

GENERALIZED ORIENTATIONS AND THE BLOCH INVARIANT

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ABSTRACT. For compact hyperbolic 3-manifolds we lift the Bloch invariant defined by Neumann and Yang to an integral class in $K_3(\mathbb{C})$. Applying the Borel and the Bloch regulators, one gets back the volume and the Chern-Simons invariant of the manifold. We also discuss the non-compact case, in which there appears a $\mathbb{Z}/2$ -ambiguity.

INTRODUCTION

Suppose that Γ is a discrete group such that the classifying space $B\Gamma$ has a model which is a closed orientable smooth manifold M of dimension m . Here as usual *closed* means compact and without boundary. According to the *Borel conjecture* for Γ , the *diffeomorphism type* of M should be completely determined by the *isomorphism type* of Γ . Therefore the question arises of how much of the *smooth geometry* of M is encoded in the group Γ . Similarly, recall that by the celebrated *Mostow Rigidity*, if M is a closed connected orientable hyperbolic manifold of dimension $n \geq 3$, then not only the Borel conjecture holds for Γ , but the isometry type of M is also completely determined by Γ . So, in this case, the question refines to how the *metric geometry* of M , typically the *hyperbolic volume* $\text{vol}(M)$ or the *Chern-Simons invariant* $\text{CS}(M)$, can be recovered from Γ .

Such questions have been addressed for instance by Goncharov [Gon99], Neumann and Yang [NY99]. In the three dimensional case, they obtained respectively a rational algebraic K -theoretical invariant, and a *Bloch invariant* in the Bloch subgroup of the scissors congruence group of hyperbolic 3-space, $\mathcal{P}(\mathbb{C})$. Later, Cisneros-Molina and Jones revisited this work in [CMJ03] from a homotopical point of view, in an attempt to lift the Bloch invariant to an integral class in $K_3(\mathbb{C})$. The later is indeed a natural candidate to contain this kind of invariant. There are two *regulators* defined on $K_3(\mathbb{C})$, the Borel regulator and the Bloch regulator. The insight of Goncharov and Neumann-Yang tells us that their values on the invariant should give back the volume and the Chern-Simons invariant of the manifold.

There is one constant in all three approaches: the invariant is obtained basically by pushing a fundamental class in ordinary homology into $\mathcal{P}(\mathbb{C})$. The main tool

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to relate $\mathcal{P}(\mathbb{C})$ to K -theory is the Bloch-Wigner exact sequence first published by Suslin [Sus90] and by Dupont-Sah [DS82]. One gets directly a class in the homology of $SL_2\mathbb{C}$ by considering a Spin-structure on the hyperbolic manifold (cf. [CMJ03]). To define the invariant in K -theory one has to lift this fundamental class through a Hurewicz homomorphism and this leads to an ambiguity in the definition. In [Gon99] this ambiguity is removed by using rational coefficients. In our context it is more natural to view the Bloch-Wigner exact sequence as a part of the long exact sequence in stable homotopy of a cofibration. Thus instead of a Spin-structure, which yields a KO -orientation [ABS64], we are lead to consider an orientation in stable homotopy theory, and this is provided by a stable parallelization of the (hyperbolic) 3-manifold.

For compact manifolds our main result is:

Theorem A. *Let M be a closed oriented hyperbolic manifold of dimension 3 with fundamental group $\Gamma = \pi_1(M)$. Then, to any stable parallelization of the tangent bundle of M corresponds, in a canonical way, a K -theory class $\gamma(M) \in K_3(\mathbb{C})$, which depends only on the underlying Spin-structure. The hyperbolic volume of M is determined by the equality*

$$\text{bo-reg}(\gamma(M)) = \frac{\text{vol}(M)}{2\pi^2}$$

of real numbers, where $\text{bo-reg} : K_3(\mathbb{C}) \rightarrow \mathbb{R}$ is the Borel regulator for the field of complex numbers \mathbb{C} . Furthermore, for the Chern-Simons invariant $\text{CS}(M)$ of M we have the congruence

$$\mu(\gamma(M)) \equiv \frac{-\text{CS}(M) + i \cdot \text{vol}(M)}{2\pi^2} \pmod{\mathbb{Q}}$$

of complex numbers. Here ρ stands for the composite

$$\mu : K_3(\mathbb{C}) \xrightarrow{\text{bw}} \mathcal{B}(\mathbb{C}) \xrightarrow{\text{bl-reg}} \mathbb{C}/\mathbb{Q},$$

where bw is the Bloch-Wigner map for the field \mathbb{C} , $\mathcal{B}(\mathbb{C})$ is the Bloch group of \mathbb{C} , and bl-reg is the Bloch regulator for \mathbb{C} .

In the non-compact case, the problem is more intricate. The main problem is that one has to start with a fundamental class in a relative (generalized) homology group, and this yields naturally a relative class. Even if we do not have to invert a Hurewicz homomorphism we still end up with a $\mathbb{Z}/2$ ambiguity.

Theorem B. *Let M be a non-compact oriented hyperbolic manifold of dimension 3 with finite volume. Let $\Gamma = \pi_1(M)$ be its fundamental group. Then, to any stable parallelization of the tangent bundle of M correspond two natural K -theory classes $\gamma(M)^\pm \in K_3(\mathbb{C})$, which depend only on the underlying Spin-structure. The hyperbolic volume of M is determined by the equality*

$$\text{bo-reg}(\gamma(M)^\pm) = \frac{\text{vol}(M)}{2\pi^2}.$$

Furthermore, for the Chern-Simons invariant $CS(M)$ of M we have the congruence

$$\rho \circ (\gamma(M)^\pm) \equiv \frac{-CS(M) + i \cdot \text{vol}(M)}{2\pi^2} \pmod{\mathbb{Q}}.$$

The plan of the article is the following. Section 1 is a short reminder on the theory of orientations of manifolds. Section 2 is devoted to the Bloch-Wigner exact sequence. Theorem A collects the results of Theorem 3.5 and Corollary 3.7, which are proved in Section 3. The non-compact case, Theorem B, is the object of Section 4. Our original plan was to construct an invariant in algebraic K -theory of the group ring $\mathbb{Z}\Gamma$. The fact that the Bloch-Wigner exact sequence can be reformulated in stable homotopy simplified the construction. Due to the intimate relation of $K\mathbb{Z}_*(\mathbb{Z}\Gamma)$ with the Isomorphism Conjectures, [FJ93], we decided to include our original construction in Appendix A.

We started this project in February 2005, but the paper was completed only after the first author's death. It is dedicated to the memory of our friend Michel Matthey.

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1. PARALLELIZATIONS AND ORIENTATIONS

Let M be a closed compact connected smooth manifold of dimension d . We explain in this section the relationship between stable parallelizations of the tangent bundle of M and orientations of M with respect to the sphere spectrum \mathbb{S} . For manifolds there are two ways to view orientations. The first one, rising from orientations of vector bundles, is cohomological in essence and the second one, rising from patching local compatible orientations, is homological in essence. Both definitions agree via the so-called S -duality. We call a manifold *orientable* if it is so in the classical sense (i.e. with respect to the Eilenberg-McLane spectrum $H\mathbb{Z}$). In this section E denotes a ring spectrum with unit $\varepsilon : \mathbb{S} \rightarrow E$.

1.1. Cohomological definition. Let ν_M be the stable normal bundle of M and $Th(\nu_M)$ its Thom spectrum. For each $m \in M$, consider the map from the Thom spectrum of this point induced by the inclusion $j_m : \mathbb{S} \rightarrow Th(\nu_M)$. An E -orientation of M is a class $t \in E^0(Th(\nu_M))$ such that for some (and hence every) point $m \in M$ $j_m^*(t) = \pm\varepsilon \in \pi_0(E) \cong E^0(\mathbb{S})$.

A particularly convenient setting is when the manifold is stably parallelizable, i.e. its normal bundle is stably trivial (and hence its tangent bundle also). A given parallelization ι provides a trivialization of the Thom spectrum of the normal bundle of M :

$$DT(\iota) : Th(\nu_M) \xrightarrow{\cong} \Sigma^\infty M_+.$$

By collapsing M to a point we obtain hence a map $Th(\nu_M) \rightarrow \mathbb{S}$ to the sphere spectrum representing a cohomology class in $\mathbb{S}^0(Th(\nu_M))$. Composing with the unit $\varepsilon : \mathbb{S} \rightarrow E$ we get an E -orientation.

Example 1.1. Recall Stiefel's result that any orientable 3-manifold admits stable parallelizations (see [MS74, Problem 12-B]) i.e. trivializations of the stable tangent bundle $\tau : M \rightarrow BO$. As these correspond to lifts of the map τ to the universal cover EO up to homotopy, one can apply obstruction theory to count them. Lifts to the 1-skeleton correspond to classical orientations and there are $H^0(M; \mathbb{Z}/2\mathbb{Z})$ possible choices. Further lifts to the 2-skeleton correspond to Spin-structures, and there are $H^1(M; \mathbb{Z}/2\mathbb{Z})$ choices at this stage. Finally, to lift further across the 3-skeleton one gets $H^3(M; \mathbb{Z})$ choices, the so called p_1 -structures, where p_1 stands for the first Pontrjagin class.

1.2. Homological definition. A *fundamental class* for M with respect to the homology theory E is a class $t \in E_d(M)$ such that for some (and therefore every) point $m \in M$ the image of t in $E_d(M, M - m) \simeq \tilde{E}_d(S^d) \simeq \tilde{E}_0(S^0) = \pi_0(E)$ is $\pm\varepsilon$. Notice in particular that the unit $\varepsilon : \mathbb{S} \rightarrow E$ canonically provides fundamental classes for all spheres S^d .

Example 1.2. Consider the sphere spectrum \mathbb{S} . Then the corresponding reduced homology theory is stable homotopy, $\tilde{\mathbb{S}}_n(X) \cong \pi_n^S(X)$. An \mathbb{S} -orientation for M is thus an element in $\mathbb{S}_d(M)$ with the property that its image in $\mathbb{S}_d^S(M, M - m) \cong \pi_d^S(S^d) \cong \mathbb{Z}$ is a generator.

1.3. S -duality. We now turn to the connection between the homological and cohomological point of view. We adopt the point of view of Rudyak [Rud98] on S -duality, for another point of view see Switzer [Swi02] or Adams [Ada74].

Definition 1.3. Let A, A^* be two spectra. A *duality morphism* or *duality* between A and A^* is a map of spectra $u : \mathbb{S} \rightarrow A \wedge A^*$ such that for every spectrum E the following homomorphisms are isomorphisms :

$$\begin{aligned} u_E : [A, E] &\longrightarrow [\mathbb{S}, E \wedge A^*] \\ \phi &\longmapsto (\phi \wedge 1_{A^*}) \circ u \\ \\ u^E : [A^*, E] &\longrightarrow [\mathbb{S}, A \wedge E] \\ \phi &\longmapsto (1_A \wedge \phi) \circ u \end{aligned}$$

The spectra A and A^* are said to be *S -dual*. Two spectra A and B are called *n -dual*, where $n \in \mathbb{Z}$, if A and $\Sigma^n B$ are S -dual.

Definition 1.4. Fixing two duality maps $u : \mathbb{S} \rightarrow A \wedge A^*$ and $v : \mathbb{S} \rightarrow B \wedge B^*$, the *S -dual* of a map $f : A \rightarrow B$ is then the image $f^* : B^* \rightarrow A^*$ of f under the isomorphism:

$$D : [A, B] \xrightarrow{u_B} [\mathbb{S}, B \wedge A^*] \xrightarrow{(v^{A^*})^{-1}} [B^*, A^*].$$

In particular $f \in [A, B]$ is *S -dual* to $g \in [B^*, A^*]$ if and only if $u_B(f) = v^{A^*}(g)$.

Example 1.5. For any integer n the spectra \mathbb{S}^n and \mathbb{S}^{-n} are S -dual. The duality map is simply the canonical equivalence $\mathbb{S} \rightarrow \mathbb{S}^n \wedge \mathbb{S}^{-n}$.

1.4. Orientations and S -duality for manifolds. For closed manifolds S -duality was defined by Milnor-Spanier in [MS60]. As we will need the precise form of the duality map we give it in detail. Choose an embedding $M \hookrightarrow S^N$ into a high-dimensional sphere and let U be a tubular neighborhood of M . The open manifold U can be viewed as the total space of the normal disc bundle of M , and the quotient $\overline{U}/\partial U$ is therefore a Thom space for the normal bundle. Denote by $p : \overline{U} \rightarrow M$ the projection and by $\Delta : \overline{U} \rightarrow \overline{U} \times M$ the map $\Delta(a) = (a, p(a))$. Then Δ induces a map $\Delta' : \overline{U}/\partial U \rightarrow \overline{U}/\partial U \wedge M_+$. Denote by $C : S^N \rightarrow \overline{U}/\partial U$ the map induced by collapsing the complement of U into a point. Then we have a map $f : S^N \xrightarrow{C} \overline{U}/\partial U \xrightarrow{\Delta'} (\overline{U}/\partial U) \wedge M_+$. The duality morphism is then

$$u = \Sigma^{-N} \Sigma^\infty f : \mathbb{S} \rightarrow Th\nu_M \wedge \Sigma^{-d} \Sigma^\infty M_+.$$

It induces the duality bijection $u_E : [Th(\nu_M), E] \rightarrow [\mathbb{S}, E \wedge \Sigma^{-d} \Sigma^\infty M_+]$ for any spectrum E .

Theorem 1.6. [Rud98, Corollary V.2.6] *Let M be a closed E -orientable manifold. The duality map constructed above yields a bijective correspondence between cohomological orientations of M and fundamental classes of M with respect to E . \square*

1.5. The case of 3-manifolds. In Example 1.1 we have seen that 3-manifolds are orientable in the cohomological sense. Therefore by Theorem 1.6 they admit fundamental classes. We describe now the relationship between parallelizations and homological orientations for 3-manifolds. Since we counted the former in Example 1.1 we will first count the later.

Lemma 1.7. *Let M be an orientable closed manifold of dimension 3. The Atiyah-Hirzebruch spectral sequence for the stable homotopy of M collapses at E^2 .*

Proof. The spectral sequence is concentrated on the first four columns of the first quadrant. The first column $H_0(M; \mathbb{S}_q) \cong \pi_q^S$ always survives to E^∞ since a point is a retract of M . Since M is \mathbb{S} -orientable, the suspension spectrum of the 3-sphere is a retract of $\Sigma^\infty M$, so that the fourth column $H_3(M; \mathbb{S}_q) \cong \pi_q^S$ also survives. Therefore all differentials must be zero. \square

Proposition 1.8. *Let M be an orientable closed 3-manifold. Fundamental classes of M with respect to \mathbb{S} are parametrized by $\pi_3^s(\mathbb{S}) \times H_1(M; \mathbb{Z}/2\mathbb{Z}) \times H_2(M; \mathbb{Z}/2\mathbb{Z}) \times \{\pm 1\}$.*

Proof. This follows from the previous lemma since the homomorphism $\mathbb{S}_3(M) \rightarrow \mathbb{S}_3(M, M - m)$ can be identified with the edge homomorphism $\mathbb{S}_3(M) \rightarrow H_3(M; \mathbb{Z})$. Fixing an orientation tells us that the image of t must be a fixed generator of $H_3(M; \mathbb{Z})$. \square

Example 1.9. There are precisely $2 \cdot |\pi_3^s(\mathbb{S})| = 48$ different orientations of the sphere S^3 with respect to stable homotopy.

If an \mathbb{S} -orientation of M is given, a change of trivialization can be used to modify the class in $\mathbb{S}_3(M)$ via the Dold-Thom isomorphisms:

$$\mathbb{S}_3(M) \xrightarrow{DT(\iota)^{-1}} \mathbb{S}_3(Th(\nu_M)) \xrightarrow{DT(\iota')} \mathbb{S}_3(M).$$

Lemma 1.10. *Given two stable parallelizations of S^3 which differ only by a p_1 -structure $\alpha \in H^3(S^3; \mathbb{Z})$, the corresponding \mathbb{S} -orientations differ then by $J\alpha$, where $J : \mathbb{Z} \cong \pi_3 SO \rightarrow \pi_3^S \cong \mathbb{Z}/24$ is the stable J -homomorphism.*

Proof. The change of trivialization is controlled by a map between total spaces of trivial bundles $S^3 \times \mathbb{R}^N \rightarrow S^3 \times \mathbb{R}^N$, for some large integer N . At the level of Thom spaces we get a homotopy equivalence $f : S^{N+3} \vee S^N \rightarrow S^{N+3} \vee S^N$. Fix the canonical \mathbb{S} -orientation t corresponding to the inclusion $S^{N+3} \rightarrow S^{N+3} \vee S^N$ in $\pi_{N+3}(S^{N+3} \vee S^N) \cong \pi_3^S(S^3_+) \cong \mathbb{S}_3(S^3)$ and modify it by f . The edge homomorphism $e : \mathbb{S}_3(S^3) \rightarrow \pi_3^S(S^3)$ takes both t and ft to 1, but the element in $\text{Ker } e$ is null for t and, for ft , is given by the map

$$S^{N+3} \xrightarrow{i_1} S^{N+3} \vee S^N \xrightarrow{f} S^{N+3} \vee S^N \xrightarrow{p_2} S^N.$$

This map is determined by its homotopy cofiber, a two cell complex which is seen to be homotopy equivalent to $S^N \cup_{J\alpha} e^{N+4}$, see [Ada66, Lemma 10.1]. We conclude then since J is an epimorphism in dimension 3, [Ada66, Theorem 1.5]. \square

Proposition 1.11. *Let M be an oriented, closed 3-manifold. The \mathbb{S} -orientations of M obtained from the stable parallelizations may differ by an arbitrary element of $\mathbb{Z}/24 \cong \pi_3^S \subset \text{Ker } e$.*

Proof. One obtains both stable parallelizations and \mathbb{S} -orientations for S^3 from the ones for M by collapsing the 2-skeleton. \square

2. THE BLOCH-WIGNER EXACT SEQUENCE

In this section we identify the Bloch-Wigner exact sequence with an exact sequence in stable homotopy whereas the classical point of view is homological.

2.1. Scissors congruence group of hyperbolic 3-space. A standard reference for this section is Dupont-Sah [DS82], see also Dupont [Dup01] or Suslin [Sus90]. Denote by $\text{Isom}^+(\mathcal{H}^3)$ the group of orientation-preserving isometries of the hyperbolic 3-space \mathcal{H}^3 .

Definition 2.1. The *scissors congruence group* $\mathcal{P}(\mathcal{H}^3)$ is the free abelian group of symbols $[P]$ for all polytopes P in \mathcal{H}^3 , modulo the relations:

- (1) $[P] - [P'] - [P'']$ if $P = P' \cup P''$ and $P' \cap P''$ has no interior points;
- (2) $[gP] - [P]$ for $g \in \text{Isom}^+(\mathcal{H}^3)$.

One defines analogously $\mathcal{P}(\overline{\mathcal{H}}^3)$ where one allows some vertices of the polytopes to be ideal points and $\mathcal{P}(\partial\mathcal{H}^3)$ where the polytopes are all ideal polytopes (actually there is a subtlety with the later group, see [Dup01, Chapter 8]). Finally there is a more algebraic description of these groups.

Definition 2.2. Let $\mathcal{P}(\mathbb{C})$ denote the abelian group generated by symbols $z \in \mathbb{C} - \{0, 1\}$ and satisfying, for $z_1 \neq z_2$, the relations:

$$z_1 - z_2 + \frac{z_2}{z_1} - \frac{1 - z_2}{1 - z_1} + \frac{1 - z_2^{-1}}{1 - z_1^{-1}}.$$

The four groups are related by:

Theorem 2.3. [Dup01, Corollary 8.18] *There are canonical isomorphisms*

$$\mathcal{P}(\mathcal{H}^3) \cong \mathcal{P}(\overline{\mathcal{H}^3}) \cong \mathcal{P}(\partial\mathcal{H}^3) \cong \mathcal{P}(\mathbb{C})^-,$$

where $\mathcal{P}(\mathbb{C})^-$ denotes the (-1) -eigenspace for complex conjugation. \square

2.2. The Bloch-Wigner exact sequence. Recall that the group $\text{Isom}^+(\mathcal{H}^3)$ is isomorphic to $PSL_2\mathbb{C} = SL_2\mathbb{C}/\{\pm Id\}$. It acts naturally on the boundary of hyperbolic 3-space. Fix a point $x \in \partial\mathcal{H}^3$ and denote by $P \subset SL_2(\mathbb{C})$ the preimage of a parabolic stabilizer of x . As a group, P is isomorphic to the semi-direct product $\mathbb{C} \rtimes \mathbb{C}^*$, where $z \in \mathbb{C}^*$ acts on \mathbb{C} by multiplication by z^2 . These groups are all considered only as discrete groups. Let us then denote by $\text{Cof}(i_P)$ the homotopy cofibre of the map $i_P : BP \rightarrow BSL_2(\mathbb{C})$. The following is an integral analogue of [Gon99, Lemma 2.14].

Lemma 2.4. *For $n \geq 1$ we have a commutative diagram where the vertical arrows are the Hurewicz homomorphisms and the horizontal arrows are induced by the projections $\mathbb{C} \rtimes \mathbb{C}^* \rightarrow \mathbb{C}^*$:*

$$\begin{array}{ccc} \pi_n^s(B(\mathbb{C} \rtimes \mathbb{C}^*)) & \longrightarrow & \pi_n^s(B\mathbb{C}^*) \\ \downarrow \sim & & \downarrow \\ H_n(\mathbb{C} \rtimes \mathbb{C}^*; \mathbb{Z}) & \xrightarrow{\sim} & H_n(B\mathbb{C}^*, \mathbb{Z}). \end{array}$$

Proof. From the exact sequence of groups $1 \rightarrow \mathbb{C} \rightarrow \mathbb{C} \rtimes \mathbb{C}^* \rightarrow \mathbb{C}^* \rightarrow 1$ we get a fibration $BC \rightarrow B(\mathbb{C} \rtimes \mathbb{C}^*) \rightarrow B\mathbb{C}^*$. We will prove that the Atiyah-Hirzebruch spectral sequence for stable homotopy

$$H_p(B\mathbb{C}^*, \pi_q^s(BC)) \Rightarrow \pi_{p+q}^s(B(\mathbb{C} \rtimes \mathbb{C}^*))$$

collapses. Since the stable stems π_n^s are torsion groups in degree $n \geq 1$ and \mathbb{C} is a rational vector space, the Hurewicz homomorphism $\pi_n^s(BC) \rightarrow H_n(BC; \mathbb{Z})$ is an isomorphism. This identifies the above spectral sequence with the ordinary homological spectral sequence. In particular the Hurewicz map $\pi_n^s(B(\mathbb{C} \rtimes \mathbb{C}^*)) \rightarrow H_n(B(\mathbb{C} \rtimes \mathbb{C}^*); \mathbb{Z})$ is an isomorphism.

Now, $H_q(BC; \mathbb{Z}) \cong \Lambda^q \mathbb{C}$ for any $q \geq 1$. An element $n \in \mathbb{C}^*$ acts by multiplication by n^2 on \mathbb{C} and therefore by multiplication by n^{2q} on $H_q(BC, \mathbb{Z})$. The map induced by conjugation in a group G by an element g together with the action of the same g on a G -module M induces the identity in homology with coefficients in M . As \mathbb{C}^* is abelian, in our case we have that multiplication by n^{2q} is the identity on $H_p(B\mathbb{C}^*, H_q(BC))$. But multiplication by $n^{2q} - 1$ is a isomorphism of the \mathbb{C}^* -module $H_q(BC; \mathbb{Z})$, therefore $H_p(B\mathbb{C}^*, H_q(BC)) = 0$ for $q \geq 1$. \square

Lemma 2.5. *For $n \leq 3$, the Hurewicz homomorphism $\pi_n^S(BSL_2\mathbb{C}) \rightarrow H_n(SL_2\mathbb{C})$ is an isomorphism.*

Proof. The group $SL_2\mathbb{C}$ is perfect and $H_2(SL_2\mathbb{C}; \mathbb{Z})$ is a rational vector space [Dup01, Corollary 8.20]. One concludes then by an easy Atiyah-Hirzebruch spectral sequence argument. \square

Proposition 2.6. *There is a commutative diagram with vertical isomorphisms and exact rows*

$$\begin{array}{ccccccccc} \mathbb{Q}/\mathbb{Z} & \longrightarrow & \pi_3^s(BSL_2\mathbb{C}) & \longrightarrow & \pi_3^s(Cof(i_P)) & \longrightarrow & \pi_2^s(BP) & \longrightarrow & \pi_2^s(BSL_2\mathbb{C}) \\ \downarrow & & \downarrow & & \downarrow & & \downarrow & & \downarrow \\ \mathbb{Q}/\mathbb{Z} & \longrightarrow & H_3(SL_2\mathbb{C}; \mathbb{Z}) & \longrightarrow & \mathcal{P}(\mathbb{C}) & \longrightarrow & \Lambda^2(\mathbb{C}^*/\mu_{\mathbb{C}}) & \longrightarrow & H_2(SL_2\mathbb{C}; \mathbb{Z}) \end{array}$$

where the bottom row is the Bloch-Wigner exact sequence.

Proof. The stable Hurewicz homomorphism permits us to compare the long exact sequences of the cofibration $BP \rightarrow BSL_2(\mathbb{C}) \rightarrow Cof(i_P)$ in stable homotopy and in ordinary homology:

$$\begin{array}{ccccccccc} \pi_3^s(BP) & \longrightarrow & \pi_3^s(BSL_2\mathbb{C}) & \longrightarrow & \pi_3^s(Cof(i_P)) & \longrightarrow & \pi_2^s(BP) & \longrightarrow & \pi_2^s(BSL_2\mathbb{C}) \\ \downarrow \cong & & \downarrow \cong & & \downarrow & & \downarrow \cong & & \downarrow \cong \\ H_3(\mathbb{C}^*; \mathbb{Z}) & \longrightarrow & H_3(SL_2\mathbb{C}; \mathbb{Z}) & \longrightarrow & H_3(Cof(i_P); \mathbb{Z}) & \longrightarrow & H_2(\mathbb{C}^*; \mathbb{Z}) & \longrightarrow & H_2(SL_2\mathbb{C}; \mathbb{Z}) \end{array}$$

The marked isomorphisms are given by Lemmas 2.4 and 2.5. It remains thus to compare the bottom exact sequence with the Bloch-Wigner exact sequence. We have to return to its computation by Suslin, [Sus90].

Let P_* be a projective resolution of \mathbb{Z} over $SL_2(\mathbb{C})$ and consider the complex C_* of $(n+1)$ -uples of distinct points in $\partial\mathcal{H}^3$, [Dup01, Chapter 2]. The naturally augmented complex $\epsilon : C_* \rightarrow \mathbb{Z}$ is acyclic. Let us consider the truncated complex $\tau C_* = (\ker \epsilon \rightarrow C_0)$. The inclusion of this complex in C_* allows to compare two spectral sequences. The first one, associated to the double complex $P_* \otimes \tau C_*$, yields a kind of Wang sequence, which is nothing but the long exact of the cofibration $BP \rightarrow BSL_2(\mathbb{C}) \rightarrow Cof(i_P)$. The second one, associated to the double complex $P_* \otimes C_*$, yields in low degrees the classical Bloch-Wigner sequence. In particular we get isomorphisms $H_3(Cof(i_P); \mathbb{Z}) \cong \mathcal{P}(\mathbb{C})$ and $\text{Im}(H_3(\mathbb{C}^*; \mathbb{Z}) \rightarrow H_3(SL_2\mathbb{C}; \mathbb{Z})) \cong \mathbb{Q}/\mathbb{Z}$. \square

3. LIFTING THE BLOCH INVARIANT, THE COMPACT CASE

We construct in this section a class in $K_3(\mathbb{C})$ for every closed, compact, orientable hyperbolic 3-manifold and show it coincides with the Neumann-Yang *Bloch invariant*, [NY99]. In Section 1 we have seen that one obtains from a stable parallelization of the normal bundle an \mathbb{S} -orientation. Set $\Gamma = \pi_1 M$ and let us fix a Spin-structure $\rho : \Gamma \rightarrow SL_2(\mathbb{C})$.

3.1. The invariant $\gamma(M)$. We start with an \mathbb{S} -orientation $t \in \mathbb{S}_3(B\Gamma)$ coming from a stable parallelization that extends the Spin-structure ρ (recall from Example 1.1 that ρ provides a trivialization of the normal bundle over the 2-skeleton of M). Note that the reduced homology groups are canonical direct factors of the unreduced ones for pointed spaces, so we have a projection $\mathbb{S}_3(M) \twoheadrightarrow \tilde{\mathbb{S}}_3(M) \cong \pi_3^S(M)$, sending a given orientation $t \in \mathbb{S}_3(M)$ to a *reduced orientation class* \tilde{t} in $\pi_3^S(M)$.

The idea is to use the structural map ρ to obtain an element in $\pi_3^S(BSL_2\mathbb{C})$. Then include $SL_2\mathbb{C}$ into the infinite special linear group SLC . This defines for us an element in

$$\pi_3^S(BSLC) \cong \pi_3^S(BSLC^+).$$

Lemma 3.1. *The stabilization map $\pi_3 BSLC^+ \rightarrow \pi_3^S BSLC^+$ is an isomorphism.*

Proof. Since $BSLC^+$ is simply connected, Freudenthal's suspension theorem tells us that the stabilization homomorphism $\pi_3 BSLC^+ \rightarrow \pi_3^S BSLC^+$ is an epimorphism. The infinite loop space $BSLC^+$, being the universal cover of $BGLC^+$, gives rise to the 1-connected spectrum $K\mathbb{C}\langle 1 \rangle$. The map of spectra $\Sigma^\infty BSLC^+ \rightarrow K\mathbb{C}\langle 1 \rangle$, adjunct of the identity, yields a right inverse to the stabilization map, which must therefore be a monomorphism. \square

Definition 3.2. Let M be a closed, compact, orientable hyperbolic 3-manifold with fundamental group Γ (thus $M \simeq B\Gamma$). Fix a Spin-structure $\rho : \Gamma \rightarrow SL_2(\mathbb{C})$ and a reduced stable orientation $t \in \pi_3^S(B\Gamma)$ coming from a stable parallelization extending ρ . The element $\gamma(M)$ is then the image of \tilde{t} by the homomorphism

$$\pi_3^S(B\Gamma) \xrightarrow{\rho_*} \pi_3^S(BSL_2\mathbb{C}) \xrightarrow{i} \pi_3^S(BSLC) \cong \pi_3^S(BSLC^+) \xrightarrow{\cong} K_3(\mathbb{C}).$$

3.2. Independence from the p_1 -structure. The preceding definition apparently depends on the choice of the orientation. We prove here that $\gamma(M)$ is completely determined by the Spin-structure only.

Lemma 3.3. *Let M be a closed orientable manifold of dimension d and $c_{(2)} : Th(\nu_M) \rightarrow \Sigma^d \mathbb{S}$ be the map obtained by collapsing the 2-skeleton of M . The S -dual map of $c_{(2)}$ is then, up to sign, the map $i_c : \Sigma^{-N} \mathbb{S} \rightarrow \Sigma^{-d} \Sigma^\infty M_+$ induced by the inclusion of the center of the top-dimensional cell.*

Proof. The two duality maps we consider are $u : \mathbb{S} \rightarrow Th(\nu_M) \wedge \Sigma^{-d} \Sigma^\infty M_+$ and $v : \mathbb{S} \rightarrow \mathbb{S}^d \wedge \mathbb{S}^{-d}$. By Definition 1.3, we have to prove that the maps $(c_{(2)} \wedge 1_{\Sigma^{-d} \Sigma^\infty M_+}) \circ u$ and $(1_{S^d} \wedge i_c) \circ v$ are homotopic, i.e. coincide in

$$[\mathbb{S}, S^d \wedge \Sigma^{-d} \Sigma^\infty M_+] = [\mathbb{S}, \Sigma^\infty M_+] = \pi_0^S(M_+) \cong \mathbb{Z}.$$

The collapse map $M \rightarrow pt$ induces an isomorphism $\pi_0^S(M_+) \rightarrow \pi_0^S(S^0)$ so we may postcompose with this collapse map.

Let us compute the homotopy class of the map $(1_{S^d} \wedge i_c) \circ v$

$$\begin{array}{ccccccc} \mathbb{S} & \longrightarrow & \mathbb{S}^d \wedge \mathbb{S}^{-d} & \longrightarrow & \mathbb{S}^d \wedge \Sigma^{-d} M^+ & \longrightarrow & \mathbb{S}^d \wedge \Sigma^{-d} S^0. \\ & & & & \searrow \text{Id} \swarrow & & \\ & & & & & & \end{array}$$

Since the duality map v is an equivalence this is a generator of $\pi_0^s(S^0) = \pi_0^s(M^+)$.

To compare it with $(C \wedge 1_{\Sigma^{-d}\Sigma^\infty M^+}) \circ u$, we turn back to the definition of the duality map u . One sees that the above composite is the desuspension of the stable map induced by the following map of spaces, where N stands for a sufficiently large integer:

$$S^{d+N} \xrightarrow{c(2)} Th(\nu_M) \xrightarrow{\Delta'} Th(\nu_M) \wedge M^+ \xrightarrow{Id \wedge C} Th(\nu_M) \wedge S^0 \xrightarrow{c(2)} S^{d+N} \wedge S^0 \simeq S^{d+N}$$

This map is equal to the map induced by the collapse of complement of the tubular neighborhood of M restricted to the top-dimensional cell. The tubular neighborhood restricted to the n^{th} cell is a trivial disc bundle, therefore the collapse map $S^{d+N} \rightarrow D^d \times D^N / \partial(D^d \times D^N) = S^{d+N}$ is of degree ± 1 . \square

Proposition 3.4. *Let M be a closed, compact, orientable hyperbolic 3-manifold. The reduced orientation class $\tilde{t} \in \pi_3^S(B\Gamma)$ is independent of the p_1 -structure. Consequently the element $\gamma(M)$ depends only on the Spin-structure.*

Proof. We have a cofibre sequence $Th(\nu_M|_{M^{(2)}}) \rightarrow Th(\nu_M) \xrightarrow{c(2)} \Sigma^3\mathbb{S}$ of spectra of finite type. Therefore, by [Rud98, Lemma II.2.10], we have an S -dual cofibre sequence of spectra of finite type $\Sigma^{-3}\mathbb{S} \rightarrow \Sigma^{-3}\Sigma^\infty M_+ \rightarrow (Th(\nu_M)|_{M^{(2)}})^*$, where the first map has been identified in Lemma 3.3.

As a consequence we have a commutative diagram, where the vertical arrows are induced by S -duality :

$$\begin{array}{ccccc} \mathbb{S}^0(S^3) & \longrightarrow & \mathbb{S}^0(Th\nu_M) & \longrightarrow & \mathbb{S}^0(Th\nu_m|_{M^{(2)}}) \\ \downarrow & & \downarrow & & \downarrow \\ \pi_3^S & \longrightarrow & \pi_3^S(M_+) & \longrightarrow & \mathbb{S}_0(Th(\nu_M|_{M^{(2)}})^*) \end{array}$$

The map $\mathbb{S} \rightarrow \Sigma^\infty M_+$ splits so that the bottom row is a short exact sequence and we can identify $\mathbb{S}_0(Th(\nu_M|_{M^{(2)}})^*)$ with $\pi_3^S(M)$. The diagram shows that the reduced orientation class $\tilde{t} \in \pi_3^S(M)$ is S -dual to the cohomological orientation class restricted to the 2-skeleton, which is unaffected by a change of p_1 -structure. \square

3.3. Comparison with the Bloch invariant. Let us recall how Neumann and Yang construct in [NY99] the Bloch invariant $\beta(M) \in \mathcal{B}(\mathbb{C})$. The later is the kernel of the morphism $\mathcal{P}(\mathbb{C}) \rightarrow \Lambda^2(\mathbb{C}^*/\mu_{\mathbb{C}})$ in the Bloch-Wigner exact sequence, Proposition 2.6. Since M is oriented hyperbolic, $\Gamma \subset PSL_2\mathbb{C}$ and M can be identified with the quotient \mathcal{H}^3/Γ . Choose a fundamental polytope $P \subset \mathcal{H}^3$ for the action of Γ and define $\beta(M) = [P] \in \mathcal{P}(\mathcal{H}^3)$. One can check that $\beta(M)$ coincides with the image of the fundamental class through the composite

$$H_3(M; \mathbb{Z}) \longrightarrow H_3(PSL_2\mathbb{C}; \mathbb{Z}) \longrightarrow \mathcal{P}(\mathbb{C}).$$

This proves that $\beta(M)$ is well-defined, and lies indeed in $\mathcal{B}(\mathbb{C})$.

Theorem 3.5. *Let M be a closed, compact, orientable hyperbolic 3-manifold. The element $\gamma(M)$ lifts the Bloch invariant $\beta(M)$.*

Proof. It is well-known that the cokernel of the natural map $K_3^M(\mathbb{C}) \rightarrow K_3(\mathbb{C})$ provides a splitting for $H_3(SL_2\mathbb{C}; \mathbb{Z}) \rightarrow K_3(\mathbb{C})$. Moreover the morphism $H_3(SL_2\mathbb{C}; \mathbb{Z}) \rightarrow \mathcal{P}(\mathbb{C})$ factors through $H_3(PSL_2\mathbb{C}; \mathbb{Z})$. Therefore we have a commutative diagram

$$\begin{array}{ccccc} \pi_3^S(M) & \xrightarrow{\rho} & \pi_3^S(BSL_2\mathbb{C}) & \longrightarrow & K_3(\mathbb{C}) \\ \downarrow & & \downarrow & & \downarrow \\ H_3(M; \mathbb{Z}) & \longrightarrow & H_3(PSL_2\mathbb{C}; \mathbb{Z}) & \longrightarrow & \mathcal{P}(\mathbb{C}) \end{array}$$

and obviously the reduced \mathbb{S} -orientation \tilde{t} maps to an orientation in $H_3(M; \mathbb{Z})$. \square

Remark 3.6. Our approach can be applied in higher dimensions, since the same definition can be used in a straightforward manner to define a class in $K_n(\mathbb{C})$ associated to an n -dimensional \mathbb{S} -oriented hyperbolic manifold. This definition might of course depend on the chosen orientation in general, if it exists.

Borel defined in [Bor77] the Borel regulator $\text{bo-reg}_{\mathbb{C}} : K_3(\mathbb{C}) \rightarrow \mathbb{R}$. Likewise the Bloch regulator is a map $\text{bl-reg}_{\mathbb{C}} : \mathcal{B}(\mathbb{C}) \rightarrow \mathbb{C}/\mathbb{Q}$ and the Bloch-Wigner map is a map $\text{bw}_{\mathbb{C}} : K_3(\mathbb{C}) \rightarrow \mathcal{B}(\mathbb{C})$.

Corollary 3.7. *Let M be a closed compact oriented hyperbolic manifold of dimension 3 with fundamental group Γ . Then, to a Spin-structure ρ corresponds, in a canonical way, a class $\gamma(M) \in K_3(\mathbb{C})$ such that the hyperbolic volume of M is determined by the equality*

$$\text{bo-reg}_{\mathbb{C}}(\gamma(M)) = \frac{\text{vol}(M)}{2\pi^2}.$$

Furthermore the Chern-Simmons invariant $\text{CS}(M)$ is determined by the congruence

$$\mu(\gamma(M)) \equiv \frac{-\text{CS}(M) + i \cdot \text{vol}(M)}{2\pi^2} \pmod{\mathbb{Q}}.$$

Proof. This follows directly from Theorem 3.5. Neumann and Yang prove in [NY99, Theorem 1.3] that one can recover the volume and the Chern-Simmons invariant via the Borel and Bloch regulators. \square

4. LIFTING THE BLOCH INVARIANT, THE NON-COMPACT CASE

Let M be a non-compact, orientable, hyperbolic 3-manifold of finite volume with $\Gamma = \pi_1(M)$. Since M has finite volume it has a finite number of cusps and all of them are toroidal, [Rat94, Theorem 10.2.1]. Choose such a cusp $x \in M$ and denote by $P \subset SL_2(\mathbb{C})$ the preimage of the parabolic stabilizer of x . As in Subsection 2.2, i_P denotes the map $BP \rightarrow BSL_2\mathbb{C}$. Choose a Spin-structure on M , i.e. a homomorphism $\Gamma \rightarrow SL_2(\mathbb{C})$. The representation ρ contains parabolic elements, i.e. elements fixing a point in the boundary $\partial\overline{\mathcal{H}}^3$. Choose a sufficiently small δ -horosphere around each cusp of M and denote by M_δ the compact submanifold obtained by removing these horospheres from the cups of M , [Thu97, Theorem 4.5.7]. The inclusion $M_\delta \hookrightarrow M$ is a homotopy equivalence.

4.1. A first indeterminacy for $\gamma(M)$. Let $T \subset \partial M_\delta$ denote any component of the boundary, so $T \simeq S^1 \times S^1$. Consider the composite

$$T \hookrightarrow \partial M_\delta \hookrightarrow M_\delta \xrightarrow{B\rho} BSL_2(\mathbb{C}) \longrightarrow \text{Cof}(i_P)$$

As the action of $SL_2(\mathbb{C})$ is transitive on the boundary of the hyperbolic space, all stabilizers of points in $\partial\mathcal{H}^3$ are conjugate. The inclusion of $\mathbb{Z} \oplus \mathbb{Z}$ into $SL_2(\mathbb{C})$ is then conjugate to an inclusion into P , so that the map $T \rightarrow \text{Cof}(i_P)$ is null-homotopic.

So, from the choice of the Spin-structure, we get a map $M_\delta/\partial M_\delta \rightarrow \text{Cof}(i_P)$, which is well-defined up to homotopy. A stable parallelization of the tangent bundle of M_δ gives rise to a fundamental class $t \in \mathbb{S}_3(M_\delta, \partial M_\delta) \cong \pi_3^S(M_\delta/\partial M_\delta)$. Pushing this class by the above map, we get a well-defined class $\gamma_P(M) \in \pi_3^S(\text{Cof}(i_P))$.

Theorem 4.1. *Let M be a non-compact, orientable, hyperbolic 3-manifold of finite volume. It is then always possible to lift the class $\gamma_P(M)$ to a class $\gamma(M) \in K_3(\mathbb{C})$, and there are \mathbb{Q}/\mathbb{Z} possible lifts.*

Proof. According to Proposition 2.6, the class $\gamma_P(M)$ lives in $\mathcal{P}(\mathbb{C}) \cong \pi_3^S(\text{Cof}(i_P))$. Thus our invariant $\gamma_P(M)$ coincides in fact with the Bloch invariant $\beta(M)$, defined in an analogous way to the compact case. We wish to lift it through the connecting morphism $\delta : \pi_3^S BSL_2(\mathbb{C}) \rightarrow \pi_3^S(\text{Cof}(i_P))$.

According to Neumann and Yang, [NY99, Section 5] the Bloch invariant is the scissors congruence class of any hyperbolic ideal triangulation of M and this class belongs to the kernel $\mathcal{B}(\mathbb{C})$ of $\mathcal{P}(\mathbb{C}) \rightarrow \Lambda^2(\mathbb{C}^*/\mu_{\mathbb{C}})$.

The existence of the lift follows at once from Proposition 2.6. This explains the \mathbb{Q}/\mathbb{Z} indeterminacy: the image of the map $\pi_3^S(BP) \rightarrow \pi_3^S(BSL_2(\mathbb{C}))$ is isomorphic to \mathbb{Q}/\mathbb{Z} . Now it suffices to push any lift to $\pi_3^S(BSL(\mathbb{C}))$, a group isomorphic to $K_3(\mathbb{C})$ by Lemma 3.1. \square

Remark 4.2. The fact that the Bloch invariant lies in $\mathcal{B}(\mathbb{C})$ has a nice geometrical interpretation. Hyperbolic tetrahedra up to isometry are in one to one correspondence with elements of $\mathbb{C} - \{0, 1\}$, the modulus of the tetrahedron. If one starts with a collection of such tetrahedra and wants to glue them to a hyperbolic space then a theorem of Thurston says that the moduli of the tetrahedra have to satisfy a compatibility relation in $\Lambda^2(\mathbb{C} - \{0, 1\})$, namely $\Sigma(z \wedge (1 - z)) = 0$. The above morphism $\mathcal{P}(\mathbb{C}) \rightarrow \Lambda^2(\mathbb{C}^*/\mu_{\mathbb{C}})$ is $z \mapsto 2(z \wedge (1 - z))$. In particular the image under this morphism of an ideal triangulation of the hyperbolic manifold M will be trivially 0 since we started with an hyperbolic manifold.

Theorem 4.1 immediately provides the following.

Corollary 4.3. [Gon99, Theorem 1.1] *Let M be a non-compact, orientable, hyperbolic 3-manifold of finite volume. Then M defines naturally a class $\gamma(M) \in K_3(\mathbb{C}) \otimes \mathbb{Q}$ such that $bo(\gamma(M)) = vol(M)$. \square*

4.2. Reducing the indeterminacy. To reduce the \mathbb{Q}/\mathbb{Z} indeterminacy in the non-compact case one can make use of the following fact. In the compact case we do get a class in $\pi_3^s(BSL_2\mathbb{C})$ which is further stabilized to $\pi_3^s(BSL\mathbb{C}) \simeq K_3(\mathbb{C})$. Denote by τ the involution of $\pi_3^s(BSL_2\mathbb{C})$ induced by complex conjugation.

Proposition 4.4. *If $\pi_3^s(BSL_2\mathbb{C})^\pm = \ker(1 \mp \tau)$ then*

- (1) $\pi_3^s(BSL_2\mathbb{C}) = \pi_3^s(BSL_2\mathbb{C})^+ + \pi_3^s(BSL_2\mathbb{C})^-$;
- (2) $\pi_3^s(BSL_2\mathbb{C})^+ \cap \pi_3^s(BSL_2\mathbb{C})^- \cong \mathbb{Z}/2$;
- (3) *the image of $\pi_3^s(BP) \rightarrow \pi_3^s(BSL_2\mathbb{C})$ lies in $\pi_3^s(BSL_2\mathbb{C})^+$.*

Proof. By Lemma 2.5 $\pi_3^s(BSL_2\mathbb{C}) \cong H_3(SL_2\mathbb{C}; \mathbb{Z})$, so it is enough to prove the assertion in homology. According to [Dup01, Corollary 8.20] the group $H_3(SL_2\mathbb{C}; \mathbb{Z})$ is divisible, so that any element c can be written $\frac{c+\tau(c)}{2} + \frac{c-\tau(c)}{2} \in H_3(SL_2\mathbb{C}; \mathbb{Z})^+ + H_3(SL_2\mathbb{C}; \mathbb{Z})^-$. This proves point (1).

Any element in the intersection $H_3(SL_2\mathbb{C}; \mathbb{Z})^+ \cap H_3(SL_2\mathbb{C}; \mathbb{Z})^-$ is 2-torsion. The computations in [Dup01, Corollary 8.20] show that the torsion in $H_3(SL_2\mathbb{C}; \mathbb{Z})$ is isomorphic to \mathbb{Q}/\mathbb{Z} . Point (2) follows.

The torsion subgroup of $H_3(SL_2\mathbb{C}; \mathbb{Z})$ is the image of the composite $H_3(S^1; \mathbb{Z}) \rightarrow H_3(P; \mathbb{Z}) \rightarrow H_3(SL_2\mathbb{C}; \mathbb{Z})$. The action of τ on the subgroup S^1 in P coincides with the action induced by conjugation in $SL_2(\mathbb{C})$ by the matrix $\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$. Point (3) follows since conjugation by an element of a group induces the identity. \square

For any compact hyperbolic manifold its invariant $\gamma(M)$ lies in $\pi_3^s(BSL_2\mathbb{C})^-$. Indeed the following diagram commutes:

$$\begin{array}{ccc} H_3(M; \mathbb{Z}) & \xrightarrow{\rho_*} & H_3(SL_2\mathbb{C}; \mathbb{Z}) \\ -1 \downarrow & & \downarrow \tau_* \\ H_3(M; \mathbb{Z}) & \xrightarrow{\rho_*} & H_3(SL_2\mathbb{C}; \mathbb{Z}) \end{array}$$

In view of point (3) in the above proposition it is natural to choose as lifting a class in $\pi_3^s(BSL_2\mathbb{C})^-$, and this reduces the ambiguity to $\mathbb{Z}/2$.

Theorem 4.5. *Let M be a non-compact, orientable, hyperbolic 3-manifold of finite volume. There are two natural lifts $\gamma(M)^\pm \in K_3(\mathbb{C})$ of the class $\gamma_P(M)$.* \square

APPENDIX A. ORIENTATION WITH RESPECT TO ALGEBRAIC K -THEORY

To generalize this approach to higher dimensional manifolds, one cannot follow the same strategy, as it is not known whether or not all hyperbolic manifolds are stably parallelizable. There is however an intermediate way, between stable homotopy and ordinary homology. What we have done in the three dimensional situation was to start with an \mathbb{S} -orientation, and the former approaches [Gon99], [NY99], and [CMJ03] all roughly started from the fundamental class in homology.

The first author's original insight to the question of lifting the Bloch invariant was to work with $K\mathbb{Z}$ -orientation, where $K\mathbb{Z}$ denote the connective spectrum of the algebraic K -theory of the integers. We believe that this is a point of view which is close enough to ordinary homology (or topological K -theory) so as to be able to do computations, but at the same time not too far away from the stable homotopy so that the above techniques to construct an invariant in $K_3(\mathbb{C})$ can go through.

In his foundational paper [Lod76] Loday defines a product in algebraic K -theory by means of a pairing of spectra (in the sense of Whitehead). Given two rings R and S , consider the connective Ω -spectra KR and KS corresponding to the infinite loop spaces $BGLR^+ \times K_0R$ and $BGLS^+ \times K_0S$ respectively (the deloopings are given by the spaces $BGL(S^nR)^+$ where SR denotes the suspension of the ring R). Then there exists a pairing

$$\star : KS \wedge KR \rightarrow K(S \otimes R).$$

We will be interested in the case when $S = \mathbb{Z}$. In this case the pairing goes to KR . The pairing includes in particular compatible maps

$$BGL(S^n\mathbb{Z})^+ \wedge BGLR^+ \rightarrow BGL(S^n\mathbb{Z} \otimes R)^+ \cong BGL(S^nR)^+$$

which yield a map of spectra $\star : K\mathbb{Z} \wedge BGLR^+ \rightarrow KR$. In order to compare the present construction with the previous one based on an \mathbb{S} -orientation, we will need to understand the map obtained by precomposing with $\varepsilon \wedge 1$, where $\varepsilon : \mathbb{S} \rightarrow K\mathbb{Z}$ is the unit of the ring spectrum $K\mathbb{Z}$. We first look at the global pairing of spectra.

Lemma A.1. *The composite map $\mathbb{S} \wedge KR \xrightarrow{\varepsilon \wedge 1} K\mathbb{Z} \wedge KR \xrightarrow{\star} KR$ is the identity.*

Proof. We learn from May, [May80], that KR is a ring spectrum. In particular the composite $\mathbb{S} \wedge KR \xrightarrow{\varepsilon \wedge 1} KR \wedge KR \xrightarrow{\star} K(R \otimes R) \xrightarrow{\mu} KR$ is the identity. By naturality and using the inclusion $\mathbb{Z} \hookrightarrow \mathbb{C}$ we see that the map from the statement must be the identity as well. \square

We are interested in the infinite loop space $BGLR^+$ and wish to compare it to the spectrum KR . For that purpose we use the pair of adjoint functors $\Sigma^\infty : Spaces \rightleftarrows Spectra : \Omega^\infty$, where $\Sigma^\infty X = \mathbb{S} \wedge X$ is the suspension spectrum of the space X and $\Omega^\infty E$ is the 0th term of the Ω -spectrum representing the cohomology theory E^* . If E is an Ω -spectrum, then $\Omega^\infty E = E_0$ and we write $a : \mathbb{S} \wedge E_0 \rightarrow E$ for the adjoint of the identity.

Proposition A.2. *The composite map $\mathbb{S} \wedge BGLR^+ \xrightarrow{\varepsilon \wedge 1} K\mathbb{Z} \wedge BGLR^+ \xrightarrow{\star} KR$ is homotopic to $a : \mathbb{S} \wedge BGLR^+ \rightarrow KR$.*

Proof. We consider the commutative diagram

$$\begin{array}{ccccc} \mathbb{S} \wedge \mathbb{S} \wedge BGLR^+ & \xrightarrow{\varepsilon \wedge 1 \wedge 1} & K\mathbb{Z} \wedge \mathbb{S} \wedge BGLR^+ & & \\ \downarrow 1 \wedge a & & \downarrow 1 \wedge a & \searrow \star & \\ \mathbb{S} \wedge KR & \xrightarrow{\varepsilon \wedge 1} & K\mathbb{Z} \wedge KR & \xrightarrow{\star} & KR \end{array}$$

The square is obviously commutative and the triangle commutes up to homotopy since the Loday product \star forms a Whitehead pairing, [Lod76, p.346]. \square

Thus we can recover the invariant $\gamma(M)$ as follows. Consider the composite

$$h : K\mathbb{Z} \wedge M \xrightarrow{1 \wedge B\rho} K\mathbb{Z} \wedge BSL_2(\mathbb{C}) \longrightarrow K\mathbb{Z} \wedge BGL(\mathbb{C})^+ \xrightarrow{\star} K\mathbb{C}.$$

Proposition A.3. *Let M be a closed, compact, orientable hyperbolic 3-manifold and choose a $K\mathbb{Z}$ -orientation $s \in K\mathbb{Z}_3(M) \cong \pi_3(K\mathbb{Z} \wedge M)$. The invariant $\gamma(M) \in K_3(\mathbb{C})$ is then equal to $h_*(s)$. \square*

Between the $K\mathbb{Z}$ -orientation and the invariant $\gamma(M)$ there is an interesting class in $K_3(\mathbb{Z}\Gamma)$. It is obtained as the image of the $K\mathbb{Z}$ -orientation under the composite

$$K\mathbb{Z}_3(B\Gamma) \longrightarrow K\mathbb{Z}_3(BGL(\mathbb{Z}\Gamma)^+) \longrightarrow K_3(\mathbb{Z}\Gamma),$$

where the first arrow is induced by the canonical inclusion $\Gamma \hookrightarrow GL_1(\mathbb{Z}\Gamma)$ and the second is a Loday product. It is not difficult to see that we recover $\gamma(M)$ by further composing with

$$K_3(\mathbb{Z}\Gamma) \xrightarrow{\rho_*} K_3(\mathbb{Z}SL_2\mathbb{C}) \longrightarrow K_3(M_2\mathbb{C}) \cong K_3(\mathbb{C}).$$

The second arrow is the fusion map, which takes the formal sum of invertible matrices to the actual sum in $M_2\mathbb{C}$. The final isomorphism is just Morita invariance.

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