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(3.1) THEOREM. *The $A[G]$-lattices B and $A[G]$ are factor equivalent.*

Proof. Define a $B[G]$-module structure on $B \otimes_A B$ by letting B act on the left factor and G on the right. We will show first that $B \otimes_A B$ and $B[G]$ are factor equivalent as $B[G]$-lattices. Define the canonical $B[G]$-linear map $\varphi\colon B \otimes_A B \to B[G]$ by

$$x \otimes y \mapsto \sum_{\sigma \in G} x\sigma(y) \cdot \sigma^{-1} .$$

Let H be a subgroup of G. If $\sigma_1, \ldots, \sigma_n$ are the K-embeddings of L^H in L, and if there is an A-basis $\omega_1, \ldots, \omega_n$ of B^H, then the restriction $(B \otimes_A B)^H \to B[G]^H$ of φ is a B-linear map with matrix $\big(\sigma_i(\omega_j)\big)_{ij}$ on the bases $\{1 \otimes \omega_j\}$ and $\{b_i\}$, where b_i is the formal sum of those $\sigma \in G$ for which σ^{-1} restricts to σ_i. The square of the determinant of this matrix generates the discriminant $\Delta(B^H/A)$ as an A-ideal. By localization it follows that even if B is not free over A, we have

$$\big[B[G]^H : \varphi(B \otimes_A B)^H\big]_B^2 = \Delta(B^H/A) \cdot B .$$

By Hasse's conductor discriminant product formula [15, Ch. VI, § 3] the ideal $\Delta(B^H/A)$ is a factorizable function of H, so $B \otimes_A B$ and $B[G]$ are factor equivalent $B[G]$-lattices.

In order to descend to $A[G]$-lattices, note that there exists an $A[G]$-linear injection $i\colon A[G] \to B$ by the normal basis theorem, and consider the induced $B[G]$-linear map $i_*\colon B[G] \to B \otimes_A B$ that sends $b\sigma$ to $b \otimes i(\sigma)$ for $b \in B$ and $\sigma \in G$. We have

$$\big[(B \otimes_A B)^H : i_*\big(B[G]\big)^H\big]_B = \big[B^H : i\big(A[G]\big)^H\big]_A \cdot B ,$$

and by (2.5) we know that the left hand side is a factorizable function of H. But then the A-index $\big[B^H : i\big(A[G]\big)^H\big]_A$ is also factorizable. □

4. S-UNITS

Let L/K be a Galois extension of number fields with Galois group G, and let S be a finite G-stable set of primes of L containing the infinite primes. The ring of S-integers of L consists of all elements of L that are integral outside S. Its class number is written as $h_S(L)$ and its unit group, the group of S-units of L, is denoted by $U_S(L)$. The group of roots of unity in L is denoted by μ_L and its order is written as $w(L)$.

Define the $\mathbf{Z}[G]$-lattice X_S to be the kernel of the map $\mathbf{Z}[S] \to \mathbf{Z}$ that sends each $\mathfrak{p} \in S$ to 1. We have a canonical map $\log_L \colon U_S(L) \to \mathbf{R} \otimes_{\mathbf{Z}} X_S$ sending x to the formal sum $\sum_{\mathfrak{p}\in S} (\log |x|_{\mathfrak{p}}) \otimes \mathfrak{p}$ in $\mathbf{R}[S]$. Here the normalization of the valuation at a prime $\mathfrak{p}$ of L, lying over a prime p of $\mathbf{Q}$, is given by $|u|_{\mathfrak{p}} = \left|N_{L_{\mathfrak{p}}/\mathbf{Q}_p}(u)\right|_p$, where $|\cdot|_p$ is the usual valuation on the completion $\mathbf{Q}_p$ of $\mathbf{Q}$ (with $\mathbf{Q}_p = \mathbf{R}$ if $p = \infty$). Dirichlet's unit theorem says that $\log_L$ embeds $U_S(L)/\mu_L$ as a discrete cocompact lattice in $\mathbf{R} \otimes_{\mathbf{Z}} X_S$. The S-regulator $R_S(L) \in \mathbf{R}_{>0}$ is defined to be the covolume of this lattice when the measure on $\mathbf{R} \otimes_{\mathbf{Z}} X_S$ is normalized to give $1 \otimes X_S$ covolume 1.

For a subgroup H of G we let $S(H)$ be the set of primes of L^H that extend to a prime in S. We will write $h_S(L^H)$ for $h_{S(H)}(L^H)$ and $R_S(L^H)$ for $R_{S(H)}(L^H)$. Brauer [1] has shown that the function $H \mapsto h_S(L^H)R_S(L^H)/w(L^H)$ is a factorizable function with values in $\mathbf{R}_{>0}$. The easiest way to see this is by noting that this quotient is the absolute value of the leading coefficient in the Taylor series expansion at $s = 0$ of the zeta-function $\zeta_{L^H,S}(s)$ of L^H; see Tate [17, Ch. I, 2.2]. Since $\zeta_{L^H,S}(s)$ is equal to the Artin L-series $L_S(1_H^G, s)$, the factorizability result then follows from the fact that $L_S(\chi_1 + \chi_2, s) = L_S(\chi_1, s)\, L_S(\chi_2, s)$.

The group G acts on S, so it acts on $\mathbf{Z}[S]$ and on X_S. The map $\log_L$ induces an $\mathbf{R}[G]$-linear isomorphism $\mathbf{R} \otimes_{\mathbf{Z}} U_S(L) \xrightarrow{\sim} \mathbf{R} \otimes_{\mathbf{Z}} X_S$. It follows that the $\mathbf{Q}[G]$-modules $\mathbf{Q} \otimes_{\mathbf{Z}} U_S(L)$ and $\mathbf{Q} \otimes_{\mathbf{Z}} X_S$ are isomorphic; see [3, p. 110]. In particular, there exists a $\mathbf{Z}[G]$-linear embedding $i \colon X_S \to U_S(L)$.

For a prime $\mathfrak{p}$ of L^H all primes $\mathfrak{q}$ of L lying over $\mathfrak{p}$ have the same local degree, which we denote by $n_{\mathfrak{p}}(L/L^H)$. Let $n(H)$ be the product of all $n_{\mathfrak{p}}(L/L^H)$ with $\mathfrak{p} \in S(H)$, and let $l(H)$ be their least common multiple.

(4.1) THEOREM. *For any $\mathbf{Z}[G]$-linear embedding $i \colon X_S \rightarrowtail U_S(L)$, the function*

$$H \mapsto \left[U_S(L)^H : i(X_S)^H\right] \frac{n(H)}{l(H)\, h_S(L^H)}$$

with values in $\mathbf{Q}_{>0}$ is factorizable.

Proof. For $\mathbf{Z}$-lattices L_1, L_2 spanning the same real vector space V we define the "index" $[L_2 : L_1] \in \mathbf{R}_{>0}$ as follows: choose a Haar measure on V such that L_2 has covolume 1 and let $[L_2 : L_1]$ be the covolume of L_1. Note that this notion coincides with the usual index in the case that $L_1 \subset L_2$, and that $[L_1 : L_2][L_2 : L_3] = [L_1 : L_3]$. Moreover, for any $\mathbf{R}$-linear automorphism φ of V we have $\left[L_1 : \varphi(L_1)\right] = |\det \varphi|$.

For each subgroup H of G we have an injective map $j_H\colon \mathbf{Z}[S(H)] \to \mathbf{Z}[S]$ sending $\mathfrak{p}$ to $\sum_{\mathfrak{q}|\mathfrak{p}} n_{\mathfrak{p}}(L/L^H)\cdot \mathfrak{q}$. This map respects the logarithm map in the sense that we have a commutative diagram

$$\begin{tikzcd} U_S(L^H) \arrow[r, "\log_{L^H}"] \arrow[d, equal] & \mathbf{R}\otimes X_{S(H)} \arrow[d, "1\otimes j_H"] \\ U_S(L)^H \arrow[r, "\log_L"] & \mathbf{R}\otimes X_S^H , \end{tikzcd}$$

where the vertical map on the left is inclusion. We therefore have

$$R_S(L^H) = \left[X_{S(H)} : \log_{L^H} U_S(L^H)\right] = \frac{\left[X_S^H : \log_L U_S(L)^H\right]}{\left[X_S^H : j_H(X_{S(H)})\right]} .$$

The composite map $X_S \xrightarrow{i} U_S(L) \xrightarrow{\log_L} \mathbf{R}\otimes X_S$ induces an $\mathbf{R}[G]$-linear automorphism φ of $\mathbf{R}\otimes X_S$. With the notation of (2.3) one has

$$|d_\varphi(H)| = \left[X_S^H : \varphi(X_S^H)\right] = \left[X_S^H : \log_L U_S(L)^H\right] \frac{\left[U_S(L)^H : i(X_S^H)\right]}{w(L^H)} .$$

Combining these two formulas, and dividing by $h_S(L^H)$, we get

$$\left[U_S(L)^H : i(X_S)^H\right] \frac{\left[X_S^H : j_H(X_{S(H)})\right]}{h_S(L^H)} = |d_\varphi(H)| \frac{w(L^H)}{h_S(L^H)R_S(L^H)} . \tag{4.2}$$

The right hand side is factorizable by (2.3) and Brauer's theorem. It remains to show that $\left[X_S^H : j_H(X_{S(H)})\right] = n(H)/l(H)$. In order to do this we compare the sequence defining $X_{S(H)}$ with the H-invariants of the sequence defining X_S :

$$\begin{tikzcd} 0 \arrow[r] & X_{S(H)} \arrow[r] \arrow[d] & \mathbf{Z}[S(H)] \arrow[r] \arrow[d, "j_H"] & \mathbf{Z} \arrow[r] \arrow[d, "\#H"] & 0 \\ 0 \arrow[r] & X_S^H \arrow[r] & \mathbf{Z}[S]^H \arrow[r] & \mathbf{Z} . \end{tikzcd}$$

The rows in this commutative diagram are exact and the vertical maps are injective. The cokernel C of the map j_H is the group $\bigoplus_{\mathfrak{p}\in S(H)} \mathbf{Z}/n_{\mathfrak{p}}(L/L^H)\mathbf{Z}$, which has order $n(H)$. It is not hard to see that the image of C in the cokernel of the rightmost vertical map has order $l(H)$. With the snake lemma our claim follows. $\square$

(4.3) REMARK. One can shorten this proof somewhat by using results in Tate's book on the Stark conjectures. Tate shows in [17, Ch. II, 1.1] that $[U_S(L) : i(X_S)]/h_S(L)$ is equal to the Stark-quotient $A(1, i)$, where 1 denotes the trivial character of the trivial Galois group of L over L. Compatibility of the Stark-quotient with respect to inflation and addition of characters implies that the number on the left in (4.2) equals $A(1_H^G, i)$, and that it is a factorizable function of H.

(4.4) REMARK. In order to say that (4.1) determines the factor equivalence class of $U_S(L)$ we should define factor equivalence for $\mathbf{Z}[G]$-modules with $\mathbf{Z}$-torsion. This can be done by replacing condition (2) in (2.4) by the condition that the quotient of the order of cokernel and kernel of the map $M^H \to N^H$ should be factorizable.

Alternatively, one can look at $\bar{U}(L) = U_S(L)/\mu_L$ instead of $U_S(L)$. This approach does introduce new factors into the formula because $\bar{U}(L)^H$ is not necessarily equal to $\bar{U}(L^H)$. More precisely, $c(H) = [\bar{U}(L)^H : \bar{U}(L^H)]$ is the order of the kernel of the map $H^1(H, \mu_L) \to H^1(H, U_S(L))$, so we know that it is built up from primes dividing both $w(L)$ and $\#G$. For $\mathbf{Z}[G]$-embeddings $i\colon X_S \rightarrowtail \bar{U}(L)$ it turns out that the map

$$(4.5) \qquad H \mapsto [\bar{U}(L)^H : i(X_S)^H] \frac{w(L^H)\, n(H)}{h_S(L^H)\, c(H)\, l(H)}$$

is factorizable. Thus one recovers [4, §3, Th. 3], where it is assumed that L has odd degree over K and K is totally real, so that $c(H) = n(H) = l(H) = 1$ and $w(L^H) = 2$. Brauer [1] showed that the odd part of $w(L^H)$ is a factorizable $\mathbf{Q}^*$-valued function of H, and his argument inspired the following lemma (cf. [11, Prop. 4.7]).

(4.6) LEMMA. *Let G be a group, let D be a subgroup of G and let N be a normal subgroup of D of index n such that D/N is cyclic. For every divisor d of n and subgroup H of G, let $m_d(H) \in \mathbf{Z}$ be the number of D-orbits of G/H that split up into exactly d orbits under the action of N. Then $m_d(H)$ is a factorizable $\mathbf{Z}$-valued function of H.*

Proof. Let $\chi\colon D \to \mathbf{C}^*$ be a complex linear character such that $\chi(N) = 1$, and let χ^G be the induced character of G. We claim that $\langle \chi^G, 1_H^G \rangle_G$ is the sum of those $m_d(H)$ for which d is a multiple of the order of χ. Since $\langle \cdot, \cdot \rangle_G$ is a bilinear operation on characters of G (see [16, §7.2]) the integer $\langle \chi^G, 1_H^G \rangle_G$ is a factorizable function of H. We deduce the lemma from the claim by taking χ of order d and using induction: we start with $n = d$ and then successively remove prime factors from d. It remains to show the claim.

By Frobenius reciprocity one has $\langle \chi^G, 1_H^G \rangle_G = \langle \chi, 1_H^G |_D \rangle_D$, which is equal to the multiplicity of χ in the complex representation $\mathbf{C}[G/H]$ of D. The D-set G/H is D-isomorphic to a disjoint union $\coprod_X D/D_X$, where X runs over the D-orbits of G/H, and each D_X is a subgroup of D. The multiplicity of χ in $\mathbf{C}[D/D_X]$ is either 0 or 1, and it is 1 if and only if $D_X \subset \operatorname{Ker} \chi$. Since $N \subset \operatorname{Ker} \chi$, and D/N is cyclic, it follows that $\langle \chi^G, 1_H^G \rangle_G$ is equal to the number of X for which the order of χ divides $[D : ND_X]$. This index is the number of N-orbits of D/D_X, so the claim follows. □

If for a prime number p the roots of unity in L of p-power order generate a cyclic extension of K, then one can show with the lemma (with $D = G$) that the p-part of $w(L^H)$ is a factorizable $\mathbf{Q}^*$-valued function of H. The condition holds for all $p > 2$, so the odd part of $w(L^H)$ is factorizable.

For any prime $\mathfrak{p}$ of K and $d \in \mathbf{Z}$ the number of primes in L^H extending $\mathfrak{p}$ with residue degree d is a $\mathbf{Z}$-valued factorizable function of H. This follows from the lemma if we take D and N to be the decomposition group and the inertia group of $\mathfrak{p}$. If $\mathfrak{p}$ has a cyclic decomposition group D then one can also take $N = 1$, and deduce the same statement with "residue degree" replaced by "local degree".

It follows that the factor $n(H)$ in (4.1) can be replaced by the product of the ramification indices in the extension L/L^H of those primes $\mathfrak{p} \in S(H)$ that extend to a prime of L with non-cyclic decomposition group in L/K. In particular, $n(H)$ is factorizable if S contains no finite ramified primes.

5. APPLICATIONS

Without giving proofs we indicate some concrete applications of the factor equivalence results given in the last two sections.

(5.1) CYCLIC SUBFIELD INTEGER INDEX. Let K be a Galois extension of $\mathbf{Q}$ with abelian Galois group G and ring of integers $\mathcal{O}_K$. For a $\mathbf{Z}[G]$-module M let $c_G(M)$ be the index in M of $\sum M^H$, where the sum is taken over those subgroups H of G for which G/H is cyclic. In particular,