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Finally in Section 9 we show how to compute the circuit series of a free product of graphs (an analogue of the free products of groups, *via* their Cayley graph), and in Section 10 do the same for direct products of graphs.

3. APPLICATIONS TO OTHER FIELDS

The original motivation for Formula 2.2 was its implication of a well-known result in the theory of random walks on discrete groups.

3.1 APPLICATIONS TO RANDOM WALKS ON GROUPS

In this section we show how G is related to random walks and F to cogrowth. This will give a generalization of the main formula (1.1) to homogeneous spaces Π/Ξ , where Ξ does not have to be normal and Π is a free product of infinite-cyclic and order-two groups. For a survey on the topic of random walks see [MW89,Woe94].

Throughout this subsection we will have F(t) = F(0,t). We recall the notion of growth of groups:

DEFINITION 3.1. Let Γ be a group generated by a finite symmetric set S. For a $\gamma \in \Gamma$ define its length

$$|\gamma| = \min\{n \in \mathbf{N} : \gamma \in S^n\} .$$

The growth series of (Γ, S) is the formal power series

$$f_{(\Gamma,S)}(t) = \sum_{\gamma \in \Gamma} t^{|\gamma|} \in \mathbf{N}[[t]].$$

Expanding $f_{(\Gamma,S)}(t) = \sum f_n t^n$, the growth of (Γ,S) is

$$\alpha(\Gamma, S) = \limsup_{n \to \infty} \sqrt[n]{f_n}$$

(this supremum-limit is actually a limit and is smaller than |S|-1).

Let R be a subset of Γ . The growth series of R relative to (Γ, S) is the formal power series

$$f_{(\Gamma,S)}^R(t) = \sum_{\gamma \in R} t^{|\gamma|} \in \mathbf{N}[[t]].$$

Expanding $f_{(\Gamma,S)}^R(t) = \sum f_n t^n$, define the growth of R relative to (Γ,S) as

$$\alpha(R; \Gamma, S) = \limsup_{n \to \infty} \sqrt[n]{f_n} .$$

If X is a transitive right Γ -set, the *simple random walk* on (X,S) is the random walk of a point on X, having probability 1/|S| of moving from its current position x to a neighbour $x \cdot s$, for all $s \in S$. Fix a point $* \in X$, and let p_n be the probability that a walk starting at * finish at * after n moves. We define the *spectral radius* (which does not depend on the choice of *) of the random walk as

$$\nu(X,S) = \limsup_{n \to \infty} \sqrt[n]{p_n} .$$

A group Π is *quasi-free* if it is a free product of cyclic groups of order 2 and ∞ . Equivalently, there exists a finite set S and an involution $\overline{\cdot}: S \to S$ such that, as a monoid,

$$\Pi = \langle S \mid s\bar{s} = 1 \quad \forall s \in S \rangle$$
.

 Π is then said to be *quasi-free on S*. All quasi-free groups on *S* have the same Cayley graph, which is a regular tree of degree |S|.

Every group Γ generated by a symmetric set S is a quotient of a quasifree group in the following way: let $\bar{\cdot}$ be an involution on S such that for all $s \in S$ we have the equality $\bar{s} = s^{-1}$ in Γ . Then Γ is a quotient of the quasi-free group $\langle S \mid s\bar{s} = 1 \quad \forall s \in S \rangle$.

The *cogrowth series* (respectively *cogrowth*) of (Γ, S) is defined as the growth series (respectively growth) of $\ker(\pi \colon \Pi \to \Gamma)$ relative to (Π, S) , where Π is a quasi-free group on S.

Associated with a group Π generated by a set S and a subgroup Ξ of Π , there is a |S|-regular graph \mathcal{X} on which Π acts, called the *Schreier graph* of (Π, S) relative to Ξ . It is given by $\mathcal{X} = (V, E)$, with

$$V = \Xi \backslash \Pi$$

and

$$E = V \times S$$
, $(v, s)^{\alpha} = v$, $(v, s)^{\omega} = vs$, $\overline{(v, s)} = (vs, s^{-1})$;

i.e. two cosets A,B are joined by at least one edge if and only if $AS \supset B$. (This is the Cayley graph of (Π,S) if $\Xi=1$.) There is a circuit in $\mathcal X$ at every vertex $\Xi v \in \Xi \backslash \Pi$ such that $s \in v^{-1}\Xi v$ for some $s \in S$; and there is a multiple edge from Ξv to Ξw in $\mathcal X$ if there are $s,t \in v^{-1}\Xi w$ with $s \neq t \in S$.

COROLLARY 3.2 (of Corollary 2.6). Let Π be a quasi-free group, presented as a monoid as

$$\Pi = \langle S \mid s\bar{s} = 1 \quad \forall s \in S \rangle .$$

Let $\Xi < \Pi$ be a subgroup of Π . Let $\nu = \nu(\Xi \backslash \Pi, S)$ denote the spectral radius of the simple random walk on $\Xi \backslash \Pi$ generated by S; and $\alpha = \alpha(\Xi; \Pi, S)$ denote the relative growth of Ξ in Π . Then we have

(3.1)
$$\nu = \begin{cases} \frac{\sqrt{|S|-1}}{|S|} \left(\frac{\alpha}{\sqrt{|S|-1}} + \frac{\sqrt{|S|-1}}{\alpha} \right) & \text{if } \alpha > \sqrt{|S|-1}, \\ \frac{2\sqrt{|S|-1}}{|S|} & \text{if } \alpha \le \sqrt{|S|-1}. \end{cases}$$

Proof. Let \mathcal{X} be the Schreier graph of (Π, S) relative to Ξ defined above. Fix the endpoints $\star = \dagger = \Xi$, the coset of 1, and give \mathcal{X} the length labelling. Let G and F be the circuit and proper circuit series of \mathcal{X} . In this setting, expressing $F(t) = \sum f_n t^n$ and $G(t) = \sum g_n t^n$, we see that $|S|\nu$ is the growth rate $\limsup \sqrt[n]{g_n}$ of circuits in \mathcal{X} , and α the growth rate $\limsup \sqrt[n]{f_n}$ of proper circuits in \mathcal{X} . As both F and G are power series with non-negative coefficients, $1/(|S|\nu)$ is the radius of convergence of G and $1/\alpha$ the radius of convergence of F. Let d = |S| and consider the function

$$(t)\phi = \frac{t}{1 + (d-1)t^2}$$
.

This function is strictly increasing for $0 \le t < 1/\sqrt{d-1}$, has a maximum at $t = 1/\sqrt{d-1}$ with $(t)\phi = 1/(2\sqrt{d-1})$, and is strictly decreasing for $t > 1/\sqrt{d-1}$.

First we suppose that $\alpha \geq \sqrt{d-1}$, so ϕ is monotonously increasing on $[0,1/\alpha]$. We set u=1 in (2.2) and note that, for t<1, it says that F has a singularity at t if and only if G has a singularity at $(t)\phi$. Now as $1/\alpha$ is the singularity of F closest to 0, we conclude by monotonicity of ϕ that the singularity of G closest to 0 is at $(1/\alpha)\phi$; thus

$$\frac{1}{d\nu} = \frac{1/\alpha}{1 + (d-1)/\alpha^2} = (1/\alpha)\phi$$
.

Suppose now that $\alpha < \sqrt{d-1}$. If $d\nu < 2\sqrt{d-1}$, the right-hand side of (2.2) would be bounded for all $t \in \mathbf{R}$ while the left-hand side diverges at t=1. If $d\nu > 2\sqrt{d-1}$, there would be a $t \in [0,1/\sqrt{d-1}[$ with $(t)\phi = d\nu$; and F would have a singularity at $t < 1/\alpha$. The only case left is $d\nu = 2\sqrt{d-1}$. \square

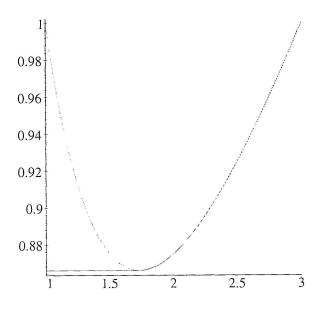


Figure 1

The function $\alpha \mapsto \nu$ relating cogrowth and spectral radius (for d=4)

COROLLARY 3.3 (Grigorchuk [Gri78b]). Let Γ be a group generated by a symmetric finite set S, let ν denote the spectral radius of the simple random walk on Γ , and let α denote the cogrowth of (Γ, S) . Then

(3.2)
$$\nu = \begin{cases} \frac{\sqrt{|S|-1}}{|S|} \left(\frac{\alpha}{\sqrt{|S|-1}} + \frac{\sqrt{|S|-1}}{\alpha} \right) & \text{if } \alpha > \sqrt{|S|-1}, \\ \frac{2\sqrt{|S|-1}}{|S|} & \text{else}. \end{cases}$$

A variety of proofs exist for this result: the original [Gri78b] by Grigorchuk, one by Cohen [Coh82], an extension by Northshield to regular graphs [Nor92], a short proof by Szwarc [Szw89] using operator theory, one by Woess [Woe94], etc.

Proof. Present Γ as Π/Ξ , with Π a quasi-free group and Ξ the normal subgroup of Π generated by the relators in Γ , and apply Corollary 3.2.

We note in passing that if $\alpha < \sqrt{|S|-1}$, then necessarily $\alpha = 0$. Equivalently, we will show that if $\alpha < \sqrt{|S|-1}$, then $\Xi = 1$, so the Cayley graph $\mathcal X$ is a tree. Indeed, suppose $\mathcal X$ is not a tree, so it contains a circuit λ at \star . As $\mathcal X$ is transitive, there is a translate of λ at every vertex, which we will still write λ . There are at least $|S|(|S|-1)^{t-2}(|S|-2)$ paths p of length t in $\mathcal X$ starting at \star such that the circuit $p\lambda \bar p$ is proper; thus

$$\alpha \ge \limsup_{t \to \infty} \sqrt[2t+|\lambda|]{|S|(|S|-1)^{t-2}(|S|-2)} = \sqrt{|S|-1}$$
.

In fact it is known that $\alpha > \sqrt{|S|-1}$; see [Pas93].