Traces on group $C^*$-algebras, sofic groups and Lück’s conjecture

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Abstract

We give an alternate proof of a Theorem of Elek and Szabo establishing Lück’s determinant conjecture for sofic groups. Our proof is based on traces on group $C^*$-algebras. We briefly discuss the relation with Atiyah’s problem on the integrality of $L^2$-Betti numbers.

Introduction

In [6], B. Fuglede and R.V. Kadison introduce a determinant function $\Delta : M \to \mathbb{R}_+$ where $M$ is a $\Pi_1$ factor, by setting $\Delta(x) = \exp(\tau(\ln |x|))$ (where $\tau$ is the trace of $M$). This function satisfies many of the usual properties of a determinant.

In connexion with many problems and conjectures concerning discrete groups, W. Lück (see [10]) introduced a modified determinant by setting $\Delta_+(x) = \exp(\tau(\ln_+ |x|))$ where $\ln_+(t) = 0$ if $t = 0$ and $\ln_+(t) = \ln t$ for $t > 0$. He conjectured that for any group $G$ and any $x \in M_n(\mathbb{Z}G)$ we have $\Delta_+(|x|) \geq 1$.

Lück’s determinant conjecture is related with many interesting problems (cf. [9,10]). In particular:

- Let us recall a problem stated first by Atiyah in the torsion free case, and extended by various authors (cf. [10,15,14] for more details): investigate the possible values of von Neumann dimensions of the kernels of elements in $M_n(\mathbb{Z}G)$. Validity of Lück’s conjecture ensures a kind of stability of the von Neumann dimension of the kernel of an element in $M_n(\mathbb{Z}G)$ and allows its computation in some cases.

- For CW complexes whose fundamental group satisfies this conjecture, one can define $L^2$ torsion ([10]). In [11], Lück, Sauer and Wegner prove that the $L^2$-torsion is invariant under uniform measure equivalence.

In [13,15], Schick shows that amenable groups satisfy Lück’s conjecture. He shows that the class of groups satisfying Lück’s conjecture is closed under taking subgroups, direct limits and inverse limits.
In [4], Elek and Szabo generalize Schick’s results by proving that sofic groups satisfy Lück’s conjecture. Sofic groups were introduced by Gromov [8] as a generalization of both amenable and profinite groups. In a sense, sofic groups are the groups that can be well approximated by finite groups, i.e. that can be almost embedded into permutation groups.

In this paper we give a reformulation of Lück’s conjecture in terms of traces on $C^*(F_\infty)$ and use it to reformulate the proof of [4] in a somewhat more conceptual way. We hope that it may help understanding the proofs of [13] and [4].

We say that a trace $\tau$ on $C^*(F_\infty)$ satisfies Lück’s condition if for all $f \in M_n(ZF_\infty)$, we have $\tau(ln(|f|)) \geq 0$. In this sense, a group $G$ satisfies Lück’s conjecture if and only if the trace $\tau_G \circ \pi$ satisfies Lück’s condition, where $\tau_G$ is the canonical trace on $G$ and $\pi$ a surjective morphism $F_\infty \rightarrow G$ (i.e. a generating system of $G$). It is then easily seen (a detailed account is given in the sequel) that:

**Fact 1.** (proposition 2.3) A permutational trace i.e. a trace of the form $tr \circ \sigma$ satisfies Lück’s condition where $\sigma$ is a finite dimensional representation of $F_\infty$ by permutation matrices and $tr$ is the normalized trace on matrices.

**Fact 2.** (proposition 2.6) The set of traces satisfying Lück’s condition is closed (for the weak topology).

**Fact 3.** (proposition 3.4) A group $G$ is sofic if and only if the associated trace $\tau_G \circ \pi$ as above is in the closure of permutational traces.

Moreover, we notice that the stability condition of the von Neumann dimension established in [13, 14] is a consequence of the following fact:

**Fact 4.** (proposition 4.1) For $a \in M_n(ZF_\infty)$, the map $\tau \mapsto \dim_r ker a$ is continuous on the set of traces satisfying Lück’s condition.

Finally, we extend this result to $a \in M_n(QF_\infty)$. We moreover prove that, for any trace of $C^*(F_\infty)$ in the closure of permutational traces, the dimension $\dim_r(ker a)$ does not depend on the embedding $\mathbb{Q} \subset \mathbb{C}$. We deduce the following formulation of a result of [3] to sofic groups which is proved by A. Thom in (the proof of) [16, Theorem 4.3].

**Fact 5** (corollary 4.6) Let $\Gamma$ be a sofic group and $a \in M_n(\mathbb{Q}\Gamma)$. The von Neumann dimension (with respect to the group trace of $\Gamma$) does not depend on the embedding $\mathbb{Q} \subset \mathbb{C}$.

This paper is organized as follows: In the first section, we fix notation and recall definitions of the determinant of Fuglede-Kadison and the modified determinant of Lück.

In the second section, we define Lück’s condition for a trace and establish facts 1 and 2 above.

In the third section we recall the definition of a sofic group and establish fact 3.

In section 4, we explain the relation with Atiyah’s problem and establish facts 4 and 5.

*All traces that we consider throughout the paper are positive finite traces.*
1 Positive traces and determinants

1.1 Traces and semi-continuous functions

Let \( A \) be a unital \( C^* \)-algebra. We endow the set \( \mathcal{T}_A \) of (finite positive) traces on \( A \) with the pointwise convergence.

Let \( \tau \in \mathcal{T}_A \) be a trace on \( A \) and \( a \) a self-adjoint element of \( A \), and \( \mu_{\tau,a} \) the corresponding spectral measure. If \( f : \text{Sp} \ a \to \mathbb{R} \cup \{+\infty\} \) is a lower semi-continuous function, we may write \( f = \sup f_n \) where \( f_n \) is an increasing sequence of continuous functions. Since \( f \) is bounded below, we may define \( \mu_{\tau,a}(f) = \sup \mu_{\tau,a}(f_n) = \sup \tau(f_n(a)) \). In the sequel, this “number” will be denoted by \( \tau(f(a)) \).

In the same way, we define \( \tau(f(a)) \in \mathbb{R} \cup \{-\infty\} \) for \( f : \text{Sp} \ a \to \mathbb{R} \cup \{-\infty\} \) upper semi-continuous.

We obviously have:

1.1 Proposition. If \( f : \text{Sp} \ a \to \mathbb{R} \cup \{+\infty\} \) is lower (resp. upper) semi-continuous, then the map \( \tau \mapsto \tau(f(a)) \) is lower (resp. upper) semi-continuous.

Proof. Assume \( f = \sup f_n \) is lower semi-continuous where \( (f_n) \) is an increasing sequence of continuous functions. Then \( \tau \mapsto \tau(f(a)) \) is the supremum of the continuous functions \( \tau \mapsto \tau(f_n(a)) \) and is therefore lower semi-continuous.

The upper semi-continuous case is obtained by replacing \( f \) by \(-f\).

1.2 Remark. Let \( \varphi : A \to B \) be a unital morphism of \( C^* \)-algebras and \( \tau \) a trace on \( B \). Then, for every self-adjoint element \( a \in A \) and every lower semi-continuous function \( f : \text{Sp} \ a \to \mathbb{R} \cup \{+\infty\} \), writing \( f = \sup f_n \) with continuous \( f_n \), we find \( f_n(\varphi(a)) = \varphi(f_n(a)) \); hence passing to the supremum, one gets \( \tau(f(\varphi(a))) = \tau \circ \varphi(f(a)) \).

The same equality holds of course for upper semi-continuous \( f \).

1.2 The Fluglede-Kadison determinant ([6])

The function \( \ln : \mathbb{R}_+ \to \mathbb{R} \cup \{-\infty\} \) is upper semi-continuous on \( \mathbb{R}_+ \).

Let \( A \) be a unital \( C^* \)-algebra and \( \tau \in \mathcal{T}_A \) a (finite, positive) trace on \( A \).

The Fuglede-Kadison determinant of \( x \in A \) is \( \Delta_\tau(x) = \exp(\tau(\ln(|x|))) \).

Recall from [6] that, for \( x,y \in A \), we have \( \Delta_\tau(xy) = \Delta_\tau(x)\Delta_\tau(y) \).
2.1 Definition. Let \( G \) condition if for \( 1 \). Suppose that \( \psi \) is a (discrete) group, we denote by \( \psi^* \) (counted with their multiplicity).

2.2 Proposition. Let \( G \) and \( H \) be groups and \( \psi : G \to H \) a group homomorphism. We still denote by \( \psi : C^*(G) \to C^*(H) \) its extension to group \( C^* \)-algebras. Let \( \tau \) be a trace on \( C^*(H) \).

1. If \( \tau \in \Lambda_H \) (i.e. \( \tau \) satisfies Lück’s condition), \( \tau \circ \psi \in \Lambda_G \).

2. If \( \psi \) is onto, the converse is true, i.e. if \( \tau \circ \psi \in \Lambda_G \), then \( \tau \in \Lambda_H \).

Proof. 1. Suppose that \( \tau \) satisfies Lück’s condition.

We denote by \( \psi : M_n(C^*(G)) \to M_n(C^*(H)) \) the extension of \( \psi \) to matrices. For all \( a \in M_n(\mathbb{Z}G) \), since \( \psi(a) \in M_n(\mathbb{Z}H) \), we have, by remark [1.2]

\[
(\tau \otimes \text{Tr}_n)(\psi(\ln_+ |a|)) = (\tau \otimes \text{Tr}_n)(\ln_+ |\psi(a)|) \geq 0.
\]
2. If $\psi$ is surjective, for all $a \in M_m(\mathbb{Z}H)$ there exists $b \in M_n(\mathbb{Z}G)$ such that $a = \psi(b)$. If $\tau \circ \psi$ satisfies Lück’s condition then $(\tau \otimes \text{Tr}_n)(\ln_+ (|a|)) = (\tau \otimes \text{Tr}_n) \circ \psi(\ln_+ (|b|)) \geq 0$. □

Let $\alpha_k : \mathcal{S}_k \to \mathcal{U}_k$ be the representation of the symmetric group $\mathcal{S}_k$ by permutation matrices. Denote also by $\alpha_k$ the associated morphism $C^*(\mathcal{S}_k) \to M_k(\mathbb{C})$. We denote by $\tau_k$ the trace on $C^*(\mathcal{S}_k)$ defined by $\tau_k(f) = \frac{1}{k} \text{Tr}_k(\alpha_k(f))$ for all $f \in C^*(\mathcal{S}_k)$, where $\text{Tr}_k$ is the unnormalized trace on $M_k(\mathbb{C})$.

Then, for $\sigma \in \mathcal{S}_k$, we have

$$\tau_k(\sigma) = \frac{\text{card} \{ x | \sigma(x) = x \}}{k}.$$  

2.3 Proposition. (cf. [10]) Let $n \in \mathbb{N}^*$. The trace $\tau_k$ on $\mathcal{S}_k$, satisfies Lück’s condition.

Proof. Let $\text{Tr}_{kn}$ be the unnormalized trace on $M_{kn}(\mathbb{Z})$. For $a \in M_m(\mathbb{Z} \mathcal{S}_k)$ we have

$$\tau_k \otimes \text{Tr}_n(a) = \frac{1}{k} \text{Tr}_{kn}(\alpha_k(a)).$$

Now, $\Delta_{\text{Tr}_{kn}}(\alpha_k(|a|))^2 = \exp(2k(\tau_k \otimes \text{Tr}_n)(\ln_+ (|a|)))$ is the product of non-zero eigenvalues of $\alpha_k(a^*a)$ (counted with multiplicity): it is the modulus of the non-zero coefficient of lowest degree of the characteristic polynomial of $\alpha_k(a^*a)$.

Since $\alpha_k(a^*a) \in M_{kn}(\mathbb{Z})$, it follows that its characteristic polynomial has integer coefficients so that $\Delta_{\text{Tr}_{kn}}(a^*a) \in \mathbb{N}^*$. □

2.4 Definition. We call permutational trace on a group $G$, a trace of the form $\tau_k \circ f$ where $f$ is a group morphism from $G$ to $\mathcal{S}_k$.

It follows from 2.2 and 2.3 that permutational traces satisfy Lück’s condition.

We will also use the following more general sets of traces.

2.5 Notation. Let $A$ be a unital $C^*$-algebra, $d \in \mathbb{N}$ and $a \in M_d(A)$. Let $s \in \mathbb{R}$. Denote by $\Lambda_{a,s} \subset \mathcal{T}_A$ the set of traces on $A$ such that $(\tau \otimes \text{Tr}_d)(\ln_+ (|a|)) \geq s$.

2.6 Proposition. 1. Let $A$ be a unital $C^*$-algebra, $d \in \mathbb{N}$ and $a \in M_d(A)$. Let $s \in \mathbb{R}$. The set $\Lambda_{a,s}$ is closed in $\mathcal{T}_A$ (for the pointwise topology on traces).

2. Let $G$ be a group. The set $\Lambda_G$ is closed in the set $\mathcal{T}_G$ of traces on $C^*(G)$ for the pointwise topology.

Proof. 1. Since $\ln_+$ is upper semi-continuous, the map $\tau \mapsto (\tau \otimes \text{Tr}_d)(\ln_+ |a|)$ is upper semi-continuous by prop. 1.1 therefore the set $\Lambda_{a,s}$ is closed.

2. The set $\Lambda_G$ is the intersection over all $k \in \mathbb{N}$ and $a \in M_d(\mathbb{Z}G)$ of the closed subsets $\Lambda_{a,0}$. It is closed. □

Note that the set $\Lambda_{a,s}$ only depends on the abelian $C^*$-subalgebra of $M_d(A)$ generated by $a^*a$ and that the prop. 2.6 can immediately be extended to all positive forms.

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3 Sofic groups and traces

Denote by $\delta_k$ the Hamming distance on $\mathfrak{S}_k$ defined by

$$\delta_k(\sigma_1, \sigma_2) = \frac{1}{k} \text{card} \{x \in \{1, \ldots, k\} | \sigma_1(x) \neq \sigma_2(x)\}$$

with $\sigma_1, \sigma_2 \in \mathfrak{S}_k$.

3.1 Remarks. 1. The distance $\delta_k$ is left and right-invariant, i.e. for $\alpha, \beta, \sigma_1, \sigma_2 \in \mathfrak{S}_k$, we have

$$\delta_k(\alpha \circ \sigma_1 \circ \beta, \alpha \circ \sigma_2 \circ \beta) = \delta_k(\sigma_1, \sigma_2).$$

2. For $\sigma \in \mathfrak{S}_k$, we have

$$\delta_k(\sigma, \text{Id}_k) = 1 - \tau_k(\sigma).$$

In particular, $\tau_k$ is 1-lipschitz for $\delta_k$.

Let $(k_n)_{n \in \mathbb{N}}$ be a sequence of integers. Put

$$\bigoplus_{n \in \mathbb{N}} \mathfrak{S}_{k_n} = \{(\sigma_n)_{n \in \mathbb{N}} \in \prod_{n \in \mathbb{N}} \mathfrak{S}_{k_n} | \delta_{k_n}(\sigma_n, \text{Id}_{k_n}) \to 0\} \subset \prod_{n \in \mathbb{N}} \mathfrak{S}_{k_n}.$$

By the invariance property, it is a normal subgroup of $\prod_{n \in \mathbb{N}} \mathfrak{S}_{k_n}$.

Recall Gromov’s definition of a sofic group (cf. [8]; see also [5, 12] for a very nice presentation of sofic groups).

3.2 Definition. A countable group $\Gamma$ is said to be sofic if there exists a sequence of maps $(f_n)_{n \in \mathbb{N}} : \Gamma \to \mathfrak{S}_{k_n}$ such that:

a) For all $x, y \in \Gamma$, $\delta_{k_n}(f_n(x)f_n(y), f_n(xy)) \to 0$,

b) For all $x \in \Gamma$, $x \neq 1$, $\delta_{k_n}(f_n(x), \text{Id}) \to 1$.

Such a sequence $(f_n)_{n \in \mathbb{N}}$ is called a sofic approximation of $\Gamma$.

3.3 Remark. Let $q : \prod_{n \in \mathbb{N}} \mathfrak{S}_{k_n} \to \bigoplus_{n \in \mathbb{N}} \mathfrak{S}_{k_n} \setminus \bigoplus_{n \in \mathbb{N}} \mathfrak{S}_{k_n}$ be the quotient map. Property (a) of definition 3.2 means that $g = q \circ (f_n)_{n \in \mathbb{N}} : \Gamma \to \bigoplus_{n \in \mathbb{N}} \mathfrak{S}_{k_n} \setminus \bigoplus_{n \in \mathbb{N}} \mathfrak{S}_{k_n}$ is a morphism.

In particular, if (a) is satisfied, $(f_n(1)) \in \bigoplus_{n \in \mathbb{N}} \mathfrak{S}_{k_n}$. Therefore conditions (a) and (b) are equivalent to (a) and

b') For all $x \in \Gamma$, $\tau_{k_n}(f_n(x)) \to \tau_T(x)$.

We now prove the rather easy characterization of sofic groups in terms of traces:
3.4 Proposition. Let $\Gamma$ be a countable group. Denote by $\tau_\Gamma$ the canonical trace on $C^*(\Gamma)$. The following are equivalent:

(i) The group $\Gamma$ is sofic.

(ii) There exists a group $G$ and a surjective morphism $\varphi : G \to \Gamma$ such that $\tau_\Gamma \circ \varphi$ is in the closure of the permutational traces.

(iii) For every surjective morphism $\varphi : F_\infty \to \Gamma$ (i.e. for every generating system of $\Gamma$), $\tau_\Gamma \circ \varphi$ is in the closure of permutational traces.

Proof. (iii) $\Rightarrow$ (ii) is obvious.

(ii) $\Rightarrow$ (i) Assume that there is an onto morphism $\varphi : G \to \Gamma$ and a sequence $(\pi_n)_{n \in \mathbb{N}}$ of morphisms $\pi_n : G \to \mathfrak{S}_{k_n}$ such that for $y \in G$,

$$
\tau_{k_n}(\pi_n(y)) \to \tau_\Gamma(\varphi(y)) \quad (3.1)
$$

Let $s$ be any section of $\varphi$ and put $f_n = \pi_n \circ s$. We show that the sequence $f = (f_n)$ is a sofic approximation, by establishing conditions (a) and (b')

(b') Let $x \in \Gamma$. Applying (3.1) to $y = s(x)$, we get (b').

(a) The family $\pi = (\pi_n)$ determines a morphism $\pi : G \to \prod_{n \in \mathbb{N}} \mathfrak{S}_{k_n}$. For $y \in \ker \varphi$, since,

$$
\tau_\Gamma(\varphi(y)) = 1, \text{ we find } \delta_{k_n}(1, \pi_n(y)) = 1 - \tau_{k_n}(\pi_n(y)) \to 0; \text{ therefore } \pi(y) \in \bigoplus_{n \in \mathbb{N}} \mathfrak{S}_{k_n} = \ker q. \text{ It follows that } q \circ f \text{ is a morphism, and (a) is satisfied.}
$$

(i) $\Rightarrow$ (iii) Let $f = (f_n)$ be a sofic approximation of $\Gamma$. Then $q \circ f : \Gamma \to \prod_{n \in \mathbb{N}} \mathfrak{S}_{k_n}/\bigoplus_{n \in \mathbb{N}} \mathfrak{S}_{k_n}$ is a morphism.

Since $F_S$ is free, the morphism $q \circ f \circ \varphi$ lifts to a morphism $\pi = (\pi_n) : F_S \to \prod_{n \in \mathbb{N}} \mathfrak{S}_{k_n}$.

Now, for $y \in F_S$, since $\pi(y)^{-1}f \circ \varphi(y) \in \ker q$, we find $\delta_{k_n}(\pi_n(y), f_n(\varphi(y))) \to 0$, whence (since $\tau_{k_n}$ is 1-lipschitz), $|\tau_{k_n}(\pi_n(y)) - \tau_{k_n}(f_n(\varphi(y)))| \to 0$. The property (b') of the sofic approximation $f$ yields $\tau_{k_n}(\pi_n(y)) \to \tau_\Gamma \circ \varphi(y) \quad \square$

3.5 Theorem. (cf. [4]) Every sofic group satisfies Lück’s conjecture.

Proof. Let $\Gamma$ be a sofic group. Then, there exists a surjective morphism $\varphi : F_\infty \to \Gamma$. By prop. 3.3, the trace $\tau_\Gamma \circ \varphi$ is the limit of permutational traces on $C^*(F_\infty)$.

By proposition 2.3, the canonical trace on $\mathfrak{S}_n$ satisfies Lück’s conjecture and the same is true for a permutational trace on $C^*(F_\infty)$ by proposition 2.2 (i).

Then $\tau_\Gamma \circ \varphi \in \Lambda_{F_\infty}$ because $\Lambda_{F_\infty}$ is closed in the set of traces on $C^*(F_\infty)$ by proposition 2.6.

Since $\varphi$ is surjective, we conclude by proposition 2.2 (ii), that $\tau_\Gamma$ satisfies Lück’s conjecture. \square
3.6 Remark. A convenient way to state this result is to define the set of sofic traces on a group $G$ as being the closure of permutational traces. Then

1. A group is sofic if and only if the trace it defines on $\mathbb{F}_\infty$ is sofic.

2. Every sofic trace satisfies Lück’s condition.

On the other hand, not every trace on $\mathbb{F}_\infty$ satisfies Lück’s condition. It becomes then a quite natural question to study the set of traces on $\mathbb{F}_\infty$ satisfying Lück’s condition, the set of sofic traces, etc. Such a study is undertaken in [2].

3.7 Remark on hyperlinear groups and traces. (see e.g. [12] for a definition of hyperlinear groups) In the same way, we may define linear traces as the characters of finite dimensional representations and the set of hyperlinear traces as the closure of the set of linear traces. One then easily shows that a group is hyperlinear if and only if the trace it defines on $\mathbb{F}_\infty$ is hyperlinear.

One actually proves (see [2] for details):

Let $\Gamma$ be a countable group. Denote by $\tau_\Gamma$ the canonical trace on $C^*(\Gamma)$. The following are equivalent:

(i) The group $\Gamma$ is hyperlinear.

(ii) There exists a group $G$ and a surjective morphism $\varphi : G \to \Gamma$ such that the trace $\tau_\Gamma \circ \varphi$ is hyperlinear.

(iii) There exists a group $G$, a surjective morphism $\varphi : G \to \Gamma$ and a hyperlinear trace $\tau$ on $G$ such that \( \{ g \in G ; \tau(g) = 1 \} = \ker \varphi \).

(iv) For every surjective morphism $\varphi : \mathbb{F}_\infty \to \Gamma$ (i.e. for every generating system of $\Gamma$), the trace $\tau_\Gamma \circ \varphi$ on $\mathbb{F}_\infty$ is hyperlinear.

4 Relation with Atiyah’s problem

Lück’s conjecture implies a kind stability of von Neumann dimension. This stability allows computing $L^2$-Betti numbers, and proving integrality in some cases ([10, 9, 14], ...), or actually disproving their rationality ([7, 11])

4.1 The method

Let $A$ be a unital $C^*$-algebra, $k \in \mathbb{N}$ and $a \in A$. The characteristic function $\chi_0$ of \{0\} is upper semi-continuous. Given a trace $\tau$ on $A$, we put $\dim_\tau(\ker a) = \tau(\chi_0(|a|))$.

Note that if $(h_n)$ is a decreasing sequence of continuous functions on $\mathbb{R}_+$ converging to the characteristic function of \{0\}, we have $\dim_\tau(\ker a) = \lim_{n} \tau(h_n(|a|))$.

Lück’s method of handling Atiyah’s problem can be understood in terms of traces via the following quite easy fact:
4.1 Proposition. Let $A$ be a unital $C^*$-algebra, $a \in A$ and $s \in \mathbb{R}$. The map $\tau \mapsto \dim_r(\ker a)$ is continuous on $\Lambda_{a,s}$.

**Proof.** For $s' \in \mathbb{R}_+$, the set of traces $\Omega_{a,s'} = \{\tau; \tau(|a|) < s'\}$ is open. We only need to establish continuity on $\Lambda_{a,s} \cap \Omega_{a,s'}$. For $t \in \mathbb{R}_+$, put $\theta(t) = t - \ln_+(t)$. The function $\theta: \mathbb{R}_+ \to \mathbb{R}$ is continuous on $\mathbb{R}_+^*$, satisfies $\theta(t) > 0$ for $t \neq 0$ and $\lim_{t \to 0^+} \theta(t) = +\infty$. Moreover, for every $\tau \in \Lambda_{a,s} \cap \Omega_{a,s'}$, we have $\tau(\theta(|a|)) \leq s' - s$.

The proposition is an immediate consequence of the following Lemma. □

4.2 Lemma. Let $\theta: \mathbb{R}_+ \to \mathbb{R}_+$ be continuous on $\mathbb{R}_+^*$, and satisfy $\theta(t) > 0$ for $t \neq 0$ and $\lim_{t \to 0^+} \theta(t) = +\infty$. Let $h_n: \mathbb{R}_+ \to [0,1]$ be a decreasing sequence of continuous functions converging (pointwise) to $\chi_0$. Let $m \in \mathbb{R}_+$ and denote by $\Lambda_{a,m,\theta}$ the set of traces $\tau$ on $A$ such that $\tau(\theta(|a|)) \leq m$. Then the sequence $(\tau(h_n(|a|)))$ converges to $\dim_r(\ker a)$ uniformly on $\Lambda_{a,m,\theta}$.

**Proof.** The functions $v_n$ defined on $\mathbb{R}_+$ by $v_n(t) = \begin{cases} \frac{h_n(t)}{\theta(t)} & \text{if } t \neq 0 \\ 0 & \text{if } t = 0 \end{cases}$ are continuous. The sequence $(v_n)$ decreases to $0$; by Dini’s theorem it converges uniformly to $0$ on $\text{Sp}|a|$. For $\tau \in \Lambda_{a,m,\theta}$, we have $0 \leq \tau(h_n(|a|)) - \dim_r(\ker a) = \tau(v_n\theta(|a|)) \leq m\|v_n\|_\infty$. □

It follows that, if the group $\Gamma$ is either a direct limit, or a subgroup of an inverse limit (e.g. a residually finite group), or a sofic group, then for any $a \in M_k(\mathbb{Z}[\Gamma])$ the von Neumann dimension of $\ker a$ can be computed as a limit of simpler terms.

4.2 Algebraic coefficients

We now see that proposition 4.1 applies also for $a \in M_n(\mathbb{C}[\Gamma])$ with algebraic coefficients (see [3]).

If $A$ is a unital $C^*$-algebra, $a \in A$ and $\tau$ is a trace on $A$, we define the rank $\text{rk}_\tau(a)$ of $a$ to be the trace $\tau$ as the von Neumann dimension of the closure of the image of $a$; we of course have $\text{rk}_\tau(a) = \text{codim}_\tau(\ker a) = \tau(1) - \dim_r(\ker a)$. We will use the following Lemma.

4.3 Lemma. Let $A$ be a unital $C^*$-algebra, $a, b, c \in A$ with $a$ and $c$ invertible. Then for any trace $\tau$ on $A$ we have $\tau(\ln_+ |abc|) \leq \tau(\ln_+ |a||b||c|)\text{rk}_\tau(b) + \tau(\ln_+ |b|)$.

**Proof.** We first prove this inequality when $c = 1$: we prove, for invertible $a$,

$$
\tau(\ln_+ |ab|) \leq \tau(\ln_+ |a|)\text{rk}_\tau(b) + \tau(\ln_+ |b|).
$$

(***)

We may replace $A$ by $\pi_\tau(A)^\prime\prime$ and thus assume $A$ is a von Neumann algebra and $\tau$ a faithful normal trace. Let $b = u|b|$ be the polar decomposition of $b$. Let $p = u^*u$ be the domain projection of $b$ and $A_p = pAp$. Let $\tau_p$ be the restriction of $\tau$ to $A_p$. 

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Now $|b|$ and $|au|$ are injective elements of $A_p$ so that the Fuglede-Kadison determinant $\Delta_{t_p}$ and Lück’s modified determinant $\Delta_{t_p}^+$ coincide on them. We therefore have $\tau(\ln_+ (|a\|b)) = \tau(\ln_+ (|au|)) + \tau(\ln_+ (|b|))$. Finally, $\ln_+ (|au|) \leq \ln \|a\|p$, and $\tau(p) = \text{rk}_r(b)$.

To end, since $\tau(\ln_+ |x|) = \tau(\ln_+ |x^*|)$ we find (using (**))

$$\tau(\ln_+ |bc|) \leq \ln(||c||)\text{rk}_r(b^*) + \tau(\ln_+ |b|).$$

Replacing $b$ by $bc$ in (**) and noting that $\text{rk}_r(b) = \text{rk}_r(bc)$, we find:

$$\tau(\ln_+ |abc|) \leq \ln(||a||)\text{rk}_r(bc) + \tau(\ln_+ |bc|) \leq \ln(||a||||c||)\text{rk}_r(b) + \tau(\ln_+ |b|).$$

\[\square\]

4.4 Proposition. Let $a \in M_n(\mathbb{Q}\mathbb{F}_\infty)$.

a) There exists a constant $m$ such that for any tracial state $\tau \in \Lambda_{\mathbb{F}_\infty}$ (i.e. a tracial state on $C^*(\mathbb{F}_\infty)$ satisfying Lück’s property) we have $(\tau \otimes \text{Tr}_n)(\ln_+ |a|) \geq m$.

b) The map $\tau \mapsto \dim_r(\ker a)$ is continuous on $\Lambda_{\mathbb{F}_\infty}$.

Proof. Note that (a) is an immediate consequence of (a) and prop. 4.1.

We prove (b). Let $K$ be a finite extension of $\mathbb{Q}$ containing the coefficients of $a$, i.e. such that $a \in M_d(K\mathbb{F}_\infty)$.

Choosing a $\mathbb{Q}$ basis of $K$, we obtain an embedding $i : K \rightarrow M_d(\mathbb{Q})$ (where $d$ is the dimension of $K$ over $\mathbb{Q}$).

Giving all the embeddings of $K$ to $\mathbb{C}$, we obtain an embedding $j = (j_1, \ldots, j_d) : K \rightarrow \mathbb{C}^d$.

We will assume that the given embedding $K \subset \mathbb{C}$ is $j_1$.

These two embeddings are conjugate in $M_d(\mathbb{C})$: There exists an invertible matrix $c \in M_d(\mathbb{C})$ such that, for $x \in K$, the matrix $c i(x)c^{-1}$ is the diagonal matrix with coefficients $j_{\ell}(x)$.

Write then $i(a) = k^{-1}b$ where $b \in M_{dn}(\mathbb{Z}\mathbb{F}_\infty)$ and $k \in \mathbb{N}^*$.

For every $\tau \in \Lambda_{\mathbb{F}_\infty}$, we have

- $\tau(\ln_+ (b)) \geq 0$ (by definition of $\Lambda_{\mathbb{F}_\infty}$);
- it follows that $\tau(\ln_+ (i(a))) \geq -nd\ln k$;
- using lemma 4.3 we find $\sum_{\ell=1}^{d} \tau(\ln_+ (j_{\ell}(a))) \geq -nd\ln k - nd\ln(||c||||c^{-1}||)$.
- On the other hand for all $\ell$, we have $\tau(\ln_+ (j_{\ell}(a))) \leq n\max(0, \ln \|j_{\ell}(a)||)$;
- we find $\tau(\ln_+ (a)) = \tau(\ln_+ (j_1(a))) \geq -nd\ln(k||c||c^{-1}||) - n\sum_{\ell=2}^{d} \max(0, \ln \|j_{\ell}(a)||).$ \[\square\]
Generalizing a result of [3], we find:

4.5 Proposition. Let \( a \in M_n(\mathbb{Q}\mathbb{F}_\infty) \). For any sofic trace of \( C^*(\mathbb{F}_\infty) \), the dimension \( \dim_\tau(\ker a) \) does not depend on the embedding \( \mathbb{Q} \subset \mathbb{C} \).

Proof. Denote by \( \Sigma_a \) the set of tracial states on \( C^*(\mathbb{F}_\infty) \) satisfying Lück’s property and for which \( \dim_\tau(\ker j(a)) \) does not depend on the embedding \( j : \mathbb{Q} \to \mathbb{C} \). We wish to prove that every sofic trace is in \( \Sigma_a \).

It follows from proposition 4.4 (applied to \( j \) and \( j(a) \) where \( j \) is another inclusion of \( \mathbb{Q} \) in \( \mathbb{C} \) that the set \( \Sigma_a \) is closed in \( \Lambda_{\mathbb{F}_\infty} \) and therefore in \( \mathcal{T}_{\mathbb{F}_\infty} \).

Let \( q : \mathbb{F}_\infty \to \mathbb{S}_k \) be a morphism and \( \tau_q \) the corresponding trace on \( C^*(\mathbb{F}_\infty) \). Denote still by \( q \) the corresponding morphism \( q : M_n(\mathbb{Q}\mathbb{F}_\infty) \to M_{kn}(\mathbb{Q}) \). For any embedding \( j : \mathbb{Q} \to \mathbb{C} \), we have \( j \circ q = q \circ j : M_n(\mathbb{Q}\mathbb{F}_\infty) \to M_{kn}(\mathbb{C}) \), so that we have

\[
\dim_{\tau_q}(\ker j(a)) = \frac{1}{k} \dim_{\tau} j \circ q(a) = \frac{1}{k} \dim_{\tau} q(a).
\]

It is independent of \( j \).

In other words, \( \Sigma_a \) is closed and contains all permutational traces. Therefore \( \Sigma_a \) contains the closure of permutational traces: the sofic traces.

We immediately find the following:

4.6 Corollary. Let \( \Gamma \) be a sofic group and \( a \in M_n(\mathbb{Q}\Gamma) \), then the von Neumann dimension (with respect to the group trace of \( \Gamma \)) of \( \ker a \) does not depend on the embedding \( \mathbb{Q} \subset \mathbb{C} \). \( \Box \)

A particular case of this corollary is proved by A. Thom [16, theorem 4.3.(ii)]. Note that Thom’s proof actually establishes this result.

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