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# HOMOMORPHISMS TO $\mathbb{R}$ CONSTRUCTED FROM RANDOM WALKS

by Anna ERSCHLER & Anders KARLSSON

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ABSTRACT. — We give a construction of homomorphisms from a group into the reals using random walks on the group. The construction is an alternative to an earlier construction that works in more general situations. Applications include an estimate on the drift of random walks on groups of subexponential growth admitting no nontrivial homomorphism to the integers and inequalities between the asymptotic drift and the asymptotic entropy. Some of the entropy estimates obtained have applications independent of the homomorphism construction, for example a Liouville-type theorem for slowly growing harmonic functions on groups of subexponential growth and on some groups of exponential growth.

RÉSUMÉ. — Nous donnons une construction d'homomorphismes d'un groupe dans les nombres réels en utilisant une marche aléatoire sur le groupe. Cette construction est une alternative à une construction antécédente qui de plus s'applique dans des cas plus généraux. Les applications comprennent une estimation de la vitesse de fuite de marches aléatoires sur des groupes de croissance sous-exponentielle n'admettant pas d'homomorphismes non triviaux dans les nombres entiers et des inégalités entre la vitesse de fuite asymptotique et l'entropie asymptotique. Certaines des estimations d'entropie obtenues ont des applications indépendantes de la construction de l'homomorphisme, comme par exemple un théorème à la Liouville pour les fonctions harmoniques croissant lentement sur les groupes de croissance sous-exponentielle et certains groupes de croissance exponentielle.

## 1. Introduction

Let  $G$  be a finitely generated group and  $\mu$  a probability measure on  $G$ . We say that  $\mu$  is *non-degenerate* if its support generates  $G$  as a semi-group. We assume that  $\mu$  has *finite first moment* (with respect to a word metric  $l = l_S$  which we fix):

$$L(\mu) := \sum l(g)\mu(g) < \infty.$$

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It is clear that the property to have a finite first moment does not depend on the choice of finite generating set  $S$ . Finite first moment implies the finiteness of the entropy of  $\mu$

$$H(\mu) := - \sum_G \mu(g) \log \mu(g) < \infty.$$

The entropy of the random walk is

$$h(\mu) = \lim_{n \rightarrow \infty} \frac{H(\mu^{*n})}{n}.$$

This limit exists by subadditivity. If the entropy of  $\mu$  is finite, then this limit is finite. The entropy criterion asserts that the Poisson boundary of  $(G, \mu)$  is trivial if and only if  $h(\mu) = 0$  ([16, Theorem 1.1] and [6]). Let  $H(n) = H(\mu^{*n})$ . Proposition 1.3 in [16] asserts that

$$H(n+1) - H(n) \searrow h(\mu).$$

The expectation of the displacement from the origin is

$$L(n) := \sum_{g \in G} l(g) \mu^{*n}(g).$$

The following limit exists in view of subadditivity:

$$l = l(\mu) = \lim_{n \rightarrow \infty} \frac{1}{n} L(n),$$

which is called the *linear drift* of a.s. random walk trajectory by the sub-additive ergodic theorem.

In [17] Ledrappier and the second named author proved that if a finite first moment random walk has zero entropy and positive drift, then the group has a non-trivial homomorphism to  $\mathbb{R}$ . In this paper we establish criteria for the existence of homomorphisms to  $\mathbb{R}$  even in cases when the drift of the random walk might be zero.

**THEOREM A.** — *Suppose that  $\mu$  is non-degenerate with  $\mu(e) > 0$ , has finite second moment and that for some sequence  $n_k$  such that  $L(n_k + 1) - L(n_k) > 0$  and*

$$\sqrt{H(n_k + 1) - H(n_k)} / (L(n_k + 1) - L(n_k)) \rightarrow 0$$

*as  $k \rightarrow \infty$ . Then  $G$  admits a non-trivial homomorphism to  $\mathbb{R}$ .*

This theorem has the following corollaries. Let  $G$  be a group of subexponential growth at most  $\exp(n^b)$ ,  $b < 1$  and without nontrivial homomorphisms to  $\mathbb{R}$ . Let  $\mu$  be a non-degenerate, probability measure with  $\mu(e) > 0$

and of finite second moment. Then there exists  $a < 1$  (depending only on  $b$ ) such that for some  $C > 0$ ,

$$L(n) \leq Cn^a.$$

This applies for example to the first Grigorchuk group, see Corollary 5.6. For symmetric finitely supported random walk this was already known [8] and follows from Varopoulos' long range estimates [21]. Mathieu [18] has shown that for a finitely supported measure on a group, such that all elements of this support are torsion elements, Varopoulos-Carne type estimates hold, and that, therefore, for such measures, entropy of random walks is zero if and only if the drift is zero. In particular, this shows that the drift of finitely supported probability measure on groups of subexponential growth generated by torsion elements is zero. A similar result, based on Mathieu's inequality, was announced in [20]. For non-symmetric random walk the result in [17] states that the drift of any finite first moment random walk is zero, that is,  $L(n)$  is sublinear. Our results provide quantitative estimates of  $L(n)$ . In this context, let us recall that even if we restrict ourselves to the class of (symmetric) simple random walks on groups of subexponential growth,  $L(n)$  can be arbitrarily close to linear [11]. This is in the contrast with the fact that for any finitely supported measure  $\mu$  on the first Grigorchuk group  $G$  (and, more generally, for any  $(G, \mu)$  such that  $G$  is of growth at most  $\exp(n^b)$ ,  $\mu$  is a measure with finite second moment and the group generated by the support of  $\mu$  does not admit non-trivial homomorphism to  $\mathbb{Z}$ ), the drift of the random walk  $(G, \mu)$  is at most  $Cn^{(b+1)/2}$ , see Corollary 5.6.

Another corollary is:

**COROLLARY 1.1.** — *For a symmetric, non-degenerated with support containing  $e$ , finite second moment random walk on a finitely generated group, there is a constant  $C > 0$ , such that for all  $n > 1$ ,*

$$H(n) \geq C \frac{L(n)^2}{n}.$$

It is easy to see (e.g. Lemma 7 in [8]) that Gaussian long range estimates imply the conclusion of the corollary above. Such estimates hold for finitely supported symmetric measures on groups (Varopoulos [21]), more generally for any finitely supported centered measure on a group (here centered means that the projection of  $\mu$  on the abelianization of  $G$  is centered, see Mathieu [18] for a partial result in this direction and Dungey [7] for the general statement). Though, at least in the symmetric case, this type of the estimates hold also for measures with a very quick decay [19], observe

that they certainly do not hold for the class of measures with finite second moment, as in the corollary above. It was previously known, however, that  $l > 0$  implies  $h > 0$  for symmetric finitely supported random walks (Varopoulos [21]) and, more generally, for centered finite first moment random walks ([17]). We stress that the more general inequality in the corollary above the condition of the second first moment cannot be removed, see the remark after Corollary 5.2.

Among the ingredients of the criteria for homomorphisms are entropy estimates in Section 5. One of the direct corollaries of these estimates is for example the following Liouville-type result

**THEOREM B.** — *Consider a random walk on  $G$  and assume that the measure  $\mu$  is non-degenerate and has finite support including the identity. Take an increasing function  $f_{\text{harm}}(n) \geq 0$ . Suppose that at least one of the following assumption holds:*

- i) *For all  $n$ ,  $H(n) \leq f_H(n)$ , where  $f_H(n)$  is a non-decreasing function. And  $f_{\text{harm}}(n) \geq 0$  satisfies*

$$f_{\text{harm}}(n) \sqrt{f_H(n+1) - f_H(n)} \rightarrow 0,$$

*as  $n \rightarrow \infty$ .*

- ii) *There exists an infinite sequence  $n_k$  such that*

$$f_{\text{harm}}(n_k) \sqrt{H(n_k+1) - H(n_k)} \rightarrow 0,$$

*as  $k \rightarrow \infty$ .*

*Then every harmonic functions on  $G$  of growth at most  $f_{\text{harm}}$  is constant.*

If  $H(n)$  grows linearly, the theorem implies the almost obvious fact that if a harmonic function tends to zero as the word length of its argument tends to infinity, then this function is equal to zero. The theorem is of interest when  $H(n)$  is sublinear. In this case it is well-known that all bounded harmonic functions are constant, see Avez [1] for this implication in the case of finitely supported measures and Kaimanovich, Vershik [16] and Derriennic [6] for the general form of the entropy criterion: For any non-degenerate finite entropy probability measure the two following conditions are equivalent.

- 1) Every bounded harmonic function with respect to this measure is constant;
- 2)  $H(n)$  grows sublinear.

The theorem shows that bounds on  $H(n)$  can be used to show the absence of non-constant harmonic function of slow growth, and not only of non-constant bounded harmonic functions.

The theorem implies in particular, that if  $G$  is a group of subexponential growth  $\leq \exp(n^a)$ , for example the first Grigorchuk group, then there exists  $b > 0$ , depending only on  $a$ , such that all  $\mu$ -harmonic functions of growth at most  $n^b$  are constant. Recall that for infinitely supported measures on groups of subexponential growth the situation could be quite different: Some of such measure can admit non-constant bounded harmonic functions ([9, 10]).

Another application of the theorem concerns simple (symmetric) random walks on iterated wreath products of  $\mathbb{Z}$ . For these random walks,  $H(n)$  is bounded by  $n^a$ ,  $a < 1$  ([8]), and hence there exists  $b > 0$  such that all  $\mu$ -harmonic functions of growth at most  $n^b$  are constant. Finally, the same conclusion holds for a certain simple random walk on the Basilica group [3] and for a more general class of groups that includes this group [15].

## 2. Preliminaries on entropy and drift

Let  $G$  be a finitely generated group, with word length  $l_S$  and non-degenerate probability measure  $\mu$  of finite first moment. When the generating set  $S$  is understood we often write  $l(g)$  instead of  $l_S(g)$ . Recall the fundamental inequality [13]:

$$h \leq lv,$$

where  $v$  is the exponential growth rate of the number of elements  $g$  with  $l(g) \leq R$  in  $G$ . This inequality is implied by the following standard lemma:

LEMMA 2.1. — *Let  $\mu$  be a probability measure of finite first moment on a group  $G$ . Then*

- i) *for any  $\varepsilon > 0$ , there is a constant  $C > 0$ , depending on cardinality of  $S$  and not depending on  $\mu$ , such that for all  $n$*

$$H(n) \leq (v + \varepsilon)L(n) + C.$$

- ii) *Moreover, if the growth function of the group  $G$  satisfies  $v_G(n) \leq A \exp(n^b)$ ,  $b < 1$ , then  $H(n) \leq Cn^b$  for some constant  $C$ . Here the constant  $C$  depends only on  $A$  and cardinality of  $S$ .*

*Proof (cf. [17]).*

- i) Let  $S_*$  be an arbitrary finite generating set, and denote by  $l_*$  the corresponding word metric. Let  $a_n$  denote the number of elements  $g$  of word length  $l_*(g) = n$ , so  $a_n \leq (2|S_*|)^n$ . Let  $\nu'$  be the probability measure

on  $G$  defined by  $\nu'(g) = 2^{-l_*(g)-1}/a_{l_*(g)}$ . Then for any probability measure  $\nu$  of finite first moment we have

$$H(\nu) - \sum_{g \in G} \nu(g) \log(2^{l_*(g)+1} a_{l_*(g)}) = - \sum_{g \in G} \nu(g) \log \frac{\nu(g)}{\nu'(g)} \leq 0,$$

where the last inequality comes from the elementary inequality  $-\log t \leq 1/t - 1$ . Therefore

$$\begin{aligned} H(\nu) &\leq \sum_{g \in G} \nu(g) \log(2^{l_*(g)+1}) + \sum_{g \in G} \nu(g) \log(a_{l_*(g)}) \\ &\leq \sum_{g \in G} \nu(g) (l_*(g) + 1) \log 2 + \sum_{g \in G} \nu(g) l_*(g) \log(2 |S_*|) \\ &\leq \log(4 |S_*|) \sum_{g \in G} \nu(g) l_*(g) + \log 2. \end{aligned}$$

Apply the above inequality to  $\nu := \mu^{*n}$ , with  $S_* := S_k = \{g : l(g) \leq k\}$  and note that  $l_*(g) \leq l(g)/k + 1$ . It is then clear that given  $\varepsilon > 0$ , for all sufficiently large  $k$  and  $n$  there is a constant  $C$  making the inequality valid.

ii) From the proof of the first part of the lemma we know that for any generating set  $S_*$

$$H(\mu^{*n}) = H(n) \leq \log(4 |S_*|) \sum \mu^{*n}(g) l_*(g) + \log 2.$$

We apply it to  $S_* = S_n = \{g : l(g) \leq n\}$ . We have that

$$H(n) \leq \log(4A \exp(n^b)) \sum \mu^{*n}(g) (l(g)/n + 1) + \log 2.$$

The triangle inequality applied to the word metric shows that the first moment of the convolution of two measures is not greater than the sum of their first moments, and thus  $\sum_g \mu^{*n} l(g) \leq n \sum_g \mu^{*n} l(g) = L(\mu)n$ . This implies that

$$H(n) \leq (L(\mu) + 1)n^b + \log(4A)(L(\mu) + 1) + \log 2 \leq Cn^b$$

for an appropriate constant  $C$  and all  $n$ . □

We will furthermore make use of:

LEMMA 2.2. — *There are constants  $c$  and  $C$  such that for any probability measure  $\nu$  on  $\mathbb{Z}_+$  with finite first moment,*

$$H(\nu) \leq c \log(L(\nu) + 1) + C.$$

Moreover, for any  $c = 1 + \epsilon$ ,  $\epsilon > 0$  one can choose  $C$  such that the inequality holds.

*Proof.* — Assume first that  $\nu$  has finite support and let  $p_i = \nu(i)$ . Lemma 1.1 [4] asserts that for any finite sequence  $a_i$  of numbers it holds that

$$H(\nu) = - \sum p_i \log p_i \leq - \sum p_i a_i + \log \sum e^{a_i},$$

where the sums are taken over the  $i$  such that  $p_i \neq 0$ . Fix an  $\varepsilon > 0$ . We apply this inequality to  $a_i := -(1 + \varepsilon) \log(i + 1)$  and get

$$H(\nu) \leq (1 + \varepsilon) \sum p_i \log(i + 1) + \log \sum \frac{1}{(i + 1)^{1+\varepsilon}}.$$

Note that the following constant is independent of  $\nu$ :

$$C := \log \sum_{i=0}^{\infty} \frac{1}{(i + 1)^{1+\varepsilon}}.$$

Using the convexity of  $-\log$  we get

$$H(\nu) \leq (1 + \varepsilon) \log \left( \sum p_i (i + 1) \right) + C = (1 + \varepsilon) \log \left( 1 + \sum p_i i \right) + C.$$

Since  $\varepsilon$  and  $C$  are independent of  $\nu$ , this inequality extends to general  $\nu$  of finite first moment. □

For estimates of  $H(n)$  from below, one has Lemma 7 in [8] which states that for any symmetric finitely supported measure  $\mu$  it holds that for some  $C > 0$ :

$$H(n) \geq C \frac{1}{n} L(n)^2 - \log n,$$

and as  $H(n) \geq C_1 \log(n)$  (which follows from the stronger general estimate on the transition probabilities  $\mu^{*n}(g) \leq Cn^{-1/2+\varepsilon}$ ) this in turn implies that

$$H(n) \geq C_2 \frac{1}{n} L(n)^2.$$

This is a corollary of Varopoulos' long range estimate ([21]), see [5] for a simple proof and this precise formulation:

$$\mu^{*n}(g) \leq C e^{-al(g)^2/n}$$

for some constants  $C, a > 0$ .

### 3. Definition and properties of $T_n$

Let  $G$  be a finitely generated group and  $\mu$  a non-degenerate probability measure on  $G$  with finite first moment (with respect to a word metric  $l_S$  which we fix and sometimes denote by  $l$ ). Define

$$T_n(g) = \sum_{h \in G} (l(gh) - l(h)) \mu^{*n}(h).$$



Note that  $|T_n(g)| \leq l(g)$ .

LEMMA 3.1. — *We have that*

$$\sum_{g \in G} T_n(g) \mu(g) = L(n+1) - L(n).$$

*Proof.* — We have

$$\begin{aligned} \sum T_n(g) \mu(g) &= \sum_{g \in G} \sum_{h \in G} (l(gh) - l(h)) \mu^{*n}(h) \mu(g) \\ &= \sum_{h \in G} \left( \sum_{g \in G} l(gh) \mu(g) - l(h) \right) \mu^{*n}(h) \\ &= \sum_{h \in G} l(h) \left( \mu^{*(n+1)}(h) - \mu^{*n}(h) \right) \\ &= L(n+1) - L(n). \end{aligned}$$

□

Consider  $\beta(n)$  such that for every  $g \in G$  there exists a constant  $C(g)$  such that

$$(*) \quad \sum_{h \in G} |g \mu^{*n}(h) - \mu^{*n}(h)| \leq C(g) \beta(n).$$

*Remark.* — Observe, that if such  $C(g)$  exists and if the measure is non-degenerate (or, more generally *adapted*, i.e. the support generates  $G$  as a group), we can choose  $C(g) = C l_S(g)$ , where  $S$  is a finite generating set, and  $C$  is the maximum of  $C(g)$  over  $g \in S$ . ( $\beta$  is then the maximum over  $S$  of the left hand side.)

Since the left hand side of (\*) is bounded by 2, the existence of such  $\beta(n)$  is not an issue. Note that if the entropy  $h = 0$  and the random walk is aperiodic, one can choose a sequence  $\beta(n) \rightarrow 0$  as  $n \rightarrow \infty$  ([16]). In general, if we do not assume that the measure is adapted, the claim of the Remark above does not need to be true.

LEMMA 3.2. — *For any  $g_1, g_2 \in G$  and any  $S$*

$$|T_n(g_1 g_2) - T_n(g_1) - T_n(g_2)| \leq l_S(g_2) C(g_1) \beta(n).$$

*Proof.* — We have that

$$\begin{aligned} &|T_n(g_1 g_2) - T_n(g_1) - T_n(g_2)| \\ &= \left| \sum_{h \in G} (l_S(g_1 g_2 h) - l_S(g_1 h) - l_S(g_2 h) + l_S(h)) \mu^{*n}(h) \right| \end{aligned}$$

$$\begin{aligned}
 &= \left| \sum_{h \in G} (l_S(g_1 g_2 h) - l_S(g_1 h) - (l_S(g_2 h) - l_S(h))) \mu^{*n}(h) \right| \\
 &= \left| \sum_{h \in G} (l_S(g_2 h) - l_S(h)) (g_1 \mu^{*n}(h) - \mu^{*n}(h)) \right| \\
 &\leq l_S(g_2) \sum_{h \in G} |(g_1 \mu^{*n}(h) - \mu^{*n}(h))| \leq l_S(g_2) C(g_1) \beta(n).
 \end{aligned}$$

□

Take a finite generating set  $S$  of  $G$  and denote by  $\gamma_S(n)$  the maximum of the absolute value of  $T_n(g)$ ,  $g \in S$ .

LEMMA 3.3. — *For any finite generating set  $S$  there exist positive constants  $C$  and  $C_1$  such that for any  $g$  in the group, generated by the support of  $\mu$ , it holds*

$$|T_n(g)| \leq \gamma_S(n) l_S(g) + C_1 l_S(g)^2 \beta(n).$$

*Proof.* — Let  $m = l_S(g)$ . There exist  $g_1, g_2, \dots, g_m \in S$  such that  $g_1 g_2 \dots g_m = g$ . Observe that by Lemma 3.2 for any  $j$ ,  $1 \leq j \leq m$

$$\begin{aligned}
 |T_n(g_1 g_2 \dots g_j) - T_n(g_1 g_2 \dots g_{j-1}) - T_n(g_j)| &\leq l_S(g_j) C(g_1 g_2 \dots g_j) \beta(n) \\
 &\leq C_0 l_S(g_1 g_2 \dots g_j) \beta(n) \\
 &= C_0 j \beta(n).
 \end{aligned}$$

Therefore,

$$\begin{aligned}
 |T_n(g_1 g_2 \dots g_m) - T_n(g_1) - T_n(g_2) - \dots - T_n(g_m)| &\leq C_0 (1 + 2 + \dots + m) \\
 &\leq C_1 m^2 \beta(n).
 \end{aligned}$$

Finally note that

$$|T_n(g_1) + T_n(g_2) + \dots + T_n(g_m)| \leq m \gamma_S(n),$$

which completes the proof of the lemma. □

LEMMA 3.4. — *If  $\mu$  is a symmetric measure with finite second moment, then for some positive constant  $C$  and all  $g$  in the group, generated by the support of  $\mu$  it holds*

$$\left| \sum_g T_n(g) \mu(g) \right| \leq C \beta(n)$$

and

$$|L(n + 1) - L(n)| \leq C \beta(n).$$

*Proof.* — From the definition of  $T_n$  we know that  $T_n(e) = 0$ . Therefore, by Lemma 3.2 and the remark preceding it, we have that

$$|T_n(g) + T_n(g^{-1})| \leq C_1 l(g) l(g^{-1}) X S \beta(n) = C_1 l^2(g) \beta(n).$$

Summing over  $g$  and using the fact that the second moment of  $\mu$  is finite, we get

$$\sum_g |T_n(g) + T_n(g^{-1})| \mu(g) \leq C_1 \sum_g l^2(g) \mu(g) \beta(n) \leq C \beta(n).$$

Therefore,

$$\left| \sum_g (T_n(g) + T_n(g^{-1})) \mu(g) \right| \leq C \beta(n).$$

If  $\mu$  is symmetric, then

$$\sum_g T_n(g^{-1}) \mu(g) = \sum_g T_n(g^{-1}) \mu(g^{-1}) = \sum_g T_n(g) \mu(g),$$

and this implies the first claim of the lemma. The second one follows from the first one in view of Lemma 3.1.  $\square$

Note that the conclusion of the lemma does not hold without the assumption on the second moment, see the discussion after Corollary 5.2.

## 4. Construction of limits of $T_n$

### 4.1. Simplest case

We may take a subsequence  $n_k \rightarrow \infty$  such that limit

$$T(g) = \lim_{k \rightarrow \infty} T_{n_k}(g)$$

exists for every  $g$  (by the diagonal process argument).

Lemmas 3.1 and 3.2 in the previous section imply that:

- If the entropy of the random walk is zero, then  $T$  is homomorphism. Indeed, it follows from Lemma 3.2 and the following property of the entropy: Zero entropy of an aperiodic random walk on a group is equivalent to that for every  $g$

$$\sum_{h \in G} |g \mu^{*n}(h) - \mu^{*n}(h)| \rightarrow 0 \text{ as } n \rightarrow \infty.$$

See [16, Theorem 4.2].

- If the drift  $l$  of the random walk is positive, then for an appropriately chosen subsequence of  $n$ 's,  $T$  is not identically zero: Indeed, we can choose a sequence  $n_k$  in such a way that  $L(n_k + 1) - L(n_k) \geq l - \varepsilon_k$  with  $\varepsilon_k \rightarrow 0$  and such that  $T(g) = \lim_{k \rightarrow \infty} T_{n_k}(g)$  converges. Lemma 3.1 then implies that

$$\sum_{g \in G} T(g)\mu(g) \geq l.$$

### 4.2. General case

Fix a finite generating set  $S$  in  $G$ . For every integer  $i > 0$ , let  $\gamma_S(i)$  denote  $\max |T_i(g)|$ , where the maximum is taken over  $g \in S$ .

Assume that  $S$  and  $i$  are such that  $\gamma_S(i) \neq 0$ . Put  $\alpha_S(i) = 1/\gamma_S(i)$  and take  $g$  with  $l_S(g) = m$ ,  $g = g_1 g_2 \dots g_m$ , for  $g_j \in S$ . By Lemma 3.3 we know that

$$\alpha_S(i)|T_i(g)| \leq \alpha_S(i)\gamma_S(i)m + C_1 m^2 \beta(i)\alpha_S(i) = m + C_1 m^2 \beta(i)\alpha_S(i).$$

In order to take the limit, we want that  $\gamma_S(i) \neq 0$  and that  $\alpha_S(i)\beta(i)$  remains bounded along some infinite subsequence. We may then take a subsequence  $n_k \rightarrow \infty$  of our subsequence such that the limit

$$T_\alpha(g) = \lim_{k \rightarrow \infty} \alpha_S(n_k)T_{n_k}(g)$$

exists for every  $g$ . Observe, that for any  $i$  there exists  $g \in S$  such that  $\alpha_S(i)T_i(g) = 1$ , and therefore by construction  $T_\alpha$  is not identically zero.

Lemma 3.2 implies that under some conditions on  $\mu$  and  $\alpha(i)$  (so that  $\alpha_S(i)\beta(i)$  tends to zero) the constructed map  $T_\alpha$  is a homomorphism.

Therefore, to ensure that our construction provides a non-trivial homomorphism to  $\mathbb{R}$  it is sufficient to know that there exists a generating set  $S$  and a subsequence such that

- $\gamma_S(n_k)$  is not zero, and
- $\beta(n_k)/\gamma_S(n_k)$  tends to zero.

PROPOSITION 4.1. — *Suppose that  $\mu$  is non-degenerate, has finite second moment and that for some sequence  $n_k$  it holds that  $L(n_k + 1) - L(n_k) > 0$  and*

$$\beta(n_k)/(L(n_k + 1) - L(n_k)) \rightarrow 0$$

*as  $n \rightarrow \infty$ . Then  $G$  admits a non-trivial homomorphism to  $\mathbb{R}$  (constructed as  $T_\alpha$  with respect to some subsequence of  $n_k$ ).*

*Proof.* — We know from Lemma 3.3 that

$$|T_n(g)| \leq l_S(g)\gamma_S(n) + l_S(g)^2 C\beta(n),$$

and hence

$$\sum_{g \in G} |T_n(g)|\mu(g) \leq C_1\gamma_S(n) + C_2\beta(n),$$

for suitable constants  $C_1$  and  $C_2$ , since the first and the second moment of  $\mu$  are finite (with respect to  $S$ ). By Lemma 3.1, this implies that for all  $n$

$$(L(n + 1) - L(n)) \leq C_1\gamma_S(n) + C_2\beta(n).$$

In particular, for our subsequence  $n_k$

$$\begin{aligned} L(n_k + 1) - L(n_k) &\leq C_1\gamma_S(n_k) + C_2\beta(n_k) \\ &\leq C_1\gamma_S(n_k) + C_2\epsilon(L(n_k + 1) - L(n_k)), \end{aligned}$$

where  $\epsilon$  can be chosen arbitrarily small if  $k$  is large enough. Therefore,

$$(L(n_k + 1) - L(n_k))(1 - \epsilon C_2) \leq C_1\gamma_S(n_k).$$

If  $k$  is large enough, we can choose  $\epsilon$  such that  $\epsilon C_2 < 1/2$ . For such  $k$

$$1/2(L(n_k + 1) - L(n_k)) \leq C_1\gamma_S(n_k).$$

This implies that for sufficiently large  $k$ ,  $\gamma_S(n_k) \neq 0$ . Therefore,  $\alpha_S(n_k) = 1/\gamma_S(n_k)$  from the construction of  $T_\alpha$  is well-defined. Observe that for sufficiently large  $k$

$$\alpha_S(n_k)(L(n_k + 1) - L(n_k)) \leq 2C_1$$

and therefore, by assumption,  $\alpha(n_k)\beta(n_k)$  tends to 0 as  $k \rightarrow \infty$ . Since  $\alpha(n_k)\beta(n_k)$  is bounded,  $T_\alpha$  is well-defined along some subsequence of  $n_k$ . Since  $\alpha(n_k)\beta(n_k)$  tends to zero, it follows from Lemma 3.2 that  $T_\alpha$  is a homomorphism. By the construction of  $T_\alpha$  it is not identically zero.  $\square$

### 5. Entropy and differences of shifted convolutions

The results of this section, except for two of the three corollaries, are independent from previous sections.

LEMMA 5.1. — *Let  $S$  be a finite set in the support of  $\mu$ . Assume that the identity  $e$  is in the support of  $\mu$*

i) *Then there exists  $C_0 > 0$  such that for any  $g \in S$*

$$H(n + 1) - H(n) \geq C_0 \sum_{h: \mu^{*n}(gh) + \mu^{*n}(h) > 0} \frac{(\mu^{*n}(gh) - \mu^{*n}(h))^2}{\mu^{*n}(gh) + \mu^{*n}(h)}.$$

ii) There exists  $C_1 > 0$  such that for any  $g \in S$

$$\sum_h |\mu^{*n}(gh) - \mu^{*n}(h)| \leq C_1 \sqrt{H(n+1) - H(n)}.$$

*Proof.*

i) Let  $g_0, g_1, g_2, \dots$  be the support of  $\mu$  and we assume that  $g_0 = e$  the identity, and  $g_1 = g$  in the statement. Let  $p_i = \mu(g_i)$  and  $\nu_i = g_i \mu^{*n}$ . Note that

$$\nu := \mu^{*(n+1)} = \sum p_i \nu_i$$

and that all  $\nu_i$  have the same (weight) distribution, so in particular  $H(\nu_i) = H(\nu_0)$  for all  $i$ . By the basic concavity property of entropy we have that

$$\begin{aligned} H(\nu) &= H\left((p_0 + p_1)\left(\frac{p_0}{p_0 + p_1}\nu_0 + \frac{p_1}{p_0 + p_1}\nu_1\right) + p_2\nu_2 + p_3\nu_3 + \dots\right) \\ &\geq (p_0 + p_1)H\left(\frac{p_0}{p_0 + p_1}\nu_0 + \frac{p_1}{p_0 + p_1}\nu_1\right) + \sum_{i \geq 2} p_i H(\nu_i) \\ &= (p_0 + p_1)H\left(\frac{p_0}{p_0 + p_1}\nu_0 + \frac{p_1}{p_0 + p_1}\nu_1\right) + (1 - p_0 - p_1)H(\nu_0). \end{aligned}$$

Let

$$D := \sum_{h: \nu_1(h) + \nu_0(h) > 0} \frac{(\nu_1(h) - \nu_0(h))^2}{\nu_1(h) + \nu_0(h)}$$

and  $p = p_0/(p_0 + p_1)$ . By symmetry we may assume that  $p \leq 1/2$  and by concavity:

$$H\left(2p\left(\frac{1}{2}\nu_0 + \frac{1}{2}\nu_1\right) + (1 - 2p)\nu_1\right) \geq 2pH\left(\frac{1}{2}(\nu_0 + \nu_1)\right) + (1 - 2p)H(\nu_1).$$

Therefore, in order to show the desired inequality, it remains to show that

$$H\left(\frac{1}{2}(\nu_0 + \nu_1)\right) \geq \frac{1}{2}H(\nu_0) + \frac{1}{2}H(\nu_1) + CD$$

for some constant  $C > 0$ . This is proved by summation of the following inequality, for  $a, b > 0$ , there is a constant  $C$  such that

$$-\frac{1}{2}(a + b) \log((a + b)/2) + \frac{1}{2}(a \log a + b \log b) \geq C \frac{(a - b)^2}{a + b}.$$

To prove this inequality, we may assume that  $a + b = 2$ . Indeed, if not, then we multiply  $a$  and  $b$  with  $x = 2/(a + b)$  and observe that

$$\begin{aligned} &\frac{1}{2}(x(a + b) \log(x(a + b)/2) - (xa \log xa + xb \log xb)) \\ &= \frac{1}{2}x\left((a + b) \log((a + b)/2) - (a \log a + b \log b)\right) \end{aligned}$$

while the right hand side becomes  $Cx \frac{(a-b)^2}{a+b}$ .

So now we assume that  $a + b = 2$ . Let us assume also that  $a \geq b$ . Take  $\epsilon$  such that  $a = 1 + \epsilon$ ,  $b = 1 - \epsilon$ . We have to show that for all  $\epsilon: 0 \leq \epsilon \leq 1$  and for some positive  $C$

$$((1 + \epsilon) \log(1 + \epsilon) + (1 - \epsilon) \log(1 - \epsilon)) \geq 16C\epsilon^2.$$

Observe that  $((1 + \epsilon) \log(1 + \epsilon) + (1 - \epsilon) \log(1 - \epsilon)) > 0$  for any  $\epsilon: 0 < \epsilon \leq 1$ , and therefore it suffices to prove the inequality above for  $\epsilon$  in the neighborhood of zero. Let us write  $\log(1 + \epsilon)$  and  $\log(1 - \epsilon)$  as series in  $\epsilon$  (at 0):  $\log(1 + \epsilon) = \epsilon - 1/2\epsilon^2 - 1/3\epsilon^3 \dots$

$$\begin{aligned} & ((1 + \epsilon) \log(1 + \epsilon) + (1 - \epsilon) \log(1 - \epsilon)) \\ &= -2(1/2\epsilon^2 + 1/4\epsilon^4 + 1/6\epsilon^6 + \dots) + 2\epsilon(\epsilon - 1/3\epsilon^3 + \dots) \\ &\geq 2(\epsilon^2(1 - 1/2) + \epsilon^4(1/3 - 1/4) + \dots) \geq C_2\epsilon^2, \end{aligned}$$

for any  $\epsilon: 0 \leq \epsilon \leq 1$ .

ii) Now we will show that i) implies ii). Put  $E = H(n + 1) - H(n)$ . Observe that

$$\begin{aligned} & \sum_h |\mu^{*n}(gh) - \mu^{*n}(h)| \\ &= \sum_{h: |\mu^{*n}(gh) - \mu^{*n}(h)| / (\mu^{*n}(gh) + \mu^{*n}(h)) \geq \sqrt{E}} |\mu^{*n}(gh) - \mu^{*n}(h)| \\ &+ \sum_{h: |\mu^{*n}(gh) - \mu^{*n}(h)| / (\mu^{*n}(gh) + \mu^{*n}(h)) < \sqrt{E}} |\mu^{*n}(gh) - \mu^{*n}(h)|. \end{aligned}$$

The second sum is at most

$$\begin{aligned} & \sum_{h: |\mu^{*n}(gh) - \mu^{*n}(h)| / \mu^{*n}(gh) < 2\sqrt{E}} |\mu^{*n}(gh) - \mu^{*n}(h)| \\ &+ \sum_{h: |\mu^{*n}(gh) - \mu^{*n}(h)| / \mu^{*n}(h) < 2\sqrt{E}} |\mu^{*n}(gh) - \mu^{*n}(h)|, \end{aligned}$$

which is at most  $4\sqrt{E}$ . Now we estimate the first sum. This sum is at most the right hand side from i) divided by  $\sqrt{E}$ , and, therefore, it is smaller than  $C_2\sqrt{E}$ . □

**COROLLARY 5.2.** — *For a symmetric non-degenerate, finite second moment random walk with  $\mu(e) > 0$  it holds*

i) *for some  $C > 0$  and all  $n > N$*

$$L(n + 1) - L(n) \leq C\sqrt{H(n + 1) - H(n)},$$

ii) for some  $C > 0$  and all  $n > N$

$$H(n) \geq C \frac{L(n)^2}{n}.$$

*Proof.*

- i) follows from the second part of Lemma 5.1 and Lemma 3.4 in Section 3.
- ii) follows from i): We know that for some  $C > 0$

$$\sqrt{H(n+1) - H(n)} \geq C(L(n+1) - L(n)).$$

Therefore,

$$H(n+1) - H(n) \geq C^2(L(n+1) - L(n))^2.$$

Hence by summation

$$H(n) \geq \sum_{i=0}^{n-1} C^2(L(i+1) - L(i))^2.$$

To finish the proof of ii) observe that

$$\sum_{i=0}^{n-1} (L(i+1) - L(i))^2 \geq \frac{1}{n} \left( \sum_{i=0}^{n-1} (L(i+1) - L(i)) \right)^2 = \frac{L(n)^2}{n}. \quad \square$$

*Remark.* — The assumption that the second moment is finite is important. For any  $\epsilon > 0$  there is a measure with finite  $2 - \epsilon$  moment on  $\mathbb{Z}$  for which the conclusion of the statement does not hold. Indeed, take  $\alpha: 1, 2 - \epsilon < \alpha < 2$  and consider a symmetric finite first moment measure on  $\mathbb{Z}$  in the domain of the attraction of the Stable Law with parameter  $\alpha$ . Since this is a finite first moment measure on  $\mathbb{Z}$ , we have  $H(n) \leq C' \log(L(n) + 1) + C_1 \leq C' \log(n) + C_1$  (follows from Lemma 2.2).

On the other hand, since the limit stable law has finite first moment, we have  $L(n)/n^{1/\alpha} \geq C$ .

This implies that the assumption about the second moment is also necessary in Lemma 3.4, since the corollary follows from this lemma and Lemma 5.1, and the latter holds for any measure.

Moreover, the same example shows that the assumption about second moment is important in Proposition 4.1. Indeed, observe that for a symmetric measure on any abelian  $G$  it holds  $T_n(g) = T_n(g^{-1})$  for any  $g$  and any  $n$ . This implies that, whatever normalizing we consider, if in this case the constructed limit  $T_\alpha$  is a homomorphism, then it is identically zero.

Now we are going to show that the second part of Lemma 5.1 implies Theorem B.



*Proof of Theorem B.* — We start with showing that the assumption i) implies the assumption ii), namely that that if i) holds, then there exists a subsequence  $n_k$  such that

$$f_{\text{harm}}(n_k)\sqrt{H(n_k + 1) - H(n_k)} \rightarrow 0.$$

First observe, that since  $f_{\text{harm}}(n)\sqrt{f_H(n + 1) - f_H(n)}$  tends to 0, there exists a sequence tending to infinity of positive numbers  $M_n$  such that

$$M_{n+1} \left( f_{\text{harm}}(n)\sqrt{f_H(n + 1) - f_H(n)} \right)$$

tends to 0. Put  $K_n = M_n^2/2$ . Observe that we can choose a sufficiently slowly growing sequence  $M_n$  above satisfying in addition the following property:

$$(**) \quad \frac{K_{n+1}}{K_n} \leq \frac{1}{(2 - f_H(n + 1)/f_H(n))},$$

since by the assumption of the theorem for all  $n$  the expression on the right hand side is greater than 1.

$K_n$  tends to infinity, and therefore, for infinitely many  $n$  it holds

$$H(n + 1) - H(n) \leq K_{n+1}f_H(n + 1) - K_n f_H(n).$$

(Indeed, otherwise for all sufficiently large  $n$  we have  $H(n + 1) - H(n) \geq K_{n+1}f_H(n + 1) - K_n f_H(n)$ . This implies that  $H(n) \geq K_n f_H(n) - \text{Const}$ , and therefore that  $1 \geq H(n)/f_H(n) = K_n - \text{Const}/H(n) \geq K_n - \text{Const}/H(0)$ . This shows that  $K_n$  is bounded and we get a contradiction.)

Now observe that the property  $(**)$  implies that

$$K_{n+1}f_H(n + 1) - K_n f_H(n) \leq 2K_{n+1}(f_H(n + 1) - f_H(n)).$$

Combining this with the previous observation we see that there exists an infinite subsequence  $n_k$  along which we have

$$\begin{aligned} H(n_k + 1) - H(n_k) &\leq 2K_{n_k+1}(f_H(n_k + 1) - f_H(n_k)) \\ &= M_{n_k+1}^2(f_H(n_k + 1) - f_H(n_k)). \end{aligned}$$

It holds for all  $k$

$$f_{\text{harm}}\sqrt{H(n_k + 1) - H(n_k)} \leq \left( f_{\text{harm}}\sqrt{f_H(n_k + 1) - f_H(n_k)} \right) M_{n_k+1}$$

and hence  $f_{\text{harm}}\sqrt{H(n_k + 1) - H(n_k)}$  tends to 0 as  $k \rightarrow \infty$ .

Therefore it suffices to prove the theorem under the assumption ii). Consider a harmonic function  $\phi: G \rightarrow R$ . Take  $g_1, g_2 \in G$ . Observe that for all  $k$

$$\phi(g_1) - \phi(g_2) = \sum_h \phi(g_1 h)\mu^{*n_k}(g_1 h) - \sum_h \phi(g_2 h)\mu^{*n_k}(g_2 h).$$

This is at most  $f_{\text{harm}}(n_k)$  multiplied by

$$\sum_h (\mu^{*n_k}(h) - \mu^{*n_k}(g_2 g_1^{-1} h)) \leq C_1 \sqrt{H(n_k + 1) - H(n_k)},$$

where the inequality above is from the claim of the second part of Lemma 5.1. Thus we see that as  $k \rightarrow \infty$ ,

$$\sum_h \phi(g_1 h) \mu^{*(n_k)}(g_1 h) - \sum_h \phi(g_2 h) \mu^{*(n_k)}(g_2 h) \rightarrow 0,$$

and this shows that for any  $g_1, g_2 \in G$  it holds  $\phi(g_1) = \phi(g_2)$ . □

LEMMA 5.3. — Suppose that the entropy of a random walk is such that for all  $n$  we have  $H(n) \leq f_H(n)$ , where the function  $f_H(n)$  satisfies  $f_H(0) = 0$ . Then for all  $n$  we have  $H(n + 1) - H(n) \leq f_H(n)/n$ .

In particular, if for all  $n$  we have  $H(n) \leq Cn^\alpha$ ,  $0 < \alpha < 1$ . Then for some  $C > 0$  and all  $n$

$$H(n + 1) - H(n) \leq \frac{C}{n^{(1-\alpha)}}.$$

*Proof.* — Follows from the fact that  $H(n + 1) - H(n)$  is non-increasing. □

COROLLARY 5.4. — Take a group  $G$  such that its growth function is bounded above by  $\exp(Cn^a)$ , for some  $a < 1$ . There exists  $b > 0$  such that every harmonic function on  $G$  with respect to a finitely supported non-degenerate measure, of growth at most  $n^b$ , is constant. Moreover, if a harmonic function  $\phi$  with respect to some finitely supported measure satisfies the following condition: There exist an infinite sequence  $n_k$  such that for all  $k$  and all  $g: l_S(g) \leq n_k$  the value  $\phi(g) \leq n_k^b$ , then the function  $\phi$  is constant.

*Example.* —  $G$  is the first Grigorchuk group, [12].

*Proof.* — The assumption implies that for all  $n$  it holds  $H(n) \leq Cn^a$ . Then by Lemma 5.3 for all  $n$  it holds  $H(n + 1) - H(n) \leq \frac{C}{n^{(1-\alpha)}}$ . Take  $b$  such that  $2b < 1 - a$ , put  $f_{\text{harm}}(n) = n^b$  and apply Theorem B. □

Recall that for finitely generated groups of polynomial growth, harmonic functions with respect to symmetric finitely supported measures and of sublinear growth are constant ([14], Theorem 6.1).

### 5.1. Corollaries of the statements about homomorphisms taking into account the estimates of entropy

*Proof of Theorem A.* — Follows from Proposition 4.1 and the second part of Lemma 5.1. □

COROLLARY 5.5. — Suppose that  $\mu$  is non-degenerate with  $\mu(e) > 0$ , has finite second moment and that  $G$  admits no nontrivial homomorphism into  $\mathbb{R}$ . Then there is a constant  $c$  such that for all  $n$ ,

$$H(n) \geq c \frac{L(n)^2}{n}.$$

*Proof.* — In view of Theorem A and the assumption on  $G$ , there must be a  $c > 0$  such that for every  $n$  such that  $L(n+1) - L(n) > 0$ ,

$$\sqrt{H(n+1) - H(n)} / (L(n+1) - L(n)) \geq c.$$

For all  $n$  we hence have

$$\sqrt{H(n+1) - H(n)} \geq c(L(n+1) - L(n)).$$

Therefore, as in the proof of Corollary 5.2,

$$H(n) \geq cL(n)^2/n. \quad \square$$

COROLLARY 5.6. — Consider a non-degenerate, with  $e$  in the support, finite second moment random walk on a group  $G$  of intermediate growth at most  $\exp(n^b)$ ,  $b < 1$ , which do not admit non-zero homomorphisms to  $\mathbb{R}$ . There exists a constant  $C$  such that for all sufficiently large  $n$  it holds  $L(n) \leq Cn^{(b+1)/2}$ .

*Proof.* — This is an immediate consequence of the previous corollary and Lemma 2.1. □

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