\forall_n \forall_{\lambda \in E_n} f(\lambda) \in \mathcal{B}(\mathbb{C}^n, \mathbb{C}^n \otimes \mathcal{H}).$$

Just as before, we declare a graded \mathcal{H} -valued function defined on a finitely open set Ω in \mathbb{M}^d to be holomorphic if for each n , $f|_{\Omega_n}$ is a holomorphic mapping of Ω_n into $\mathcal{B}(\mathbb{C}^n, \mathbb{C}^n \otimes \mathcal{H})$. We let $\text{Hol}_{\mathcal{H}}(\Omega)$ denote the collection of graded \mathcal{H} -valued functions and view $\text{Hol}_{\mathcal{H}}(\Omega)$ as a complete metric space endowed with the topology of uniform convergence on finitely compact subsets of Ω .

A special class of graded functions arise by formalizing certain algebraic properties of free polynomials. If $E \subseteq \mathbb{M}^d$ we say that E is an *nc-set* if E is closed with respect to direct sums. We define the class of *nc-functions* as follows.

Definition 1.4. Let \mathcal{H} be a Hilbert space, let E be an nc-set, and assume that f is a function defined on E . We say that f is an *\mathcal{H} -valued nc-function on E* if the following conditions hold.

(i) f is *\mathcal{H} -graded*, i.e.,

$$\forall_n \forall_{\lambda \in E \cap \mathbb{M}_n} f(\lambda) \in \mathcal{B}(\mathbb{C}^n, \mathbb{C}^n \otimes \mathcal{H}).$$

(ii) f *preserves direct sums*, i.e.,

$$\forall_{\lambda, \mu \in E} \lambda \oplus \mu \in E \implies f(\lambda \oplus \mu) = f(\lambda) \oplus f(\mu).$$

In this formula, if $\lambda \in E_m$ and $\mu \in E_m$, we identify $\mathbb{C}^m \oplus \mathbb{C}^n$ and \mathbb{C}^{m+n} and identify $(\mathbb{C}^m \otimes \mathcal{H}) \oplus (\mathbb{C}^n \otimes \mathcal{H})$ and $\mathbb{C}^{m+n} \otimes \mathcal{H}$.

(iii) f *preserves similarity*, i.e.,

$$f(S\lambda S^{-1}) = (S \otimes \text{id}_{\mathcal{H}})f(\lambda)S^{-1}$$

whenever $n \geq 1$, $S \in \mathbb{M}_n$ is invertible, and both λ and $S\lambda S^{-1}$ are in E_n .

When $f : E \rightarrow \mathbb{M}^1 \otimes \mathcal{H}$ is an nc-function and E is a finitely open nc-set condition (iii) above becomes very strong and yields the following proposition, which lies at the heart of nc analysis (see [10] or [13, Thm. 7.2]). We say a function f is bounded on E if $\sup_{\lambda \in E} \|f(\lambda)\| < \infty$.

Proposition 1.5. *Let Ω be a finitely open nc-set. If f is a bounded nc-function defined on Ω , then f is holomorphic on Ω .*

Proposition 1.5 suggests the following terminology. We say that a set $\Omega \subseteq \mathbb{M}^d$ is an *nc-domain* if Ω is a finitely open nc-set and we say that a topology τ on \mathbb{M}^d is an *nc-topology* if τ has a basis consisting of nc-domains. We then define special classes of functions in non-commuting variables as follows.

Definition 1.6. Let $\Omega \subseteq \mathbb{M}_n^d$, τ be an nc-topology, and assume that $f : \Omega \rightarrow \mathbb{M}^1 \otimes \mathcal{H}$ is an \mathcal{H} -valued function. We say that f is *τ -holomorphic* if f is a τ -locally bounded nc function on Ω .² We let $\text{Hol}_{\mathcal{H}}^{\tau}(\Omega)$ denote the collection of τ -holomorphic \mathcal{H} -valued functions defined on Ω .

²That is, f is an nc-function on Ω in the sense of Definition 1.4 and for each $\lambda \in \Omega$, there exists $B \subseteq \Omega$ such that $\lambda \in B \in \tau$ and $f|_B$ is bounded.

Evidently, Proposition 1.5 guarantees that if τ is an nc-topology and f is a τ -holomorphic function in the sense of Definition 1.6, then f is holomorphic, i.e.,

$$\text{Hol}_{\mathcal{H}}^{\tau}(\Omega) \subseteq \text{Hol}_{\mathcal{H}}^{\text{nc}}(\Omega) \subseteq \text{Hol}_{\mathcal{H}}(\Omega),$$

where $\text{Hol}_{\mathcal{H}}^{\text{nc}}(\Omega)$ denotes the set of functions in $\text{Hol}_{\mathcal{H}}(\Omega)$ that are nc.

We can now state our second main result, the non-commutative version of Theorem 1.2.

Theorem 1.7. *Assume that τ is an nc-topology, $\Omega \in \tau$, \mathcal{H} is a Hilbert space, and $\{u^k\}$ is a τ -locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}^{\tau}(\Omega)$. There exist $u \in \text{Hol}_{\mathcal{H}}^{\tau}(\Omega)$, a sequence $\{U^k\}$ of unitary operators on \mathcal{H} , and an increasing sequence of indices $\{k_l\}$ such that $(\text{id}_n \otimes U^{k_l}) u^{k_l} \rightarrow u$ in $\text{Hol}(\Omega)$.*

As an application of Theorem 1.7, in Section 5 we prove that the cones

$$\mathcal{P} = \{u(\mu)^* u(\lambda) : u \in \text{Hol}_{\mathcal{H}}(\Omega) \text{ for some Hilbert space } \mathcal{H}\}$$

and

$$\mathcal{C} = \left\{ \begin{array}{c} \text{id}_{\mathbb{C}^J} \\ \otimes \\ u(\mu)^* \end{array} \left(\text{id} - \begin{array}{c} \delta(\mu)^* \delta(\lambda) \\ \otimes \\ \text{id}_{\mathcal{H}} \end{array} \right) \begin{array}{c} \text{id}_{\mathbb{C}^J} \\ \otimes \\ u(\lambda) \end{array} : u \in \text{Hol}_{\mathcal{H}}(B_{\delta}) \text{ and } u \text{ is nc} \right\}$$

are closed. In this last formula, δ is a J -by- J matrix of free polynomials, and $B_{\delta} = \{x : \|\delta(x)\| < 1\}$ is a non-commutative polynomial polyhedron. (We adopt the convention of [16] and write the tensors vertically for legibility.)

Proving that the cones are closed is the key step in proving realization formulas for free holomorphic functions; see [1, 2, 7].

In Section 6 we show that the assumptions in Proposition 3.2 below can be weakened to just requiring convergence on a set of uniqueness, which yields a graded version of the Arendt-Nikolski theorem.

2. A MONTEL THEOREM FOR HILBERT SPACE VALUED HOLOMORPHIC FUNCTIONS

In this section we prove Theorem 1.2 from the introduction.

2.1. Notation and definitions. If Ω is an open set in \mathbb{C}^d and \mathcal{H} is a Hilbert space, we let $\text{Hol}_{\mathcal{H}}(\Omega)$ denote the space of holomorphic \mathcal{H} -valued functions on Ω . If $u \in \text{Hol}_{\mathcal{H}}(\Omega)$ and $E \subseteq \Omega$, we let

$$\|u\|_E = \sup_{\lambda \in E} \|u(\lambda)\|_{\mathcal{H}}.$$

If $\|u\|_{\Omega} < \infty$, then we say that u is *bounded on Ω* . If $\{u^k\}$ is a sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$, we say that $\{u^k\}$ is *uniformly bounded on Ω* if

$$\sup_k \|u^k\|_{\Omega} < \infty,$$

and we say that $\{u^k\}$ is *locally uniformly bounded on Ω* if for each $\lambda \in \Omega$ there exists a neighborhood B of λ such that $\{u^k\}$ is uniformly bounded on B . Recall that if such a neighborhood exists, then a Cauchy estimate implies that $\{u^k\}$ is *equicontinuous at λ* ; i.e., for each $\varepsilon > 0$ there exists a ball B_0 such that $\lambda \in B_0 \subseteq B$ and

$$\forall \mu \in B_0 \quad \forall k \quad \|u^k(\mu) - u^k(\lambda)\| < \varepsilon.$$

We equip $\text{Hol}_{\mathcal{H}}(\Omega)$ with the usual topology of *uniform convergence on compacta*. Thus, a sequence $\{u^k\}$ in $\text{Hol}_{\mathcal{H}}(\Omega)$ is *convergent* precisely when there is a function $u \in \text{Hol}_{\mathcal{H}}(\Omega)$ such that

$$\lim_{k \rightarrow \infty} \|u^k - u\|_E = 0$$

for every compact $E \subseteq \Omega$. We say that a sequence $\{u^k\}$ in $\text{Hol}_{\mathcal{H}}(\Omega)$ is a *Cauchy sequence* if for each compact $E \subseteq \Omega$, $\{u^k\}$ is *uniformly Cauchy on E*; i.e., for each $\varepsilon > 0$, there exists N such that

$$k, l \geq N \implies \|u^k - u^l\|_E < \varepsilon.$$

It is well known that $\text{Hol}_{\mathcal{H}}(\Omega)$ is *complete*; i.e., every Cauchy sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$ converges. The following result is proved in [5, Thm. 2.1]; we include a proof that easily generalizes to Proposition 3.2.

Proposition 2.1. *Assume that Ω is an open set in \mathbb{C}^d , $\{\lambda_i\}$ is a dense sequence in Ω , and \mathcal{H} is a Hilbert space. If $\{u^k\}$ is a sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$ that is locally uniformly bounded on Ω and for each fixed i , $\{u^k(\lambda_i)\}$ is a convergent sequence in \mathcal{H} , then $\{u^k\}$ is a convergent sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$.*

Proof. Fix a compact set $E \subseteq \Omega$ and $\varepsilon > 0$. Note that as $\{u^k\}$ is assumed to be locally uniformly bounded on Ω , $\{u^k\}$ is equicontinuous at each point of Ω . Hence, as E is compact, we may construct a finite collection $\{B_r : r = 1, \dots, m\}$ of open balls in \mathbb{C}^d such that

$$(2.2) \quad E \subseteq \bigcup_{r=1}^m B_r \subseteq \Omega$$

and

$$(2.3) \quad \forall_r \forall_{\mu_1, \mu_2 \in B_r} \forall_k \|u^k(\mu_1) - u^k(\mu_2)\| < \varepsilon/3.$$

As $\{\lambda_i\}$ is assumed dense in Ω ,

$$(2.4) \quad \forall_r \exists_{i_r} \lambda_{i_r} \in B_r.$$

Consequently, as for each fixed i we assume that $\{u^k(\lambda_i)\}$ is a convergent (and hence Cauchy) sequence in \mathcal{H} , there exists N such that

$$(2.5) \quad \forall_r k, j \geq N \implies \|u^k(\lambda_{i_r}) - u^j(\lambda_{i_r})\| < \varepsilon/3.$$

Now, fix $\lambda \in E$. Use (2.2) to choose r such that $\lambda \in B_r$. Use (2.4) to choose i_r such that $\lambda_{i_r} \in B_r$. As λ and λ_{i_r} are both in B_r , we see from (2.3) that

$$\forall_k \|u^k(\lambda) - u^k(\lambda_{i_r})\| < \varepsilon/3.$$

Hence, using (2.5), we have that if $k, j \geq N$, then

$$\begin{aligned} & \|u^k(\lambda) - u^j(\lambda)\| \\ & \leq \|u^k(\lambda) - u^k(\lambda_{i_r})\| + \|u^k(\lambda_{i_r}) - u^j(\lambda_{i_r})\| + \|u^j(\lambda_{i_r}) - u^j(\lambda)\| \\ & < \varepsilon. \end{aligned}$$

□

Since the concluding estimate in the previous paragraph holds for an arbitrary point $\lambda \in E$, $\{u^k\}$ is uniformly Cauchy on E . Since E is an arbitrary compact subset of Ω , $\{u^k\}$ is a Cauchy sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$. Therefore, $\{u^k\}$ converges in $\text{Hol}_{\mathcal{H}}(\Omega)$.

2.2. The proof of Theorem 1.2. Theorem 1.2 follows quickly from Proposition 2.1 and the following lemma.

Lemma 2.6 (Wandering Isometry Lemma). *Assume that Ω is an open set in \mathbb{C}^d , $\{\lambda_i\}$ is a sequence in Ω , and \mathcal{H} is a Hilbert space. If $\{u^k\}$ is a sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$ that is locally uniformly bounded on Ω , then there exists a subsequence $\{u^{k_l}\}$ and a sequence $\{V^l\}$ of unitary operators on \mathcal{H} such that for each fixed i , $\{V^l u^{k_l}(\lambda_i)\}$ is a convergent sequence in \mathcal{H} .*

Proof. If \mathcal{H} is finite dimensional, one can let each unitary be the identity, and the result is the regular Montel theorem. So we shall assume that \mathcal{H} is infinite dimensional. Let $\{e_i\}$ be an orthonormal basis for \mathcal{H} . For each fixed k let

$$\mathcal{H}^k = \text{span} \{e_1, e_2, \dots, e_k\},$$

$$\mathcal{M}_i^k = \text{span} \{u^k(\lambda_1), u^k(\lambda_2), \dots, u^k(\lambda_i)\}, \quad i = 1, \dots, k.$$

For each k choose a unitary $U^k \in \mathcal{B}(\mathcal{H})$ satisfying

$$U^k \mathcal{M}_i^k \subseteq \mathcal{H}^i, \quad i = 1, \dots, k.$$

Observe that with this construction, for each fixed i ,

$$\{U^k u^k(\lambda_i)\}_{k=i}^{\infty}$$

is a bounded sequence in \mathcal{H}^i , a finite dimensional Hilbert space. Therefore, there exist $v_i \in \mathcal{H}$ and an increasing sequence of indices $\{k_l\}$ such that

$$U^{k_l} u^{k_l}(\lambda_i) \rightarrow v_i \quad \text{in } \mathcal{H} \quad \text{as } l \rightarrow \infty.$$

Applying this fact successively with $i = 1, i = 2$, and so on, at each stage taking a subsequence of the previously selected subsequence, leads to a sequence $\{v_i\}$ in \mathcal{H} and an increasing sequence of indices $\{k_l\}$ such that

$$U^{k_l} u^{k_l}(\lambda_i) \rightarrow v_i \quad \text{in } \mathcal{H} \quad \text{as } l \rightarrow \infty$$

for all i . The lemma then follows if we let $V^l = U^{k_l}$. □

Proof of Theorem 1.2. Assume that Ω is an open set in \mathbb{C}^d , \mathcal{H} is a Hilbert space, and $\{u^k\}$ is a locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$. The theorem follows from the classical Montel theorem (with $U^k = \text{id}_{\mathcal{H}}$ for all k) if $\dim \mathcal{H} < \infty$. Therefore, we may assume that $\dim \mathcal{H} = \infty$.

Fix a dense sequence $\{\lambda_i\}$ in Ω . By Lemma 2.6, there exists a subsequence $\{u^{k_l}\}$ and a sequence $\{V^l\}$ of unitary operators on \mathcal{H} such that for each fixed i , $\{V^l u^{k_l}(\lambda_i)\}$ is a convergent sequence in \mathcal{H} . Furthermore, as $\{u^k\}$ is locally uniformly bounded, so also $\{V^l u^{k_l}\}$ is locally uniformly bounded. Therefore, Proposition 2.1 implies that $\{V^l u^{k_l}\}$ is a convergent sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$. The theorem then follows by choosing $\{U^k\}$ to be any sequence of unitaries in $\mathcal{B}(\mathcal{H})$ such that $U^{k_l} = V^l$ for all l . □

3. HOLOMORPHIC FUNCTIONS IN NON-COMMUTING VARIABLES

If Ω is finitely open in \mathbb{M}^d , we may construct a *finitely compact-open exhaustion* of Ω , i.e., an increasing sequence of compact sets $\{K_i\}$ that satisfy

$$K_1 \subset \text{int}(K_2) \subset K_2 \subset \text{int}(K_3) \subset \dots$$

and with $\Omega = \bigcup_i K_i$. For a set $E \subseteq \Omega$ and $f \in \text{Hol}(\Omega)$ we let

$$\|f\|_E = \sup_{\lambda \in E} \|f(\lambda)\|$$

and then in the usual way define a metric d on $\text{Hol}(\Omega)$ with the formula

$$d(f, g) = \sum_{n=1}^{\infty} \frac{1}{2^n} \frac{\|f - g\|_{K_n}}{1 + \|f - g\|_{K_n}}.$$

It then follows that $f_k \rightarrow f$ in the metric space (Ω, d) if and only if for each finitely compact set K in Ω , $\{f_k\}$ converges uniformly to f on K , i.e.,

$$\lim_{k \rightarrow \infty} \|f - f_k\|_K = 0.$$

Furthermore, $\text{Hol}(\Omega)$ is a complete metric space when endowed with this topology of uniform convergence on finitely compact subsets of Ω .

It is a straightforward exercise to extend Montel’s theorem to the space $\text{Hol}_{\mathcal{H}}(\Omega)$ when $\dim \mathcal{H}$ is finite.

Proposition 3.1. *If Ω is a finitely open set in \mathbb{M}^d , \mathcal{H} is a Hilbert space with $\dim \mathcal{H} < \infty$, and $\{u^k\}$ is a finitely locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$, then $\{u^k\}$ has a convergent subsequence.*

Also, with the setup we have just described, mere notational changes to the proof of Proposition 2.1 yield a proof of the following proposition.

Proposition 3.2. *Assume that Ω is a finitely open set in \mathbb{M}^d , $\{\lambda_i\}$ is a dense sequence in Ω with $\lambda_i \in \mathbb{M}_{n_i}^d$ for each i , and \mathcal{H} is a Hilbert space. If $\{u^k\}$ is a sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$ that is finitely locally uniformly bounded on Ω and for each fixed i , $\{u^k(\lambda_i)\}$ is a convergent sequence in $\mathcal{B}(\mathbb{C}^{n_i}, \mathbb{C}^{n_i} \otimes \mathcal{H})$, then $\{u^k\}$ is a convergent sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$.*

Just as was the case for Proposition 2.1 in [5], it is possible to relax the assumption in Proposition 3.2 that $\{\lambda_i\}$ be a dense sequence in Ω to the assumption that $\{\lambda_i\}$ merely be a set of uniqueness for $\text{Hol}_{\mathcal{H}}(\Omega)$ (see Proposition 6.2).

We now turn to an analog of Theorem 1.2 in the non-commutative setting.

Lemma 3.3 (Wandering Isometry Lemma (non-commutative case)). *Assume that Ω is a finitely open set in \mathbb{M}^d and $\{\lambda_i\}$ is a sequence in Ω (where, for each i , $\lambda_i \in \mathbb{M}_{n_i}^d$). If \mathcal{H} is an infinite dimensional Hilbert space and $\{u^k\}$ is a sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$ with the property that $\{u^k(\lambda_i)\}$ is bounded for each i , then there exists a subsequence $\{u^{k_i}\}$ and a sequence $\{V^l\}$ of unitary operators on \mathcal{H} such that for each fixed i , $\{(\text{id}_{n_i} \otimes V^l) u^{k_i}(\lambda_i)\}$ is a convergent sequence in $\mathcal{B}(\mathbb{C}^{n_i}, \mathbb{C}^{n_i} \otimes \mathcal{H})$.*

Proof. Choose an increasing sequence $\{\mathcal{H}_i\}$ of subspaces of \mathcal{H} with the property that

$$\dim \mathcal{H}_1 = n_1^2 \quad \text{and} \quad \forall_{i \geq 1} \dim(\mathcal{H}_{i+1} \ominus \mathcal{H}_i) = n_{i+1}^2,$$

and for each n , let $\{e_1, \dots, e_n\}$ denote the standard basis of \mathbb{C}^n .

Fix k . For each $i = 1, \dots, k$, as $u^k(\lambda_i) : \mathbb{C}^{n_i} \rightarrow \mathbb{C}^{n_i} \otimes \mathcal{H}$, there exist n_i^2 vectors $x_{r,s}^{k,i} \in \mathcal{H}$, $r, s = 1, \dots, n_i$, such that

$$(3.4) \quad u^k(\lambda_i)e_r = \sum_{s=1}^{n_i} e_s \otimes x_{r,s}^{k,i}, \quad r = 1, \dots, n_i.$$

For each $i = 1, \dots, k$, define \mathcal{M}_i^k by

$$\mathcal{M}_i^k = \text{span} \{x_{r,s}^{k,i} : r, s = 1, \dots, n_i\}$$

and then define a sequence of spaces $\{\mathcal{N}_i^k\}$ by setting $\mathcal{N}_1^k = \mathcal{M}_1^k$ and

$$\mathcal{N}_i^k = (\mathcal{M}_1^k + \mathcal{M}_2^k + \dots + \mathcal{M}_i^k) \ominus (\mathcal{M}_1^k + \mathcal{M}_2^k + \dots + \mathcal{M}_{i-1}^k),$$

for $i = 2, \dots, k$. As for each $i = 1, \dots, k$, $\dim \mathcal{M}_i^k \leq n_i^2$, so also for $i = 1, \dots, k$, $\dim \mathcal{N}_i^k \leq n_i^2$. Consequently, as the spaces $\{\mathcal{N}_i^k\}$ are also pairwise orthogonal, it follows that there exists a unitary $U^k \in \mathcal{B}(\mathcal{H})$ such that

$$U^k(\mathcal{N}_1^k) \subseteq \mathcal{H}_1 \quad \text{and} \quad U^k(\mathcal{N}_i^k) \subseteq \mathcal{H}_i \ominus \mathcal{H}_{i-1} \quad \text{for } i = 2, \dots, k.$$

With this construction it follows using (3.4) that

$$(3.5) \quad (\text{id}_{n_i} \otimes U^k)u^k(\lambda_i)(\mathbb{C}^{n_i}) \subseteq \mathbb{C}^{n_i} \otimes \mathcal{H}_i, \quad i = 1, \dots, k.$$

Now observe that as (3.5) holds for each k , for each fixed i ,

$$(\text{id}_{n_i} \otimes U^k)u^k(\lambda_i)(\mathbb{C}^{n_i}) \subseteq \mathbb{C}^{n_i} \otimes \mathcal{H}_i, \quad k = i, i + 1, \dots;$$

i.e.,

$$\{(\text{id}_{n_i} \otimes U^k)u^k(\lambda_i)\}_{k=i}^\infty$$

is a bounded sequence in $\mathcal{B}(\mathbb{C}^{n_i}, \mathbb{C}^{n_i} \otimes \mathcal{H}_i)$, a finite dimensional Hilbert space. Therefore, for each fixed i , there exist $L \in \mathcal{H}$ and an increasing sequence of indices $\{k_l\}$ such that

$$U^{k_l}u^{k_l}(\lambda_i) \rightarrow L \quad \text{in } \mathcal{B}(\mathbb{C}^{n_i}, \mathbb{C}^{n_i} \otimes \mathcal{H}_i) \quad \text{as } l \rightarrow \infty.$$

Applying this fact successively with $i = 1, i = 2$, and so on, at each stage taking a subsequence of the previously selected subsequence leads to a sequence $\{L_i\}$ with $L_i \in \mathcal{B}(\mathbb{C}^{n_i}, \mathbb{C}^{n_i} \otimes \mathcal{H}_i)$ for each i and an increasing sequence of indices $\{k_l\}$ such that

$$\forall_i U^{k_l}u^{k_l}(\lambda_i) \rightarrow L_i \quad \text{in } \mathcal{B}(\mathbb{C}^{n_i}, \mathbb{C}^{n_i} \otimes \mathcal{H}_i) \quad \text{as } l \rightarrow \infty.$$

The lemma then follows if we let $V^l = U^{k_l}$. □

Lemma 3.3 suggests the following notation. Let Ω be a finitely open set in \mathbb{M}^d and let \mathcal{H} be a Hilbert space. If U is a unitary acting on \mathcal{H} and $f \in \text{Hol}_{\mathcal{H}}(\Omega)$, then we may define $U * f \in \text{Hol}_{\mathcal{H}}(\Omega)$ by the formula

$$\forall_n (U * f)|\Omega_n = (\text{id}_n \otimes U)f|\Omega_n.$$

With this notation we may formulate a non-commutative analog of Theorem 1.2 in the non-commutative setting.

Theorem 3.6. *If Ω is a finitely open set in \mathbb{M}^d , \mathcal{H} is a Hilbert space, and $\{u^k\}$ is a finitely locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$, then there exists a sequence $\{U^k\}$ of unitary operators on \mathcal{H} such that $\{U^k * u^k\}$ has a convergent subsequence.*

Proof. Assume that Ω is an open set in \mathbb{M}^d , \mathcal{H} is a Hilbert space, and $\{u^k\}$ is a finitely locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$. If $\dim \mathcal{H} < \infty$, then the theorem follows from Proposition 3.1 if we choose $U^k = \text{id}_{\mathcal{H}}$ for all k . Therefore, we assume that $\dim \mathcal{H} = \infty$.

Fix a dense sequence $\{\lambda_i\}$ in Ω . By Lemma 3.3, there exists a subsequence $\{u^{k_i}\}$ and a sequence $\{V^l\}$ of unitary operators on \mathcal{H} such that for each fixed i , $\{V^l u^{k_i}(\lambda_i)\}$ is a convergent sequence in $\mathcal{B}(\mathbb{C}^{n_i}, \mathbb{C}^{n_i} \otimes \mathcal{H})$. Furthermore, as $\{u^k\}$ is locally uniformly bounded, so also $\{V^l u^{k_i}\}$ is locally uniformly bounded. Therefore, Proposition 2.1 implies that $\{V^l u^{k_i}\}$ is a convergent sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$. The theorem then follows by choosing $\{U^k\}$ to be any sequence of unitaries in $\mathcal{B}(\mathcal{H})$ such that $U^{k_i} = V^l$ for all l . \square

4. LOCALLY BOUNDED NC FUNCTIONS

Properties of τ -holomorphic functions can be very sensitive to the choice of nc-topology τ . For example, if τ is the *fat topology* studied in [3], then τ -holomorphic functions satisfy a version of the Implicit Function Theorem. On the other hand, if τ is the *free topology*, studied in [2], then τ -holomorphic functions satisfy the Oka-Weil Approximation Theorem. Remarkably, neither of these theorems holds for the other topology.

Also notice that if f is τ -holomorphic in the sense of Definition 1.6, then necessarily Ω , the domain of f , is an open set in the τ topology: for each $\lambda \in \Omega$ there exists $B_\lambda \subseteq \Omega$ such that $\lambda \in B_\lambda \in \tau$; hence, $\Omega = \bigcup_\lambda B_\lambda \in \tau$.

There are no such subtleties between the nc-topologies when it comes to understanding the implications of local boundedness.

Definition 4.1. Assume that τ is an nc-topology and $\Omega \in \tau$. If $\{u^k\}$ is a sequence in $\text{Hol}_{\mathcal{H}}^\tau(\Omega)$, we say that $\{u^k\}$ is τ -locally uniformly bounded on Ω if for each $\lambda \in \Omega$, there exists a τ -open $B \subseteq \Omega$ such that $\lambda \in B$ and

$$\sup_k \|u^k\|_B < \infty.$$

Lemma 4.2. Assume that τ is an nc-topology and $\Omega \in \tau$. Let $u \in \text{Hol}(\Omega)$ and let $\{u^k\}$ be a sequence in $\text{Hol}_{\mathcal{H}}^\tau(\Omega)$. If $\{u^k\}$ is τ -locally uniformly bounded on Ω and $u^k \rightarrow u$ in $\text{Hol}_{\mathcal{H}}(\Omega)$, then $u \in \text{Hol}_{\mathcal{H}}^\tau(\Omega)$.

Proof. Under the assumptions of the lemma, we need to prove the following two assertions:

$$(4.3) \quad u \text{ is an nc-function on } \Omega.$$

$$(4.4) \quad u \text{ is } \tau\text{-locally bounded on } \Omega.$$

To prove (4.3), note first that as $u \in \text{Hol}_{\mathcal{H}}(\Omega)$, condition (i) in Definition 1.4 holds. To verify condition (ii), assume that $\lambda, \mu, \lambda \oplus \mu \in \Omega$. Then, as $u^k \rightarrow u$ in $\text{Hol}_{\mathcal{H}}(\Omega)$ and $u^k \in \text{Hol}_{\mathcal{H}}^\tau$ for all k ,

$$\begin{aligned} u(\lambda \oplus \mu) &= \lim_{k \rightarrow \infty} u^k(\lambda \oplus \mu) \\ &= \lim_{k \rightarrow \infty} (u^k(\lambda) \oplus u^k(\mu)) \\ &= \lim_{k \rightarrow \infty} u^k(\lambda) \oplus \lim_{k \rightarrow \infty} u^k(\mu) \\ &= u(\lambda) \oplus u(\mu). \end{aligned}$$

Finally, note that if $n \geq 1$, $S \in \mathbb{M}_n$ is invertible, and both λ and $S\lambda S^{-1}$ are in Ω_n , then

$$\begin{aligned} u(S\lambda S^{-1}) &= \lim_{k \rightarrow \infty} u^k(S\lambda S^{-1}) \\ &= \lim_{k \rightarrow \infty} (S \otimes \text{id}_{\mathcal{H}}) u^k(\lambda) S^{-1} \\ &= (S \otimes \text{id}_{\mathcal{H}}) u(\lambda) S^{-1}, \end{aligned}$$

which proves condition (iii).

To prove (4.4), fix $\lambda \in \Omega$. As $\{u^k\}$ is τ -locally uniformly bounded on Ω , Definition 4.1 implies that there exist $B \subseteq \Omega$ and a constant ρ such that $\lambda \in B \in \tau$ and

$$\sup_k \|u^k\|_B \leq \rho.$$

Fix $\mu \in B$. As we assume that $u^k \rightarrow u$ in $\text{Hol}_{\mathcal{H}}(\Omega)$, it follows that

$$\|u(\mu)\| = \lim_{k \rightarrow \infty} \|u^k(\mu)\| \leq \rho.$$

But then,

$$\|u\|_B \leq \rho.$$

As $B \in \tau$, this proves that u is τ -locally bounded on Ω . □

Definition 4.1 and Lemma 4.2 allow one to easily deduce Theorem 1.7 as a corollary of Theorem 3.6.

Proof of Theorem 1.7. As we assume that $\{u^k\}$ is a τ -locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}^{\tau}(\Omega)$, $\{u^k\}$ is finitely locally uniformly bounded in $\text{Hol}_{\mathcal{H}}(\Omega)$. Therefore, Theorem 3.6 implies that there exists a sequence $\{U^k\}$ of unitary operators on \mathcal{H} such that $\{U^k * u^k\}$ has a subsequence that converges in $\text{Hol}_{\mathcal{H}}(\Omega)$. Consequently, we may choose $u \in \text{Hol}_{\mathcal{H}}(\Omega)$ and an increasing sequence of indices $\{k_l\}$ such that $U^{k_l} * u^{k_l} \rightarrow u$ in $\text{Hol}(\Omega)$. The proof is completed by observing that Lemma 4.2 implies that $u \in \text{Hol}_{\mathcal{H}}^{\tau}(\Omega)$. □

Let us emphasize that Theorem 1.7 asserts that $U^{k_l} * u^{k_l}$ converges to u , which is in $\text{Hol}_{\mathcal{H}}^{\tau}(\Omega)$, uniformly on sets that are compact in the finite topology; it does not say that it converges uniformly on compact sets in the τ topology.

Note that the proofs of Lemma 4.2 and Theorem 1.7 work identically if u^k are just assumed to be in $\text{Hol}_{\mathcal{H}}^{\text{nc}}(\Omega)$, so we get

Theorem 4.5. *Let Ω be a finitely open set in \mathbb{M}^d , let \mathcal{H} be a Hilbert space, and let $\{u^k\}$ be a finitely locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}^{\text{nc}}(\Omega)$. Then there exists a sequence $\{U^k\}$ of unitary operators on \mathcal{H} such that $\{U^k * u^k\}$ has a subsequence that converges finitely locally uniformly to an element of $\text{Hol}_{\mathcal{H}}^{\text{nc}}(\Omega)$.*

5. SOME APPLICATIONS

A useful construct in the study of τ -holomorphic functions is the *duality construction*. If Ω is a finitely open set it is natural to consider the algebraic tensor product $\text{Hol}(\Omega)^* \otimes \text{Hol}(\Omega)$. This space can concretely be realized as the set of functions A defined on

$$\Omega \boxtimes \Omega = \bigcup_{n=1}^{\infty} (\Omega \cap \mathbb{M}_n^d) \times (\Omega \cap \mathbb{M}_n^d)$$

and such that there exist a finite dimensional Hilbert space \mathcal{H} and $u, v \in \text{Hol}_{\mathcal{H}}(\Omega)$ such that

$$A(\lambda, \mu) = v(\mu)^*u(\lambda), \quad (\lambda, \mu) \in \Omega \boxtimes \Omega.$$

As the functions in $\text{Hol}(\Omega)^* \otimes \text{Hol}(\Omega)$ are holomorphic in λ for each fixed μ and anti-holomorphic in μ for each fixed λ , we may complete $\text{Hol}(\Omega)^* \otimes \text{Hol}(\Omega)$ in the topology of uniform convergence on finitely compact subsets of $\Omega \boxtimes \Omega$ to obtain the space of *hereditary holomorphic functions on Ω* , $\text{Her}(\Omega)$. Inside $\text{Her}(\Omega)$, we may define a cone \mathcal{P} by

$$\mathcal{P} = \{u(\mu)^*u(\lambda) : u \in \text{Hol}_{\mathcal{H}}(\Omega) \text{ for some Hilbert space } \mathcal{H}\}.$$

Theorem 5.1. \mathcal{P} is closed in $\text{Her}(\Omega)$.

Proof. Assume that $\{v^k\}$ is a sequence with $v^k \in \text{Hol}_{\mathcal{H}_k}(\Omega)$ for each k and with $v^k(\mu)^*v^k(\lambda) \rightarrow A$ in $\text{Her}(\Omega)$. We may assume that \mathcal{H}_k is separable for each k . Fix a separable infinite dimensional Hilbert space \mathcal{H} and for each k choose an isometry $V^k : \mathcal{H}_k \rightarrow \mathcal{H}$. If for each k we let $u^k = V^k * v^k$, then $\{u^k\}$ is a sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$ and $u^k(\mu)^*u^k(\lambda) \rightarrow A$ in $\text{Her}(\Omega)$.

Now, as $u^k(\mu)^*u^k(\lambda) \rightarrow A$ in $\text{Her}(\Omega)$ it follows that $\{u^k\}$ is a finitely locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$. Hence, by Theorem 3.6, there exists a sequence U^k of unitary operators on \mathcal{H} such that $\{U^k * u^k\}$ has a convergent subsequence; i.e., there exists $u \in \text{Hol}_{\mathcal{H}}(\Omega)$ and an increasing sequence of indices $\{k_l\}$ such that $U^{k_l} * u^{k_l} \rightarrow u$. But then, for each $(\lambda, \mu) \in \Omega \boxtimes \Omega$,

$$\begin{aligned} A(\lambda, \mu) &= \lim_{k \rightarrow \infty} u^k(\mu)^*u^k(\lambda) \\ &= \lim_{l \rightarrow \infty} u^{k_l}(\mu)^*u^{k_l}(\lambda) \\ &= \lim_{l \rightarrow \infty} (U^{k_l} * u^{k_l})(\mu)^*(U^{k_l} * u^{k_l})(\lambda) \\ &= u(\mu)^*u(\lambda), \end{aligned}$$

i.e., $A \in \mathcal{P}$. □

We also may use wandering Montel theorems to study sums of τ -holomorphic dyads. We let $\text{Her}^{\tau}(\Omega)$ denote the closure of

$$\{v(\mu)^*u(\lambda) : u, v \in \text{Hol}_{\mathcal{H}}^{\tau}(\Omega) \text{ for some finite dimensional Hilbert space } \mathcal{H}\}$$

inside $\text{Her}(\Omega)$ and define \mathcal{P}^{τ} in $\text{Her}^{\tau}(\Omega)$ by

$$\mathcal{P}^{\tau} = \{u(\mu)^*u(\lambda) : u \in \text{Hol}_{\mathcal{H}}^{\tau}(\Omega) \text{ for some Hilbert space } \mathcal{H}\}.$$

Theorem 5.2. Let τ be an nc-topology, and let $\Omega \in \tau$. Then \mathcal{P}^{τ} is closed in $\text{Her}^{\tau}(\Omega)$.

Proof. Assume that $u^k(\mu)^*u^k(\lambda) \rightarrow A$ in $\text{Her}(\Omega)$, where, as in the proof of Theorem 5.1, we may assume that $u^k \in \text{Hol}_{\mathcal{H}}^{\tau}(\Omega)$ for each k . By Theorem 1.7, there exist $u \in \text{Hol}_{\mathcal{H}}^{\tau}(\Omega)$, a sequence U^k of unitary operators on \mathcal{H} , and an increasing sequence of indices $\{k_l\}$ such that $U^{k_l} * u^{k_l} \rightarrow u$. But then as in the proof of Theorem 5.1, $A(\lambda, \mu) = u(\mu)^*u(\lambda)$ for all $(\lambda, \mu) \in \Omega \boxtimes \Omega$, i.e., $A \in \mathcal{P}^{\tau}$. □

Finally, we shall prove that the model cone is closed; this is the key ingredient in the proof of the realization formula for free holomorphic functions [1, 2, 7]. Let

δ be a J -by- L matrix whose entries are free polynomials in d variables. We define B_δ to be the polynomial polyhedron

$$B_\delta := \{x \in \mathbb{M}^d : \|\delta(x)\| < 1\}.$$

The free topology is the nc-topology generated by the sets B_δ , as δ ranges over all matrices of polynomials. The model cone \mathcal{C} is the set of hereditary functions on B_δ of the form

$$(5.3) \quad \mathcal{C} := \left\{ \begin{array}{c} \text{id}_{\mathbb{C}^J} \\ \otimes \\ u(\mu)^* \end{array} \left(\text{id} - \begin{array}{c} \delta(\mu)^* \delta(\lambda) \\ \otimes \\ \text{id}_{\mathcal{H}} \end{array} \right) \begin{array}{c} \text{id}_{\mathbb{C}^J} \\ \otimes \\ u(\lambda) \end{array} : u \in \text{Hol}_{\mathcal{H}}(B_\delta) \text{ and } u \text{ is nc,} \right. \\ \left. \text{for some Hilbert space } \mathcal{H} \right\}.$$

We write the tensors vertically just to enhance readability.

Theorem 5.4. *The model cone \mathcal{C} , defined in (5.3), is closed in $\text{Her}(B_\delta)$.*

Proof. Suppose u^k is a sequence of nc functions in $\text{Hol}_{\mathcal{H}}(B_\delta)$ (we may assume the space \mathcal{H} is the same for each u^k , as in the proof of Theorem 5.1), so that

$$(5.5) \quad \begin{array}{c} \text{id}_{\mathbb{C}^J} \\ \otimes \\ u^k(\mu)^* \end{array} \left(\text{id} - \begin{array}{c} \delta(\mu)^* \delta(\lambda) \\ \otimes \\ \text{id}_{\mathcal{H}} \end{array} \right) \begin{array}{c} \text{id}_{\mathbb{C}^J} \\ \otimes \\ u^k(\lambda) \end{array}$$

converges in $\text{Her}(B_\delta)$ to $A(\lambda, \mu)$. On any finitely compact set, $\|\delta(x)\|$ will be bounded by a constant that is strictly less than one. Since (5.5) converges uniformly on finitely compact subsets of $B_\delta \boxtimes B_\delta$, this means that u^k is a finitely locally uniformly bounded sequence. Therefore by Theorem 3.6, there exist unitaries U^k such that $U^k * u^k$ has a convergent subsequence which converges to some nc function $u \in \text{Hol}_{\mathcal{H}}(B_\delta)$. Then

$$A(\lambda, \mu) = \begin{array}{c} \text{id}_{\mathbb{C}^J} \\ \otimes \\ u(\mu)^* \end{array} \left(\text{id} - \begin{array}{c} \delta(\mu)^* \delta(\lambda) \\ \otimes \\ \text{id}_{\mathcal{H}} \end{array} \right) \begin{array}{c} \text{id}_{\mathbb{C}^J} \\ \otimes \\ u(\lambda) \end{array},$$

as desired. □

6. SETS OF UNIQUENESS

In this section we shall show that the assumption in Propositions 2.1 and 3.2 that $\{\lambda_i\}$ is a dense sequence in Ω can be relaxed to the assumption that $\{\lambda_i\}$ is a set of uniqueness for $\text{Hol}(\Omega)$. We remark that it is an elementary fact that if \mathcal{H} is a Hilbert space, then $\{\lambda_i\}$ is a set of uniqueness for $\text{Hol}_{\mathcal{H}}(\Omega)$ if and only if $\{\lambda_i\}$ is a set of uniqueness for $\text{Hol}(\Omega)$.

The following proposition is essentially the same as the Arendt-Nikolski Theorem 1.1, so we shall omit the proof.

Proposition 6.1. *Assume that Ω is an open set in \mathbb{C}^d , $\{\lambda_i\}$ is a sequence in Ω that is a set of uniqueness for $\text{Hol}_{\mathcal{H}}(\Omega)$,³ and \mathcal{H} is a Hilbert space. If $\{u^k\}$ is a sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$ that is locally uniformly bounded on Ω and for each fixed i , $\{u^k(\lambda_i)\}$ is a convergent sequence in \mathcal{H} , then $\{u^k\}$ converges in $\text{Hol}_{\mathcal{H}}(\Omega)$.*

Here is the graded version.

Proposition 6.2. *Assume that Ω is a finitely open set in \mathbb{M}^d , $\{\lambda_i\}$ is a sequence in Ω (with $\lambda_i \in \mathbb{M}_{n_i}^d$ for each i) that is a set of uniqueness for $\text{Hol}_{\mathcal{H}}(\Omega)$, and \mathcal{H} is a Hilbert space. If $\{u^k\}$ is a sequence in $\text{Hol}_{\mathcal{H}}(\Omega)$ that is finitely locally uniformly*

³That is, if $f \in \text{Hol}(\Omega)$ and $f(\lambda_i) = 0$ for all i , then $f(\lambda) = 0$ for all $\lambda \in \Omega$.

bounded on Ω and for each fixed i , $\{u^k(\lambda_i)\}$ is a convergent sequence in \mathcal{H} , then $\{u^k\}$ converges in $\text{Hol}_{\mathcal{H}}(\Omega)$.

Proof. The theorem will follow if we can show that $\{u^k|\Omega_n\}$ is a convergent sequence for each n . Accordingly, fix n and adopt the notation H_n for the holomorphic $\mathcal{B}(\mathbb{C}^n, \mathbb{C}^n \otimes \mathcal{H})$ -valued functions defined on Ω_n . Thus, $\{u^k|\Omega_n\}$ is a locally uniformly bounded sequence in H_n . Furthermore, if $\{\eta_j\}$ is an enumeration of $\{\lambda_i : i \geq 1\} \cap \Omega_n$, as $\{\lambda_i\}$ is a set of uniqueness for $\text{Hol}(\Omega)$, $\{\eta_i\}$ is a set of uniqueness for both $\text{Hol}(\Omega_n)$ and H_n . Finally, let $u^k(\eta_j) \rightarrow u_j$ as $k \rightarrow \infty$ for each j .

For fixed $\alpha \in \mathbb{C}^n$ and $\beta \in \mathbb{C}^n$, define $f_{\alpha,\beta}^k \in \text{Hol}(\Omega_n)$ by

$$(6.3) \quad f_{\alpha,\beta}^k(\lambda) = \langle u^k(\lambda)\alpha, \beta \rangle_{\mathbb{C}^n \otimes \mathcal{H}}, \quad \lambda \in \Omega.$$

Noting that

$$(6.4) \quad |f_{\alpha,\beta}^k(\lambda)| = |\langle u^k(\lambda)\alpha, \beta \rangle| \leq \|u^k(\lambda)\| \|\alpha\| \|\beta\|,$$

it follows that $\{f_{\alpha,\beta}^k\}$ is locally uniformly bounded on Ω_n . Therefore by Montel's theorem, $\{f_{\alpha,\beta}^k\}$ has compact closure in $\text{Hol}(\Omega_n)$.

We claim that $\{f_{\alpha,\beta}^k\}$ has a unique cluster point, for assume that $\{f_{\alpha,\beta}^{k_r}\}$ and $\{f_{\alpha,\beta}^{k_s}\}$ are subsequences of $\{f_{\alpha,\beta}^k\}$ with $\{f_{\alpha,\beta}^{k_r}\} \rightarrow f$ and $\{f_{\alpha,\beta}^{k_s}\} \rightarrow g$. Then, as we assume for each j , $u^k(\eta_j) \rightarrow u_j$ as $k \rightarrow \infty$,

$$\begin{aligned} f(\eta_i) &= \lim_{r \rightarrow \infty} f_{\alpha,\beta}^{k_r}(\eta_i) \\ &= \lim_{r \rightarrow \infty} \langle u^{k_r}(\eta_i)\alpha, \beta \rangle \\ &= \langle u_i\alpha, \beta \rangle \\ &= \lim_{s \rightarrow \infty} \langle u^{k_s}(\eta_i)\alpha, \beta \rangle \\ &= \lim_{s \rightarrow \infty} f_{\alpha,\beta}^{k_s}(\eta_i) \\ &= g(\eta_i). \end{aligned}$$

Hence, as $\{\eta_i\}$ is a set of uniqueness, $f = g$. Since $\{f_{\alpha,\beta}^k\}$ has a unique cluster point, we have shown that for each $\alpha \in \mathbb{C}^n$ and $\beta \in \mathbb{C}^n \otimes \mathcal{H}$, there exists $f_{\alpha,\beta} \in \text{Hol}(\Omega_n)$ such that

$$(6.5) \quad f_{\alpha,\beta}^k \rightarrow f_{\alpha,\beta} \text{ in } \text{Hol}(\Omega_n) \text{ as } k \rightarrow \infty.$$

Now fix $\lambda \in \Omega_n$ and define L_λ by

$$(6.6) \quad L_\lambda(\alpha, \beta) = f_{\alpha,\beta}(\lambda), \quad \alpha \in \mathbb{C}^n, \beta \in \mathbb{C}^n \otimes \mathcal{H}.$$

Observe that (6.3) and (6.5) imply that L_λ is a sesquilinear functional on $\mathbb{C}^n \times (\mathbb{C}^n \otimes \mathcal{H})$. Furthermore, (6.4) and (6.5) imply that L_λ is bounded. Therefore, by the Riesz Representation Theorem, there exists $u(\lambda) \in \mathcal{B}(\mathbb{C}^n, \mathbb{C}^n \otimes \mathcal{H})$ such that

$$\forall \alpha \in \mathbb{C}^n \quad \forall \beta \in \mathbb{C}^n \otimes \mathcal{H} \quad L_\lambda(\alpha, \beta) = \langle u(\lambda)\alpha, \beta \rangle$$

or, equivalently,

$$\forall \alpha \in \mathbb{C}^n \quad \forall \beta \in \mathbb{C}^n \otimes \mathcal{H} \quad \langle u(\lambda)\alpha, \beta \rangle = f_{\alpha,\beta}(\lambda).$$

The function u constructed in the previous paragraph has the following properties: it is holomorphic,

$$(6.7) \quad \forall \lambda \in \Omega_n \quad u^k(\lambda) \rightarrow u(\lambda) \text{ weakly in } \mathcal{B}(\mathbb{C}^n, \mathbb{C}^n \otimes \mathcal{H}) \text{ as } k \rightarrow \infty,$$

and

$$(6.8) \quad \forall_j \ u^k(\eta_j) \rightarrow u(\eta_j) \text{ in norm in } \mathcal{B}(\mathbb{C}^n, \mathbb{C}^n \otimes \mathcal{H}) \text{ as } k \rightarrow \infty.$$

Claim 6.9. Let

$$u^k(\mu)^* u^k(\lambda) \rightarrow u(\mu)^* u(\lambda) \text{ in } \text{Her}(\Omega_n) \text{ as } k \rightarrow \infty.$$

To prove this claim, first note that as we are assuming $\{u^k\}$ is a locally uniformly bounded sequence in $\text{Hol}_{\mathcal{H}}(\Omega_n)$, $\{u^k(\mu)^* u^k(\lambda)\}$ is a locally uniformly bounded sequence in $\text{Her}(\Omega_n)$. Therefore, the claim follows from Montel's theorem if we can show that

$$(6.10) \quad A(\lambda, \mu) = u(\mu)^* u(\lambda)$$

whenever $\{k_r\}$ is a sequence of indices such that

$$(6.11) \quad u^{k_r}(\mu)^* u^{k_r}(\lambda) \rightarrow A(\lambda, \mu) \text{ in } \text{Her}(\Omega_n) \text{ as } r \rightarrow \infty.$$

But if (6.11) holds, then (6.8) implies that for each independently chosen i and j ,

$$A(\eta_j, \eta_i) = \lim_{r \rightarrow \infty} u^{k_r}(\eta_i)^* u^{k_r}(\eta_j) = u^{k_r}(\eta_i)^* u^{k_r}(\eta_j).$$

Since both sides of (6.10) are holomorphic in λ and anti-holomorphic in μ and $\{\eta_i\}$ is a set of uniqueness, it follows that (6.10) holds for all $\lambda, \mu \in \Omega$. This completes the proof of Claim 6.9.

Finally, fix $\lambda \in \Omega$. By (6.7), $\{u^k(\lambda)\}$ converges weakly in $\mathcal{B}(\mathbb{C}^n, \mathbb{C}^n \otimes \mathcal{H})$ to $u(\lambda)$, and by Claim 6.9, $u^k(\lambda)^* u^k(\lambda) \rightarrow u(\lambda)^* u(\lambda)$. Therefore, $u^k(\lambda) \rightarrow u(\lambda)$ is norm in $\mathcal{B}(\mathbb{C}^n, \mathbb{C}^n \otimes \mathcal{H})$. Since this holds for all $\lambda \in \Omega$, the proof of Proposition 6.2 may be completed by an application of Proposition 3.2. \square

REFERENCES

- [1] J. Agler and J. E. McCarthy, *Global holomorphic functions in several non-commuting variables II*, Canadian Math. Bull., to appear, arXiv:1706.09973.
- [2] Jim Agler and John E. McCarthy, *Global holomorphic functions in several noncommuting variables*, Canad. J. Math. **67** (2015), no. 2, 241–285. MR3314834
- [3] Jim Agler and John E. McCarthy, *The implicit function theorem and free algebraic sets*, Trans. Amer. Math. Soc. **368** (2016), no. 5, 3157–3175. MR3451873
- [4] D. Alpay and D. S. Kalyuzhnyi-Verbovetzkiĭ, *Matrix- J -unitary non-commutative rational formal power series*, The state space method generalizations and applications, Oper. Theory Adv. Appl., vol. 161, Birkhäuser, Basel, 2006, pp. 49–113. MR2187742
- [5] W. Arendt and N. Nikolski, *Vector-valued holomorphic functions revisited*, Math. Z. **234** (2000), no. 4, 777–805. MR1778409
- [6] Sriram Balasubramanian, *Toeplitz corona and the Douglas property for free functions*, J. Math. Anal. Appl. **428** (2015), no. 1, 1–11. MR3326973
- [7] J. A. Ball, G. Marx, and V. Vinnikov, *Interpolation and transfer function realization for the non-commutative Schur-Agler class*, to appear, arXiv:1602.00762.
- [8] Joseph A. Ball, Gilbert Groenewald, and Tanit Malakorn, *Conservative structured noncommutative multidimensional linear systems*, The state space method generalizations and applications, Oper. Theory Adv. Appl., vol. 161, Birkhäuser, Basel, 2006, pp. 179–223. MR2187744
- [9] Joseph A. Ball, Gregory Marx, and Victor Vinnikov, *Noncommutative reproducing kernel Hilbert spaces*, J. Funct. Anal. **271** (2016), no. 7, 1844–1920. MR3535321
- [10] J. William Helton, Igor Klep, and Scott McCullough, *Proper analytic free maps*, J. Funct. Anal. **260** (2011), no. 5, 1476–1490. MR2749435
- [11] J. William Helton and Scott McCullough, *Every convex free basic semi-algebraic set has an LMI representation*, Ann. of Math. (2) **176** (2012), no. 2, 979–1013. MR2950768
- [12] J. William Helton, J. E. Pascoe, Ryan Tully-Doyle, and Victor Vinnikov, *Convex entire noncommutative functions are polynomials of degree two or less*, Integral Equations Operator Theory **86** (2016), no. 2, 151–163. MR3568011

- [13] Dmitry S. Kaliuzhnyi-Verbovetskyi and Victor Vinnikov, *Foundations of free noncommutative function theory*, Mathematical Surveys and Monographs, vol. 199, American Mathematical Society, Providence, RI, 2014. MR3244229
- [14] Kang-Tae Kim and Steven G. Krantz, *Normal families of holomorphic functions and mappings on a Banach space*, Expo. Math. **21** (2003), no. 3, 193–218. MR2006009
- [15] J. E. Pascoe, *The inverse function theorem and the Jacobian conjecture for free analysis*, Math. Z. **278** (2014), no. 3–4, 987–994. MR3278901
- [16] J. E. Pascoe and R. Tully-Doyle, *Free pick functions: representations, asymptotic behavior and matrix monotonicity in several noncommuting variables*, J. Funct. Anal. **273** (2017), no. 1, 283–328. MR3646301
- [17] Gelu Popescu, *Free holomorphic functions on the unit ball of $B(\mathcal{H})^n$* , J. Funct. Anal. **241** (2006), no. 1, 268–333. MR2264252

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