Tores hyperboliques pour les groupes de Coxeter finis non cristallographiques

Colloque tournant du GDR TLAG, LMB, Dijon

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$R\Gamma(X, \mathbb{Z}) \in \mathcal{D}^b(\mathbb{Z}[W])$ and equivariant cellular structures

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Also, $R\Gamma(X, \underline{\mathbb{Z}}) \in \mathcal{D}^b(\mathbb{Z}[W])$, but how to compute $R\Gamma(X, \underline{\mathbb{Z}})$?

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Definition

A CW-structure on X is W-**equivariant** if

- W acts on cells
- For $e \subset X$ a cell and $w \in W$, if $we = e$ then $w_{|e} = \mathrm{id}_e$.

Associated **cellular chain complex**: $C_*^{\mathrm{cell}}(X, W; \mathbb{Z}) \in \mathcal{C}_b(\mathbb{Z}[W])$.

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Theorem

The complex $C^*_{\mathrm{cell}}(X, W; \mathbb{Z})$ is well-defined up to homotopy and $C^*_{\mathrm{cell}}(X, W; \mathbb{Z}) \cong R\Gamma(X,\mathbb{Z})$ in $\mathcal{D}^b(\mathbb{Z}[W])$.

Illustration: $\{\pm 1\} \circlearrowright \mathbb{S}^2 \subset \mathbb{R}^3$

$C_2 = \{1, s\}$ acts on $\mathbb{S}^2$ via the antipode $s : x \mapsto -x$. We construct a C_2-equivariant cellular structure as follows:

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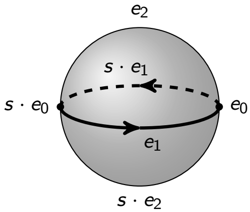

Chain complex given by

$$C_*^{\mathrm{cell}}(\mathbb{S}^2, C_2; \mathbb{Z}) = \left(\mathbb{Z}[C_2]\langle e_2 \rangle \xrightarrow{1+s} \mathbb{Z}[C_2]\langle e_1 \rangle \xrightarrow{1-s} \mathbb{Z}[C_2]\langle e_0 \rangle \right)$$

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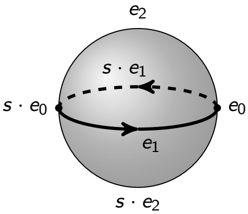

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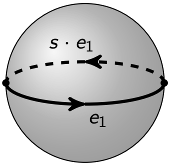

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so $R\Gamma(\mathbb{S}^2, \underline{\mathbb{Q}}) \simeq \mathbb{1} \oplus \varepsilon[-2]$ and $R\Gamma(\mathbb{S}^2, \underline{\mathbb{F}_2})$ has cohomology $H^*(\mathbb{S}^2, \mathbb{F}_2) = \mathbb{1} \oplus \mathbb{1}[-2]$, however, $R\Gamma(\mathbb{S}^2, \underline{\mathbb{F}_2})$ is indecomposable...

Position of the problem

Notation:

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- $T \simeq (\mathbb{S}^1)^n$ maximal torus of G,
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Problem (A)

Exhibit a W-equivariant triangulation of T.

- **Natural method**: Describe T as a W-equivariant simplicial complex.
- **Reduction**: use the exponential $\mathfrak{t} := \mathrm{Lie}(T) \twoheadrightarrow T$ and work with $\mathfrak{t}$.

Position of the problem

Notation:

- $\Phi \subset i\mathfrak{t}^* =: V$ *root system* of (G, T) (Bourbaki), $\Phi^\vee \subset V^*$,
- $\Pi \subset \Phi^+ \subset \Phi$ positive and simple roots, with $\Pi \approx \{1, \ldots, n\}$,
- $Q := \mathbb{Z}\Phi$ (resp. $Q^\vee := \mathbb{Z}\Phi^\vee$) (co)root lattice,
- P (resp. $P^\vee$) (co)weight lattice,
- Finally, $X(T) := \{d\lambda : \mathfrak{t} \to i\mathbb{R} \; ; \; \lambda \in \mathrm{Hom}(T, \mathbb{S}^1)\} \subset V$ character lattice of T and $Y(T) := X(T)^\wedge$ cocharacters.

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There is an isomorphism W-Lie groups:

$$\exp : V^*/Y(T) \xrightarrow{\sim} T.$$

We also have

$$P/X(T) \simeq \pi_1(G).$$

(Extended) affine Weyl groups

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Example: the type A_{n-1}:

	Simply conneted	In between	Adjoint
G	$SU_n(\mathbb{C})$		
$T \simeq \mathbb{S}^{n-1}$	$T_0 = \{\text{diagonal mat.}\} \leq SU_n$		
W	$\mathfrak{S}_n$		
$X := X(T)$	P		
$Y := Y(T)$	$Q^\vee$		
$\pi_1(G) = P/X$	1		

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W	$\mathfrak{S}_n$	$\mathfrak{S}_n$	$\mathfrak{S}_n$
$X := X(T)$	P	$Q \subset X \subset P$; $[P : X] = d$	Q
$Y := Y(T)$	$Q^\vee$	$P^\vee \supset Y \supset Q^\vee$	$P^\vee$
$\pi_1(G) = P/X$	1	$\mathbb{Z}/d\mathbb{Z}$	$\mathbb{Z}/n\mathbb{Z}$

The simply-connected case

If $\pi_1(G) = 1$ then $Y = Q^\vee$ and $Q^\vee \rtimes W \simeq W_{\mathrm{a}}$ is the **affine Weyl group**, a Coxeter group.

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For $\alpha_i \in \Pi$ let $\widehat{s}_i := s_{\alpha_i}$ and for $\alpha_0 \in \Phi^+$ the **highest root**, $\widehat{s}_0 := s_{\alpha_0} + \alpha_0^\vee$, then

$$W_{\mathrm{a}} \simeq \left\langle \widehat{s}_0, \widehat{s}_1, \ldots, \widehat{s}_n \;\middle|\; \forall 0 \leq i, j \leq n,\ (\widehat{s}_i \widehat{s}_j)^{o(s_{\alpha_i} s_{\alpha_j})} = 1 \right\rangle.$$

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Fundamental domain for $W_{\mathrm{a}} \circlearrowright V^*$? **the fundamental alcove**:

$$\mathcal{A} := \{\lambda \in V^* \ ;\ \forall \alpha \in \Phi^+,\ 0 \leq \lambda(\alpha) \leq 1\} \simeq \Delta^n.$$

The associated chain complex

Theorem

The face lattice of $\mathcal{A} \simeq \Delta^n$ induces a W_{a}-triangulation of V^* whose associated cellular complex $C_*^{\mathrm{cell}}(V^*, W_{\mathrm{a}}; \mathbb{Z})$ is

$$\cdots \longrightarrow \bigoplus_{|I|=n-k} \mathbb{Z}[W_{\mathrm{a}}^I] \xrightarrow{\partial_k} \bigoplus_{|I|=n-k+1} \mathbb{Z}[W_{\mathrm{a}}^I] \longrightarrow \cdots$$

where $W_{\mathrm{a}}^I := \{w \in W_{\mathrm{a}} \ ; \ \ell(ws_i) > \ell(w), \ \forall i \in I\} \approx W_{\mathrm{a}}/(W_{\mathrm{a}})_I$ is the set of minimal length coset representatives and

$$\{0, \ldots, n\} \backslash I = \{i_1 < \ldots < i_{k+1}\} \Rightarrow (\partial_k)_{|\mathbb{Z}[W_{\mathrm{a}}^I]} = \sum_{u=1}^{k+1} (-1)^u p^I_{I \cup \{i_u\}},$$

$$p^I_J : W_{\mathrm{a}}^I \longrightarrow\!\!\!\!\rightarrow W_{\mathrm{a}}^J \quad \textit{for} \quad I \subset J.$$

The associated W_{a}-dg-ring

Theorem

The product on the $\mathbb{Z}[W_{\mathrm{a}}]$*-dg-ring* $C^*_{\mathrm{cell}}(V^*, W_{\mathrm{a}}; \mathbb{Z})$ *is induced by the cup product*

$$\mathbb{Z}[{}^I W_{\mathrm{a}}] \otimes_{\mathbb{Z}} \mathbb{Z}[{}^J W_{\mathrm{a}}] \xrightarrow{\cup} \mathbb{Z}[{}^{I\cap J} W_{\mathrm{a}}]$$

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defined by

$${}^I x \cup {}^J y = \delta_{\max(I^c),\min(J^c)} \begin{cases} {}^{I\cap J}((xy^{-1})_J y) & \text{if } xy^{-1} \in (W_{\mathrm{a}})_I (W_{\mathrm{a}})_J, \\ 0 & \text{otherwise.} \end{cases}$$

We have denoted ${}^I W_{\mathrm{a}} \approx (W_{\mathrm{a}})_I \backslash W_{\mathrm{a}}$ *and, if* $w \in (W_{\mathrm{a}})_I (W_{\mathrm{a}})_J$*, then* w *can be uniquely written as* $w = uv$ *with* $u \in (W_{\mathrm{a}})_I^{I\cap J}$*,* $v \in (W_{\mathrm{a}})_J$ *and* $\ell(w) = \ell(u) + \ell(v)$ *and we let* $w_J := v$*.*

Consequences for T

Corollary (A1)

The $\mathbb{Z}[W]$-dg-ring $C^*_{\mathrm{cell}}(V^*/Q^\vee, W; \mathbb{Z})$ is given by

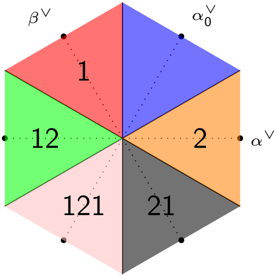
$$C^*_{\mathrm{cell}}(V^*/Q^\vee, W; \mathbb{Z}) = \mathrm{Def}_W^{W_\mathrm{a}}(C^*_{\mathrm{cell}}(V^*, W_\mathrm{a}; \mathbb{Z})),$$

with $\mathrm{Def}_W^{W_\mathrm{a}} : \mathbb{Z}[W_\mathrm{a}]-\mathbf{dgRing} \longrightarrow \mathbb{Z}[W]-\mathbf{dgRing}$ the functor induced by the deflation.
Abusing the notation, $W_I := \langle s_{\alpha_i},\ i \in I \rangle \leq W$, we have

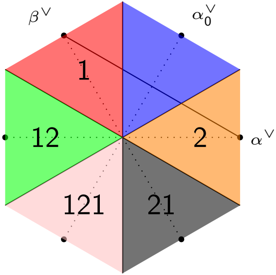
$$\forall k \geq 0,\ C^k_{\mathrm{cell}}(V^*/Q^\vee, W; \mathbb{Z}) = \bigoplus_{I \subset \{0,\dots,n\}\ ;\ |I|=n-k} \mathbb{Z}[W_I \backslash W].$$

The cohomology algebra is $H^\bullet(V^*/Q^\vee, \mathbb{Z}) \simeq \Lambda^\bullet_{\mathbb{Z}}(P)$.

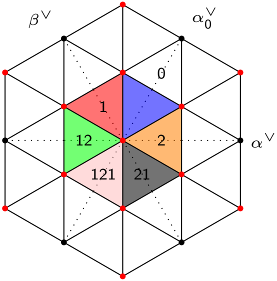
Example in type A_2



(a) Fundamental chamber (in blue) and its $\mathfrak{S}_3$-translates.



(b) What if we add a wall?



(c) Alcoves for $(\mathfrak{S}_3)_{\mathrm{a}} = \langle 1, 2, 0 \rangle$.

Figure: Chambers subdivided into alcoves.

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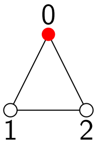
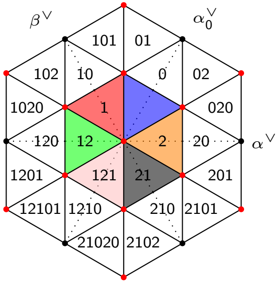
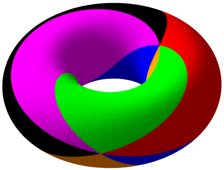


(a) Dynkin diagram of $\widetilde{A}_2$.



(b) Fundamental alcove and some of its $(\mathfrak{S}_3)_{\mathrm{a}}$-translates.



(c) Resulting $\mathfrak{S}_3$-triangulation of $S(U(1)^3) \simeq (\mathbb{S}^1)^2$.

Figure: Triangulation of the torus $S(U(1)^3)$ of $SU(3)$.

The complex $C_*^{\mathrm{cell}}(S(U(1)^3), \mathfrak{S}_3; \mathbb{Z})$ is given by

$$\mathbb{Z}[\mathfrak{S}_3] \xrightarrow{(1\ 1\ -1)} \mathbb{Z}[\mathfrak{S}_3/\langle s_\beta \rangle] \oplus \mathbb{Z}[\mathfrak{S}_3/\langle s_\alpha s_\beta s_\alpha \rangle] \oplus \mathbb{Z}[\mathfrak{S}_3/\langle s_\alpha \rangle] \xrightarrow{\begin{pmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ -1 & 0 & 1 \end{pmatrix}} \mathbb{Z}^3.$$

General case: barycentric subdivision of $\mathcal{A}$

Problem: the group Ω acts non-trivially on $\mathcal{A}$. However, we have the following comfortable result:

Lemma

Let Γ be a discrete affine group acting on a polytope Δ. Then the ***barycentric subdivision*** $\mathrm{Sd}(\Delta)$ *is a Γ-triangulation of Δ.*

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Theorem (A2)

The barycentric subdivision of the fundamental alcove induces a $\widehat{W_{\mathrm{a}}}$-equivariant triangulation of $\mathfrak{t}$. The same holds for any W-lattice $Q^\vee \subset \Lambda \subset P^\vee$ and the intermediate group W_Λ.

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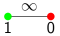
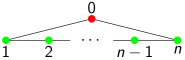
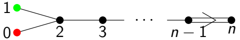
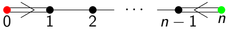
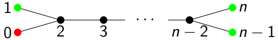
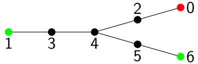
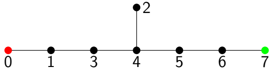
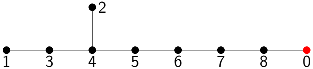
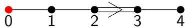
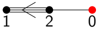
We can compute differentials and cup-product, but the formulas are not very enlightening. However, they are implemented in `GAP`.

Type	Affine Dynkin diagram	Fundamental group $\Omega \simeq P/Q$
$\widetilde{A_1}$		$\mathbb{Z}/2\mathbb{Z}$
$\widetilde{A_n}$ $(n \geq 2)$		$\mathbb{Z}/(n+1)\mathbb{Z}$
$\widetilde{B_n}$ $(n \geq 3)$		$\mathbb{Z}/2\mathbb{Z}$
$\widetilde{C_n}$ $(n \geq 2)$		$\mathbb{Z}/2\mathbb{Z}$
$\widetilde{D_n}$ $(n \geq 4)$		$\begin{cases} \mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z} & \text{if } n \text{ even} \\ \mathbb{Z}/4\mathbb{Z} & \text{if } n \text{ is odd} \end{cases}$
$\widetilde{E_6}$		$\mathbb{Z}/3\mathbb{Z}$
$\widetilde{E_7}$		$\mathbb{Z}/2\mathbb{Z}$
$\widetilde{E_8}$		1
$\widetilde{F_4}$		1
$\widetilde{G_2}$		1

Example of A_2

The homology chain complex in the case of $SU(3)$ is

$$\mathbb{Z}[W] \xrightarrow{(1\ 1\ -1)} \mathbb{Z}[W/\langle s_\beta \rangle] \oplus \mathbb{Z}[W/\langle s_\alpha s_\beta s_\alpha \rangle] \oplus \mathbb{Z}[W/\langle s_\alpha \rangle] \xrightarrow{\begin{pmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ -1 & 0 & 1 \end{pmatrix}} \mathbb{Z}^3 .$$

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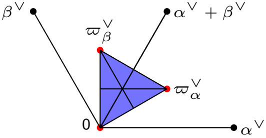

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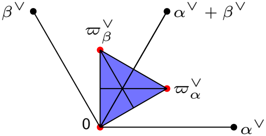

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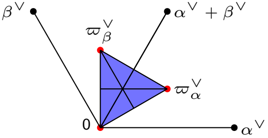

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We have $\Omega = \{1, \omega_\alpha, \omega_\beta\} \simeq \mathbb{Z}/3\mathbb{Z}$, where ω_β the rotation with center $\mathrm{bar}(\mathcal{A})$ and angle $2\pi/3$. The complex for $PSU(3)$ is

$$\mathbb{Z}[W]^2 \xrightarrow{\begin{pmatrix} 1 & 0 & -1 & 1 \\ 0 & 1 & -1 & s_\beta s_\alpha \end{pmatrix}} \mathbb{Z}[W/\langle\, s_\beta \,\rangle] \oplus \mathbb{Z}[W/\langle\, s_\alpha \,\rangle] \oplus \mathbb{Z}[W]^2 \xrightarrow{\begin{pmatrix} -1 & 1 & 0 \\ -1 & s_\beta s_\alpha & 0 \\ -1 & 0 & 1 \\ 0 & -1 & 1 \end{pmatrix}} \mathbb{Z} \oplus \mathbb{Z}[W/\langle\, s_\beta \,\rangle] \oplus \mathbb{Z}[W/\langle\, s_\alpha s_\beta \,\rangle] .$$

Compact hyperbolic extensions

The combinatorics of the complex for $\pi_1(G) = 1$ makes sense for any Coxeter system (W, S), with an additional reflection $r_W \in W$.

Problem (B)

Geometric interpretation of this analogy?

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Find a reflection giving a "nice" Coxeter extension $(\widehat{W}, S \cup \{\widehat{s}_0\})$?

"True tori": W Weyl, $r_W = s_{\widetilde{\alpha}}$ (highest root), $\widehat{W} = W_{\mathrm{a}}$.

"Non-crystallographic tori": r_W s.t. $\widehat{W}$ is **compact hyperbolic**.

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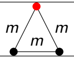
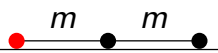
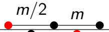
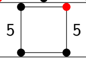
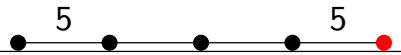
Extension	Coxeter graph
$\widehat{I_2(m)}$ $(m \equiv 1[2])$	
$\widehat{I_2(m)}$ $(m \equiv 0[4])$	
$\widehat{I_2(m)}$ $(m \equiv 2[4])$	
$\widehat{H_3}$	
$\widehat{H_4}$	

The non-commutative lattice Q

If $W = \langle s_1, \ldots, s_n \mid (s_i s_j)^{m_{i,j}} = 1 \rangle$, we let

$$\widehat{W} := \left\langle \widehat{s}_0, \widehat{s}_1, \ldots, \widehat{s}_n \;\middle|\; \forall i, j \geq 1,\ (\widehat{s}_i \widehat{s}_j)^{m_{i,j}} = (\widehat{s}_0 \widehat{s}_i)^{o(r_W s_i)} = \widehat{s}_0^2 = 1 \right\rangle.$$

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Sending $\widehat{s}_0 \in \widehat{W}$ to $r_W \in W$ induces a surjection $\pi : \widehat{W} \twoheadrightarrow W$ and we have $\widehat{W} = Q \rtimes W$, where the torsion-free subgroup

$$Q := \ker(\pi) = \left\langle (\widehat{s}_0 r_W)^{\widehat{W}} \right\rangle \lhd \widehat{W}$$

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Lemma

We have

$$\forall I \subsetneq \{\widehat{s}_0, \dots, \widehat{s}_n\},\ \widehat{W}_I \cap Q = 1.$$

Equivalently, Q is torsion-free.

Construction of $\mathbf{T}(W)$ from the Coxeter complex

Consider the **Coxeter complex**

$$\Sigma(\widehat{W}) := \left(\bigcup_{w \in \widehat{W}} w(\overline{C} \setminus \{0\}) \right) / \mathbb{R}_+^*,$$

where C is the *fundamental chamber* of $\widehat{W}$. We define

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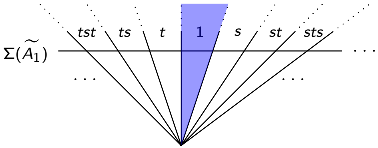
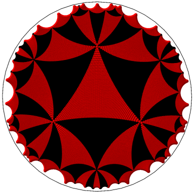


Figure: $\Sigma(\widetilde{A_1}) = \Sigma(I_2(\infty))$ as an affine line.

The example of $I_2(5)$

For $W = I_2(5)$, the simplicial structure of $\Sigma(\widehat{I_2(5)})$ induces a tessellation of the **hyperbolic plane** $\mathbb{H}^2$ (associated to the Tits form of $\widehat{I_2(5)})$ which projects on the Poincaré disk as follows:

(a) The plane $\mathbb{H}^2$ and the Poincaré disk.



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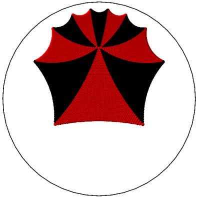
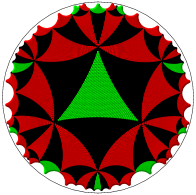


(c) Fundamental domain for Q.



(d) Q-orbit of the fundamental triangle.

The surface $\mathbf{T}(I_2(5))$ is obtained by gluing the triangles of a same orbit e.g. the green ones in the last figure.

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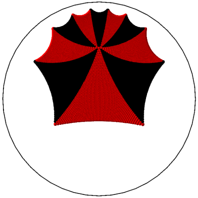

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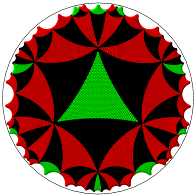

(d) Q-orbit of the fundamental triangle.

Let $I_2(5) = \left\langle s_1, s_2 \;\middle|\; s_1^2 = s_2^2 = (s_1 s_2)^5 = 1 \right\rangle$. The complex $C_*^{\text{cell}}(\mathbf{T}(I_2(5)), I_2(5); \mathbb{Z})$ is

$$\mathbb{Z}[I_2(5)] \xrightarrow{(1\;1\;-1)} \mathbb{Z}[I_2(5)/\langle\, s_2 \,\rangle] \oplus \mathbb{Z}[I_2(5)/\langle\, s_1^{s_2 s_1} \,\rangle] \oplus \mathbb{Z}[I_2(5)/\langle\, s_1 \,\rangle] \xrightarrow{\begin{pmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ -1 & 0 & 1 \end{pmatrix}} \mathbb{Z}^3.$$

Properties of $\mathbf{T}(W)$

Theorem (B)

The space $\mathbf{T}(W)$ is a W-triangulated orientable compact Riemannian manifold and $\mathbf{T}(W) \simeq K(Q,1) \simeq B_Q$. If W is a Weyl group, then $\mathbf{T}(W)$ is a torus and otherwise, $\mathbf{T}(W)$ is hyperbolic.

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Remark

The manifold $\mathbf{T}(H_4)$ is the Davis hyperbolic 4-manifold (1985) and $\mathbf{T}(H_3)$ is the Zimmermann hyperbolic 3-manifold (1993). Their Betti numbers are $b_*(\mathbf{T}(H_3)) = (1, 11, 11, 1)$ and $b_*(\mathbf{T}(H_4)) = (1, 24, 72, 24, 1)$.

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We give a presentation of $\pi_1(\mathbf{T}(W)) \simeq Q$ and describe the W-dg-ring of $\mathbf{T}(W)$, which is the one we want.

Properties of $\mathbf{T}(W)$

Let $\mathbb{Q}_W$ be a splitting field for W. We can take

$$\mathbb{Q}_{I_2(m)} = \mathbb{Q}(\cos(2\pi/m)) \text{ and } \mathbb{Q}_{H_3} = \mathbb{Q}_{H_4} = \mathbb{Q}(\sqrt{5}).$$

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If $W(q)$ (resp. $\widehat{W}(q)$) is the Poincaré series of W (resp. of $\widehat{W}$) then, as for tori,

$$\chi(\mathbf{T}(W)) = \left.\frac{W(q)}{\widehat{W}(q)}\right|_{q=1}.$$

Further details on the hyperbolic surfaces $\mathbf{T}(I_2(m))$

Corollary

Let $g \in \mathbb{N}^*$. Then $\mathbf{T}(I_2(2g+1))$, $\mathbf{T}(I_2(4g))$ and $\mathbf{T}(I_2(4g+2))$ are arithmetic Riemann surfaces with the same genus g.

We have an isomorphism

$$\mathbf{T}(I_2(4g+2)) \simeq \mathbf{T}(I_2(2g+1)),$$

and these two are not isomorphic to $\mathbf{T}(I_2(4g))$.

In particular, for $g = 1$, these are rational elliptic curves: the orbifold points in the Dirichlet domain of $PSL_2(\mathbb{Z})$.

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$\rightsquigarrow$ unusual point of view on tori!

Thank you very much!