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# Mass formulas for local Galois representations to wreath products and cross products

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Bhargava proved a formula for counting, with certain weights, degree  $n$  étale extensions of a local field, or equivalently, local Galois representations to  $S_n$ . This formula is motivation for his conjectures about the density of discriminants of  $S_n$ -number fields. We prove there are analogous “mass formulas” that count local Galois representations to any group that can be formed from symmetric groups by wreath products and cross products, corresponding to counting towers and direct sums of étale extensions. We obtain as a corollary that the above mentioned groups have rational character tables. Our result implies that  $D_4$  has a mass formula for certain weights, but we show that  $D_4$  does not have a mass formula when the local Galois representations to  $D_4$  are weighted in the same way as representations to  $S_4$  are weighted in Bhargava’s mass formula.

## 1. Introduction

Bhargava [2007] proved the following mass formula for counting isomorphism classes of étale extensions of degree  $n$  of a local field  $K$ :

$$\sum_{[L:K]=n \text{ étale}} \frac{1}{|\text{Aut}(K)|} \cdot \frac{1}{\text{Norm}(\text{Disc}_K L)} = \sum_{k=0}^{n-1} p(k, n-k) q^{-k}, \quad (1-1)$$

where  $q$  is the cardinality of the residue field of  $K$ , and  $p(k, n-k)$  denotes the number of partitions of  $k$  into at most  $n-k$  parts. Equation (1-1) is proven using the beautiful mass formula of Serre [1978] which counts totally ramified degree  $n$  extensions of a local field. Equation (1-1) is at the heart of [Bhargava 2007, Conjecture 1] for the asymptotics of the number of  $S_n$ -number fields with discriminant  $\leq X$ , and also [Bhargava 2007, Conjectures 2–3] for the relative asymptotics of  $S_n$ -number fields with certain local behaviors specified. These conjectures are theorems for  $n \leq 5$  [Davenport and Heilbronn 1971; Bhargava 2005;  $\geq 2008$ ].

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Kedlaya [2007, Section 3] has translated Bhargava’s formula into the language of Galois representations so that the sum in (1-1) becomes a sum over Galois representations to  $S_n$  as follows:

$$\frac{1}{n!} \sum_{\rho: \text{Gal}(K^{\text{sep}}/K) \rightarrow S_n} \frac{1}{q^{c(\rho)}} = \sum_{k=0}^{n-1} p(k, n-k)q^{-k}, \tag{1-2}$$

where  $c(\rho)$  denotes the Artin conductor of  $\rho$  composed with the standard representation  $S_n \rightarrow \text{GL}_n(\mathbb{C})$ .

What is remarkable about the mass formulas in (1-1) and (1-2) is that the right hand side only depends on  $q$  and, in fact, is a polynomial (independent of  $q$ ) evaluated at  $q^{-1}$ . A priori, the left hand sides could depend on the actual local field  $K$ , and even if they only depended on  $q$ , it is not clear there should be a uniform way to write them as a polynomial function of  $q^{-1}$ . This motivates the following definitions. Given a local field  $K$  and a finite group  $\Gamma$ , let  $S_{K,\Gamma}$  denote the set of continuous homomorphisms  $\text{Gal}(K^{\text{sep}}/K) \rightarrow \Gamma$  (for the discrete topology on  $\Gamma$ ) and let  $q_K$  denote the size of the residue field of  $K$ . Given a function  $c: S_{K,\Gamma} \rightarrow \mathbb{Z}_{\geq 0}$ , we define the *total mass* of  $(K, \Gamma, c)$  to be

$$M(K, \Gamma, c) := \sum_{\rho \in S_{K,\Gamma}} \frac{1}{q_K^{c(\rho)}}.$$

(If the sum diverges, we could say the mass is  $\infty$  by convention. In most interesting cases, for example see [Kedlaya 2007, Remark 2.3], and all cases we consider in this paper, the sum will be convergent.) Kedlaya gave a similar definition, but one should note that our definition of mass differs from that in [Kedlaya 2007] by a factor of  $|\Gamma|$ . In [Kedlaya 2007],  $c(\rho)$  is always taken to be the Artin conductor of the composition of  $\rho$  and some  $\Gamma \rightarrow \text{GL}_n(\mathbb{C})$ . We refer to such  $c$  as the *counting function attached to the representation*  $\Gamma \rightarrow \text{GL}_n(\mathbb{C})$ . In this paper, we consider more general  $c$ .

Given a group  $\Gamma$ , a *counting function for*  $\Gamma$  is any function

$$c: \bigcup_K S_{K,\Gamma} \rightarrow \mathbb{Z}_{\geq 0}$$

where the union is over all isomorphism classes of local fields, such that

$$c(\rho) = c(\gamma\rho\gamma^{-1})$$

for every  $\gamma \in \Gamma$ . (Since an isomorphism of local fields only determines an isomorphism of their absolute Galois groups up to conjugation, we need this condition in order for the counting functions to be sensible.) Let  $c$  be a counting function for  $\Gamma$  and  $S$  be a class of local fields. We say that  $(\Gamma, c)$  has a *mass formula* for  $S$  if

there exists a polynomial  $f(x) \in \mathbb{Z}[x]$  such that for all local fields  $K \in S$  we have

$$M(K, \Gamma, c) = f\left(\frac{1}{q_K}\right).$$

We also say that  $\Gamma$  has a mass formula for  $S$  if there is a  $c$  such that  $(\Gamma, c)$  has a mass formula for  $S$ .

Kedlaya [2007, Theorem 8.5] proved that  $(W(B_n), c_{B_n})$  has a mass formula for all local fields, where  $W(B_n)$  is the Weyl group of  $B_n$  and  $c_{B_n}$  is the counting function attached to the Weyl representation of  $B_n$ . This is in analogy with (1-2) which shows that  $(W(A_n), c_{A_n})$  has a mass formula for all local fields, where  $W(A_n) \cong S_n$  is the Weyl group of  $A_n$  and  $c_{A_n}$  is the counting function attached to the Weyl representation of  $A_n$ . Kedlaya’s analogy is very attractive, but he found that it does not extend to the Weyl groups of  $D_4$  or  $G_2$  when the counting function is the one attached to the Weyl representation; he showed that mass formulas for all local fields do not exist for those groups and those particular counting functions.

The main result of this paper is the following.

**Theorem 1.1.** *Any permutation group that can be constructed from the symmetric groups  $S_n$  using wreath products and cross products has a mass formula for all local fields.*

The mass formula of Kedlaya [2007, Theorem 8.5] for  $W(B_n) \cong S_2 \wr S_n$  was the inspiration for this result, and it is now a special case of Theorem 1.1.

Bhargava [2007, Section 8.2] asks whether his conjecture for  $S_n$ -extensions about the relative asymptotics of the number of global fields with specified local behaviors holds for other Galois groups. Ellenberg and Venkatesh [2005, Section 4.2] suggest that we can try to count extensions of global fields by quite general invariants of Galois representations. In [Wood 2008], it is shown that when counting by certain invariants of abelian global fields, such as conductor, Bhargava’s question can be answered affirmatively. It is also shown in [Wood 2008] that when counting abelian global fields by discriminant, the analogous conjectures fail in at least some cases. In light of the fact that Bhargava’s conjectures for the asymptotics of the number of  $S_n$ -number fields arise from his mass formula (1-1) for counting by discriminant, one naturally looks for mass formulas that use other ways of counting, such as Theorem 1.1, which might inspire conjectures for the asymptotics of counting global fields with other Galois groups.

In Section 2, we prove that if groups  $A$  and  $B$  have certain refined mass formulas, then  $A \wr B$  and  $A \times B$  also have such refined mass formulas, which inductively proves Theorem 1.1. Bhargava’s mass formula for  $S_n$ , given in (1-2), is our base case. In Section 3, as a corollary of our main theorem, we see that any group formed from symmetric groups by taking wreath and cross products has a rational character table. This result, at least in such simple form, is not easily found in the literature.

In order to suggest what our results say in the language of field extensions, in Section 4 we mention the relationship between Galois representations to wreath products and towers of field extensions.

In Section 5, we discuss some situations in which groups have mass formulas for one way of counting but not another. In particular, we show that  $D_4 \cong S_2 \wr S_2$  does not have a mass formula for all local fields when  $c(\rho)$  is the counting function attached to the standard representation of  $S_4$  restricted to  $D_4 \subset S_4$ . Consider quartic extensions  $M$  of  $K$ , whose Galois closure has group  $D_4$ , with quadratic subfield  $L$ . The counting function that gives the mass formula for  $D_4$  of Theorem 1.1 corresponds to counting such extensions  $M$  weighted by

$$|\text{Disc}(L|K)N_{L|K}(\text{Disc}(M|L))|^{-1},$$

whereas the counting function attached to the standard representation of  $S_4$  restricted to  $D_4 \subset S_4$  corresponds to counting such extensions  $M$  weighted by

$$|\text{Disc}(M|K)|^{-1} = |\text{Disc}(L|K)^2 N_{L|K}(\text{Disc}(M|L))|^{-1}.$$

So this change of exponent in the  $\text{Disc}(L|K)$  factor affects the existence of a mass formula for all local fields.

**Notation.** Throughout this paper,  $K$  is a local field and  $G_K := \text{Gal}(K^{\text{sep}}/K)$  is the absolute Galois group of  $K$ . All maps in this paper from  $G_K$  or subgroups of  $G_K$  are continuous homomorphisms, with the discrete topology on all finite groups. We let  $I_K$  denote the inertia subgroup of  $G_K$ . Recall that  $S_{K,\Gamma}$  is the set of maps  $G_K \rightarrow \Gamma$ , and  $q_K$  is the size of residue field of  $K$ . Also,  $\Gamma$  will always be a permutation group acting on a finite set.

### 2. Proof of Theorem 1.1

In order to prove Theorem 1.1, we prove finer mass formulas first. Instead of summing over all representations of  $G_K$ , we stratify the representations by *type* and prove mass formulas for the sum of representations of each type. Let  $\rho : G_K \rightarrow \Gamma$  be a representation such that the action of  $G_K$  has  $r$  orbits  $m_1, \dots, m_r$ . If, under restriction to the representation  $\rho : I_K \rightarrow \Gamma$ , orbit  $m_i$  breaks up into  $f_i$  orbits of size  $e_i$ , then we say that  $\rho$  is of *type*  $(f_1^{e_1} f_2^{e_2} \dots f_r^{e_r})$  (where the terms  $f_i^{e_i}$  are unordered formal symbols, as in [Bhargava 2007, Section 2]). Let  $L_i$  be the fixed field of the stabilizer of an element in  $m_i$ . So,  $[L_i : K] = |m_i|$ . Since  $I_{L_i} = G_{L_i} \cap I_K$  is the stabilizer in  $I_K$  of an element in  $m_i$ , we conclude that  $e_i = [I_K : I_{L_i}]$ , which is the ramification index of  $L_i/K$ . Thus,  $f_i$  is the inertial degree of  $L_i/K$ .

Given  $\Gamma$ , a counting function  $c$  for  $\Gamma$ , and a type

$$\sigma = (f_1^{e_1} f_2^{e_2} \dots f_r^{e_r}),$$

we define the *total mass* of  $(K, \Gamma, c, \sigma)$  to be

$$M(K, \Gamma, c, \sigma) := \sum_{\substack{\rho \in \mathcal{S}_{K, \Gamma} \\ \text{type } \sigma}} \frac{1}{q_K^{c(\rho)}}.$$

We say that  $(\Gamma, c)$  has *mass formulas for  $S$  by type* if for every type  $\sigma$  there exists a polynomial  $f_{(\Gamma, c, \sigma)}(x) \in \mathbb{Z}[x]$  such that for all local fields  $K \in S$  we have

$$M(K, \Gamma, c, \sigma) = f_{(\Gamma, c, \sigma)}\left(\frac{1}{q_K}\right).$$

Bhargava [2007, Proposition 1] actually proved that  $S_n$  has mass formulas for all local fields by type. Of course, if  $(\Gamma, c)$  has mass formulas by type, then we can sum over all types to obtain a mass formula for  $(\Gamma, c)$ .

The key step in the proof of Theorem 1.1 is the following.

**Theorem 2.1.** *If  $A$  and  $B$  are finite permutation groups,  $S$  is some class of local fields, and  $(A, c_A)$  and  $(B, c_B)$  have mass formulas for  $S$  by type, then there exists a counting function  $c$  (given in (2-3)) such that  $(A \wr B, c)$  has mass formulas for  $S$  by type.*

*Proof.* Let  $K$  be a local field in  $S$ . Let  $A$  act on the left on the set  $\mathcal{A}$  and  $B$  act on the left on the set  $\mathcal{B}$ . We take the natural permutation action of  $A \wr B$  acting on a disjoint union of copies of  $\mathcal{A}$  indexed by elements of  $\mathcal{B}$ . Fix an ordering on  $\mathcal{B}$  so that we have canonical orbit representatives in  $\mathcal{B}$ . Given  $\rho : G_K \rightarrow A \wr B$ , there is a natural quotient  $\bar{\rho} : G_K \rightarrow B$ . Throughout this proof, we use  $j$  as an indexing variable for the set  $\mathcal{B}$  and  $i$  as an indexing variable for the  $r$  canonical orbit representatives in  $\mathcal{B}$  of the  $\rho(G_K)$  action. Let  $i_j$  be the index of the orbit representative of  $j$ 's orbit. Let  $S_j \subset G_K$  be the stabilizer of  $j$ , and let  $S_j$  have fixed field  $L_j$ . We define  $\rho_j : G_{L_j} \rightarrow A$  to be the given action of  $G_{L_j}$  on the  $j$ -th copy of  $\mathcal{A}$ . We say that  $\rho$  has *wreath type*

$$\Sigma = (f_1^{e_1}(\sigma_1) \cdots f_r^{e_r}(\sigma_r)) \tag{2-1}$$

if  $\bar{\rho}$  has type  $\sigma = (f_1^{e_1} \cdots f_r^{e_r})$  (where  $f_i^{e_i}$  corresponds to the orbit of  $i$ ) and  $\rho_i$  has type  $\sigma_i$ . Note that type is a function of wreath type; if  $\rho$  has wreath type  $\Sigma$  as above where

$$\sigma_i = (f_{i,1}^{e_{i,1}} \cdots f_{i,r_i}^{e_{i,r_i}}),$$

then  $\rho$  has type  $((f_i f_{i,k})^{e_i e_{i,k}})_{1 \leq i \leq r, 1 \leq k \leq r_i}$ .

We consider the function  $c$  defined as follows:

$$c(\rho) = c_B(\bar{\rho}) + \sum_{j \in \mathcal{B}} \frac{c_A(\rho_j)}{|\{\bar{\rho}(I_K)j\}|}. \tag{2-2}$$

Since  $c_B(\bar{\rho})$  only depends on the  $B$ -conjugacy class of  $\bar{\rho}$  and  $c_A(\rho_j)$  depends only on the  $A$ -conjugacy class of  $\rho_j$ , we see that conjugation by elements of  $A \wr B$  does not affect the right hand side of (2-3) except by reordering the terms in the sum. Thus  $c$  is a counting function.

Since  $\rho_j$  and  $\rho_{i_j}$  are representations of conjugate subfields of  $G_K$  and since  $c_A$  is invariant under  $A$ -conjugation,  $c_A(\rho_j) = c_A(\rho_{i_j})$ . There are  $f_i e_i$  elements in the orbit of  $i$  under  $\bar{\rho}(G_K)$  and  $e_{i_j}$  elements in the orbit of  $j$  under  $\bar{\rho}(I_K)$ , so

$$c(\rho) = c_B(\bar{\rho}) + \sum_{i=1}^r \frac{f_i e_i}{e_i} c_A(\rho_i)$$

and thus

$$c(\rho) = c_B(\bar{\rho}) + \sum_{i=1}^r f_i c_A(\rho_i). \tag{2-3}$$

Using this expression for  $c(\rho)$ , we will prove that  $(A \wr B, c)$  has mass formulas by wreath type. Then, summing over wreath types that give the same type, we will prove that  $(A \wr B, c)$  has mass formulas by type.

**Remark 2.2.** For a permutation group  $\Gamma$ , let  $d_\Gamma$  be the counting function attached to the permutation representation of  $\Gamma$  (which is the discriminant exponent of the associated étale extension). Then we can compute

$$d_{A \wr B} = |\mathcal{A}| d_B(\bar{\rho}) + \sum_{i=1}^r f_i d_A(\rho_i),$$

which is similar to the expression given in (2-3) but differs by the presence of  $|\mathcal{A}|$  in the first term. In particular, when we have mass formulas for  $(A, d_A)$  and  $(B, d_B)$ , the mass formula for  $A \wr B$  that we find in this paper is not with the counting function  $d_{A \wr B}$ . We will see in Section 5, when  $A$  and  $B$  are both  $S_2$ , that  $S_2 \wr S_2 \cong D_4$  does not have a mass formula with  $d_{A \wr B}$ .

**Lemma 2.3.** *The correspondence  $\rho \mapsto (\bar{\rho}, \rho_1, \dots, \rho_r)$  described above gives a function  $\Psi$  from  $S_{K, A \wr B}$  to tuples  $(\phi, \phi_1, \dots, \phi_r)$  where  $\phi : G_K \rightarrow B$ , the groups  $S_i$  are the stabilizers of canonical orbit representatives of the action of  $\phi$  on  $B$ , and  $\phi_i : S_i \rightarrow A$ . The map  $\Psi$  is  $(|A|^{|\mathcal{B}|-r})$ -to-one and surjective.*

*Proof.* Lemma 2.3 holds when  $G_K$  is replaced by any group. It suffices to prove the lemma when  $\bar{\rho}$  and  $\phi$  are transitive because the general statement follows by multiplication. Let  $b \in \mathcal{B}$  be the canonical orbit representative. Given a

$$\phi : G_K \rightarrow B \quad (\text{or a } \bar{\rho} : G_K \rightarrow B)$$

for all  $j \in \mathcal{B}$ , choose a  $\sigma_j \in G_K$  such that  $\phi(\sigma_j)$  takes  $b$  to  $j$ . Given a  $\rho : G_K \rightarrow A \wr B$ , let  $\alpha_j$  be the element of  $A$  such that  $\rho(\sigma_j)$  acts on the  $b$ -th copy of  $\mathcal{A}$  by  $\alpha_j$  and

then moves the  $b$ -th copy of  $\mathcal{A}$  to the  $j$ -th copy. Then for  $g \in G_K$ , the map  $\rho$  is given by

$$\rho(g) = \bar{\rho}(g)(a_j)_{j \in \mathcal{B}} \in BA^{|\mathcal{B}|} = A \wr B, \tag{2-4}$$

where

$$a_j = \alpha_{\bar{\rho}(g)(j)} \rho_1(\sigma_{\bar{\rho}(g)(j)}^{-1} g \sigma_j) \alpha_j^{-1},$$

and  $a_j \in A$  acts on the  $j$ -th copy of  $\mathcal{A}$ . For any transitive maps  $\phi: G_K \rightarrow B$  and  $\phi_b: S_b \rightarrow A$  and for any choices of  $\alpha_j \in A$  for all  $j \in \mathcal{B}$  such that  $\alpha_b = \phi_b(\sigma_b)$ , we can check that (2-4) for  $\bar{\rho} = \phi$  and  $\rho_1 = \phi_b$  gives a homomorphism  $\rho: G_K \rightarrow A \wr B$  with  $(\bar{\rho}, \rho_1) = (\phi, \phi_b)$ , which proves the lemma.  $\square$

If  $\Sigma$  is as in (2-1), then

$$\sum_{\substack{\rho: G_K \rightarrow A \wr B \\ \text{wreath type } \Sigma}} \frac{1}{q_K^{c(\rho)}} = |A|^{|\mathcal{B}|-r} \sum_{\substack{\phi: G_K \rightarrow B \\ \text{type } \sigma}} \sum_{\substack{\phi_1: S_1 \rightarrow A \\ \text{type } \sigma_1}} \sum_{\substack{\phi_2: S_2 \rightarrow A \\ \text{type } \sigma_2}} \cdots \sum_{\substack{\phi_r: S_r \rightarrow A \\ \text{type } \sigma_r}} \frac{1}{q_K^{c_B(\phi) + \sum_{i=1}^r f_i c_A(\phi_i)}} \tag{2-5}$$

where  $S_i$  is the stabilizer under  $\phi$  of a canonical orbit representative of the action of  $\phi$  on  $\mathcal{B}$ . The right hand side of (2-5) factors, and  $S_i \subset G_K$  has fixed field  $L_i$  with residue field of size  $q_K^{f_i}$ . We conclude that

$$\begin{aligned} \sum_{\substack{\rho: G_K \rightarrow A \wr B \\ \text{wreath type } \Sigma}} \frac{1}{q_K^{c(\rho)}} &= |A|^{|\mathcal{B}|-r} \sum_{\substack{\phi: G_K \rightarrow B \\ \text{type } \sigma}} \frac{1}{q_K^{c_A(\phi)}} \sum_{\substack{\phi_1: G_{L_1} \rightarrow A \\ \text{type } \sigma_1}} \frac{1}{q_K^{f_1 c_B(\phi_1)}} \cdots \sum_{\substack{\phi_r: G_{L_r} \rightarrow A \\ \text{type } \sigma_r}} \frac{1}{q_K^{f_r c_B(\phi_r)}} \\ &= |A|^{|\mathcal{B}|-r} f_{(B, c_B, \sigma)} \left( \frac{1}{q_K} \right) \prod_{i=1}^r f_{(A, c_A, \sigma_i)} \left( \frac{1}{q_K^{f_i}} \right). \end{aligned}$$

So,  $(A \wr B, c)$  has mass formulas by wreath type, and thus by type.  $\square$

Kedlaya [2007, Lemma 2.6] noted that if  $(\Gamma, c)$  and  $(\Gamma', c')$  have mass formulas  $f$  and  $f'$ , then  $(\Gamma \times \Gamma', c'')$  has mass formula  $ff'$ , where  $c''(\rho \times \rho') = c(\rho) + c'(\rho')$ . We can strengthen this statement to mass formulas by type using a much easier version of our argument for wreath products. We define the *product type* of a representation  $\rho \times \rho': G_K \rightarrow \Gamma \times \Gamma'$  to be  $(\sigma, \sigma')$ , where  $\sigma$  and  $\sigma'$  are the types of  $\rho$  and  $\rho'$  respectively. Then

$$\sum_{\substack{\rho \times \rho': G_K \rightarrow \Gamma \times \Gamma' \\ \text{product type } (\sigma, \sigma')}} \frac{1}{q_K^{c''(\rho \times \rho')}} = \sum_{\substack{\phi: G_K \rightarrow \Gamma \\ \text{type } \sigma}} \frac{1}{q_K^{c(\rho)}} \sum_{\substack{\phi_1: G_{L_1} \rightarrow \Gamma' \\ \text{type } \sigma'}} \frac{1}{q_K^{c'(\rho')}}.$$

If  $\Gamma$  and  $\Gamma'$  have mass formulas by type, then the above gives mass formulas of  $\Gamma \times \Gamma'$  by product type. Since type is a function of product type, we can sum the mass formulas by product type to obtain mass formulas by type for  $\Gamma \times \Gamma'$ .

This, combined with Theorem 2.1 and Bhargava's mass formula for  $S_n$  by type [Bhargava 2007, Proposition 1], proves Theorem 1.1.

### 3. Groups with rational character tables

Kedlaya [2007, Proposition 5.3, Corollary 5.4, Corollary 5.5] showed that if  $c(\rho)$  is the counting function attached to  $\Gamma \rightarrow \mathrm{GL}_n(\mathbb{C})$ , then the following statement holds:  $(\Gamma, c)$  has a mass formula for all local fields  $K$  with  $q_K$  relatively prime to  $|\Gamma|$  if and only if the character table of  $\Gamma$  has all rational entries. The proofs of [Kedlaya 2007, Proposition 5.3, Corollary 5.4, Corollary 5.5] hold for any counting function  $c$  that is determined by  $\rho(I_K)$ . This suggests that we define a *proper* counting function to be a counting function  $c$  that satisfies the following: if we have

$$\rho : G_K \rightarrow \Gamma \quad \text{and} \quad \rho' : G_{K'} \rightarrow \Gamma$$

with  $q_K, q_{K'}$  relatively prime to  $|\Gamma|$ , and if  $\rho(I_K) = \rho'(I_{K'})$ , then  $c(\rho) = c(\rho')$ .

For proper counting functions, we always have partial mass formulas proven as in [Kedlaya 2007, Corollary 5.4].

**Proposition 3.1.** *Let  $a$  be an invertible residue class mod  $|\Gamma|$  and  $c$  be a proper counting function. Then  $(\Gamma, c)$  has a mass formula for all local fields  $K$  with  $q_K \in a$ .*

The following proposition says exactly when these partial mass formulas agree, again proven as in [Kedlaya 2007, Corollary 5.5].

**Proposition 3.2.** *Let  $c$  be a proper counting function for  $\Gamma$ . Then  $(\Gamma, c)$  has a mass formula for all local fields  $K$  with  $q_K$  relatively prime to  $|\Gamma|$  if and only if  $\Gamma$  has a rational character table.*

So, when looking for a group and a proper counting function with mass formulas for all local fields, we should look among groups with rational character tables (which are relatively rare, for example including only 14 of the 93 groups of order  $< 32$  [Conway 2006]). All specific counting functions that have been so far considered in the literature are proper. It is not clear if there are any interesting nonproper counting functions.

Our proof of Theorem 2.1 has the following corollary.

**Corollary 3.3.** *Any permutation group that can be constructed from the symmetric groups using wreath products and cross products has a rational character table.*

*Proof.* We first show that the counting function  $c$  defined in (2-2) is proper if  $c_A$  and  $c_B$  are proper. We consider only fields  $K$  with  $q_K$  relatively prime to  $|\Gamma|$ . Since  $c_B(\bar{\rho})$  only depends on  $\bar{\rho}(I_K)$ , it is clear that the  $c_B(\bar{\rho})$  term only depends on  $\rho(I_K)$ .

Since  $I_{L_j} = I_K \cap S_j$ , we have

$$\rho_j(I_{L_j}) = \rho(I_{L_j}) = \rho(I_K) \cap \text{Stab}(j).$$

Since  $c_A(\rho_j)$  depends only on  $\rho_j(I_{L_j})$ , we see that it depends only on  $\rho(I_K)$ . The sum in (2-2) then depends only on  $\rho(I_K)$ . So the  $c$  defined in (2-2) is proper. Clearly the  $c''(\rho \times \rho')$  defined for cross products is proper if  $c$  and  $c'$  are proper. The counting function in Bhargava’s mass formula for  $S_n$  (see (1-2)) is an Artin conductor and thus is proper. So we can prove Theorem 1.1 with a proper counting function and conclude the corollary.

One can show in a similar way that even in wild characteristics, the counting function  $c$  defined in (2-3) depends only on the images of the higher ramification groups  $G_K^m$ , that is, if

$$\rho : G_K \rightarrow A \wr B \quad \text{and} \quad \rho' : G'_K \rightarrow A \wr B$$

have  $\rho(G_K^m) = \rho'(G'^m_K)$  for all  $m \in [0, \infty)$ , then  $c(\rho) = c(\rho')$ , as long as the same is true for  $c_A$  and  $c_B$ . □

So, for example,  $((S_7 \wr S_4) \times S_3) \wr S_8$  has a rational character table. Corollary 3.3 does not seem to be a well-reported fact in the literature; the corollary shows that all Sylow 2-subgroups of symmetric groups (which are cross products of wreath products of  $S_2$ ’s) have rational character table, which was posed as an open problem in [Mazurov and Khukhro 1999, Problem 15.25] and solved in [Revin 2004; Kolesnikov 2005]. However, since

$$A \wr (B \wr C) = (A \wr B) \wr C \quad \text{and} \quad A \wr (B \times C) = (A \wr B) \times (A \wr C),$$

any of the groups of Corollary 3.3 can be constructed only using the cross product and  $\wr S_n$  operations. It is well known that the cross product of two groups with rational character tables has a rational character table. Furthermore, Pfeiffer [1994] explains how GAP computes the character table of  $G \wr S_n$  from the character table of  $G$ , and one can check that if  $G$  has rational character table then all of the values constructed in the character table of  $G \wr S_n$  are rational, which implies Corollary 3.3.

One might hope that all groups with rational character tables have mass formulas by type, but this is not necessarily the case. For example, considering

$$(C_3 \times C_3) \rtimes C_2$$

(where  $C_2$  acts nontrivially on each factor separately) in the tame case in type  $(1^3 2^1 1^1)$ , one can check that for  $q \equiv 1 \pmod{3}$  the mass is zero and for  $q \equiv 2 \pmod{3}$  the mass is nonzero.

**4. Towers and direct sums of field extensions**

Kedlaya explains the correspondence between Galois permutation representations and étale extensions in [Kedlaya 2007, Lemma 3.1]. We have seen this correspondence already in other terms. If we have a representation  $\rho : G_K \rightarrow \Gamma$  with  $r$  orbits,  $S_i$  is the stabilizer of an element in the  $i$ -th orbit, and  $L_i$  is the fixed field of  $S_i$ , then  $\rho$  corresponds to  $L = \bigoplus_{i=1}^r L_i$ . For a local field  $F$ , let  $\wp_F$  be the prime of  $F$ . In this correspondence, if  $c$  is the counting function attached to the permutation representation of  $\Gamma$ , then  $c$  is the discriminant exponent of the extension  $L/K$  [Kedlaya 2007, Lemma 3.4]. In other words,

$$\wp_K^{c(\rho)} = \text{Disc}(L|K).$$

We can interpret the representations  $\rho : G_K \rightarrow A \wr B$  as towers of étale extensions  $M/L/K$ . If we take  $\bar{\rho} : G_K \rightarrow B$ , then  $L = \bigoplus_{i=1}^r L_i$  is just the étale extension of  $K$  corresponding to  $\bar{\rho}$ . Then if  $M$  is the étale extension of  $K$  corresponding to  $\rho$ , we see that  $M = \bigoplus_{i=1}^r M_i$ , where  $M_i$  is the étale extension of  $L_i$  corresponding to  $\rho_i : G_{L_i} \rightarrow A$ . So we see that  $M$  is an étale extension of  $L$ , though  $L$  might not be a field.

Let  $c$  be the counting function of our mass formula for wreath products, given by (2-3). From (2-3), we obtain

$$\wp_K^{c(\rho)} = \wp_K^{c_B(\bar{\rho})} \prod_{i=1}^r N_{L_i|K}(\wp_{L_i}^{c_A(\rho_i)}).$$

For example, if  $c_A$  and  $c_B$  are both given by the discriminant exponent (or equivalently, attached to the permutation representation), then

$$\wp_K^{c(\rho)} = \text{Disc}(L|K) \prod_{i=1}^r N_{L_i|K}(\text{Disc}(M_i|L_i)). \tag{4-1}$$

For comparison,

$$\text{Disc}(M|K) = \text{Disc}(L|K)^{[M:L]} \prod_{i=1}^r N_{L_i|K}(\text{Disc}(M_i|L_i)).$$

As we will see for  $\Gamma = D_4$  in the next section, representations  $\rho : G_K \rightarrow \Gamma$  can give not only field extensions of  $K$  whose Galois closure has Galois group  $\Gamma$ , but also field extensions whose Galois closure has Galois group a proper subgroup of  $\Gamma$ , as well as direct sums of field extensions. One could say that representations  $\rho : G_K \rightarrow A \wr B$  correspond to towers of “ $A$ -extensions” over “ $B$ -extensions” and further relate iterated wreath products to iterated towers. Similarly, one could say

that a representation  $\rho : G_K \rightarrow A \times B$  corresponds to a direct sum of an “ $A$ -extension” and a “ $B$ -extension.” The quotes indicate that the extensions do not necessarily have Galois closure with group  $A$  or  $B$ . In fact, it seems the most convenient way to define “ $A$ -extensions” or isomorphisms of “ $A$ -extensions” is simply to use the language of Galois representations as we have in this paper.

### 5. Masses for $D_4$

By Proposition 3.2 we know, at least for proper counting functions, that the existence of a mass formula for a group  $\Gamma$  for fields with  $q_K$  relatively prime to  $|\Gamma|$  does not depend on the choice of the counting function. However, in wild characteristic this is not the case. For example,  $D_4$ , the dihedral group with 8 elements, is isomorphic to  $S_2 \wr S_2$ , so by Theorem 1.1 there is a  $c$  (given in (2-3)) for which  $D_4$  has a mass formula for all local fields. An expression for  $c$  in terms of étale extensions can be read off from (4-1). In particular, for a surjective representation  $\rho : G_K \rightarrow D_4$  corresponding to a quartic field extension  $M$  of  $K$  with a quadratic subextension  $L$ ,

$$\wp_K^{c(\rho)} = \text{Disc}(L|K)N_{L|K}(\text{Disc}(M|L)). \tag{5-1}$$

For this  $c$ , for all local fields  $K$ , we have that

$$M(K, D_4, c) := \sum_{\rho \in S_{K, D_4}} \frac{1}{q_K^{c(\rho)}} = 8 + \frac{16}{q_K} + \frac{16}{q_K^2}.$$

From the definition of  $c$  given in (2-2) and the description of the absolute tame Galois group of a local field, we can compute  $M(K, D_4, c)$  for a field  $K$  with  $q_K$  odd. By Theorem 2.1 we know the formula holds for all  $K$ .

However, the counting function for  $D_4$  that has been considered when counting global extensions (for example in [Cohen et al. 2002]) is the one attached the faithful permutation representation of  $D_4$  on a four element set (equivalently the discriminant exponent of the corresponding étale extension). We call this counting function  $d$ , and in comparison with (5-1) we have

$$\wp_K^{d(\rho)} = \text{Disc}(M|K) = \text{Disc}(L|K)^2 N_{L|K}(\text{Disc}(M|L)).$$

With  $d$ , we now show that  $D_4$  does not have a mass formula for all local fields.

Using the correspondence of Section 4, we can analyze the representations

$$\rho : G_K \rightarrow D_4 \subset S_4$$

in Table 1, where

$$I = \text{image}(\rho), \quad j = |\{s \in S_4 \mid sIs^{-1} \subset D_4\}| \quad \text{and} \quad k = |\text{Centralizer}_{S_4}(I)|.$$

We take the  $D_4$  in  $S_4$  generated by (1 2 3 4) and (1 3).

$I$	$j$	$k$	$L$
$D_4$	8	2	degree 4 field whose Galois-closure/ $K$ has group $D_4$
$C_4$	8	4	degree 4 field Galois/ $K$ with group $C_4 \cong \mathbb{Z}/4$
$\langle(12)(34), (13)(24)\rangle$	24	4	degree 4 field Galois/ $K$ with group $V_4 \cong \mathbb{Z}/2 \times \mathbb{Z}/2$
$\langle(13), (24)\rangle$	8	4	$L_1 \oplus L_2$ with $[L_i : K]=2$ and $L_i$ distinct fields
$\langle(13)(24)\rangle, \langle(12)(34)\rangle$ or $\langle(14)(23)\rangle$	24	8	$L_1 \oplus L_2$ with $[L_i : K]=2$ and $L_1 \cong L_2$ fields
$\langle(24)\rangle$ or $\langle(13)\rangle$	8	4	$L_1 \oplus K \oplus K$ with $[L_1 : K]=2$ and $L_1$ a field
1	24	24	$K \oplus K \oplus K \oplus K$

**Table 1**

Each isomorphism class of algebras appears  $\frac{j}{k}$  times from a representation  $\rho : G_K \rightarrow D_4$  (see [Kedlaya 2007, Lemma 3.1]). Let  $S(K, G, m)$  be the set of isomorphism classes of degree  $m$  field extensions of  $K$  whose Galois closure over  $K$  has group  $G$ . Then from the above table we see that

$$\begin{aligned}
 M(K, D_4, d) = & \sum_{F \in S(K, D_4, 4)} \frac{4}{|\text{Disc } F|} + \sum_{F \in S(K, C_4, 4)} \frac{2}{|\text{Disc } F|} + \sum_{F \in S(K, V_4, 4)} \frac{6}{|\text{Disc } F|} \\
 & + \sum_{\substack{F_1, F_2 \in S(K, C_2, 2) \\ F_1 \neq F_2}} \frac{2}{|\text{Disc } F_1| |\text{Disc } F_2|} + \sum_{F \in S(K, C_2, 2)} \frac{3}{|\text{Disc } F|^2} \\
 & + \sum_{F \in S(K, C_2, 2)} \frac{2}{|\text{Disc } F|} + 1,
 \end{aligned}$$

where if  $\wp_F$  is the prime of  $F$  and  $\text{Disc } F = \wp_F^m$ , then  $|\text{Disc } F| = q_F^m$ . Using the Database of Local Fields [Jones and Roberts 2006] we can compute that  $M(\mathbb{Q}_2, D_4, d) = \frac{121}{8}$ . For fields with  $2 \nmid q_K$ , the structure of the tame quotient of the absolute Galois group of a local field allows us to compute the mass to be

$$8 + \frac{8}{q_K} + \frac{16}{q_K^2} + \frac{8}{q_K^3}$$

(also see [Kedlaya 2007, Corollary 5.4]) which evaluates to 17 for  $q_K = 2$ . Thus  $(D_4, d)$  does not have a mass formula for all local fields.

As another example, Kedlaya [2007, Proposition 9.3] found that  $W(G_2)$  does not have a mass formula for all local fields of residual characteristic 2 when  $c$  is the Artin conductor of the Weyl representation. However,  $W(G_2) \cong S_2 \times S_3$  and thus it has a mass formula for all local fields with counting function the sum of the Artin conductors of the standard representations of  $S_2$  and  $S_3$ .

It would be interesting to study what the presence or absence of mass formulas tells us about a counting function, in particular with respect to how global fields can be counted asymptotically with that counting function. As in Bhargava [2007, Section 8.2], we can form an Euler series

$$M_c(\Gamma, s) = C(\Gamma) \left( \sum_{\rho \in S_{\mathbb{R}, \Gamma}} \frac{1}{|\Gamma|} \right) \prod_p \left( \frac{1}{|\Gamma|} \sum_{\rho \in S_{\mathbb{Q}_p, \Gamma}} \frac{1}{p^{c(\rho)s}} \right) = \sum_{n \geq 1} m_n n^{-s},$$

where  $C(\Gamma)$  is some simple, yet to be explained, rational constant. (We work over  $\mathbb{Q}$  for simplicity, and the product is over rational primes.) For a representation  $\rho : G_{\mathbb{Q}} \rightarrow \Gamma$ , let  $\rho_p$  be the restriction of  $\rho$  to  $G_{\mathbb{Q}_p}$ . The idea is that  $m_n$  should be a heuristic of the number of  $\Gamma$ -extensions of  $\mathbb{Q}$  (that is, surjective  $\rho : G_{\mathbb{Q}} \rightarrow \Gamma$ ) with

$$\prod_p p^{c(\rho_p)} = n,$$

though  $m_n$  is not necessarily an integer.

Bhargava [2007, Section 8.2] asks the following question.

**Question 5.1.** Does

$$\lim_{X \rightarrow \infty} \frac{\sum_{n=1}^X m_n}{|\{\text{isom. classes of surjective } \rho : G_{\mathbb{Q}} \rightarrow \Gamma \text{ with } \prod_p p^{c(\rho_p)} \leq X\}|} = 1?$$

Bhargava in fact asks more refined questions in which some local behaviors are fixed. With the counting function  $d$  for  $D_4$  attached to the permutation representation (that is, the discriminant exponent), we can form  $M_d(D_4, s)$  and compute numerically the above limit. We use the work of Cohen, Diaz y Diaz, and Oliver on counting  $D_4$ -extensions by discriminant (see [Cohen et al. 2006] for a recent value of the relevant constants) to calculate the limit of the denominator, and we use standard Tauberian theorems (see [Narkiewicz 1983, Corollary, p. 121]) and PARI/GP [2006] to calculate the limit of the numerator. Of course,  $C(D_4)$  has not been decided, but it does not appear (by using the `algdep` function in PARI/GP) that any simple rational  $C(D_4)$  will give an affirmative answer to the above question.

In light of our mass formula for a different counting function  $c$  for  $D_4$ , we naturally wonder about Question 5.1 in the case of  $D_4$  and that  $c$ . Answering this question would require counting  $D_4$  extensions  $M$  with quadratic subfield  $L$  by

$$\text{Disc}(L|\mathbb{Q}) N_{L|\mathbb{Q}}(\text{Disc}(M|L))$$

instead of by discriminant, which is

$$\text{Disc}(L|\mathbb{Q})^2 N_{L|\mathbb{Q}}(\text{Disc}(M|L)).$$

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