2.1 COHOMOLOGY RINGS OF 6-MANIFOLDS

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2.1 Cohomology rings of 6-manifolds

Let (r, H, w, τ, F, p) be a system of invariants as in section 1; recall that it is admissible iff for every $W \in H$, $T \in H^\vee$ with $\bar{W} = w \pmod 2$, $\bar{T} \equiv \tau \pmod 2$ the following congruence holds:

$$(*) \qquad W^3 \equiv (p + 24T)(W) \pmod{48}.$$

Lemma 1. *(r, H, w, τ, F, p) is admissible if and only if there exist $W_\circ \in H$, $T_\circ \in H^\vee$ with $\bar{W}_\circ \equiv w \pmod 2$, $\bar{T}_\circ \equiv \tau \pmod 2$, such that*

i) $W_\circ^3 \equiv (p + 24T_\circ)(W_\circ) \pmod{48}$

ii) $p(x) \equiv 4x^3 + 6x^2 W_\circ + 3x W_\circ^2 \pmod{24}$ $\forall x \in H$.

Proof. Obvious since the set of integral lifts of w is a coset $W_\circ + 2H$.

Definition 3. *Let $F \in S^3 H^\vee$ be a symmetric trilinear form on a finitely generated free abelian group H. An element $W \in H$ is characteristic for F iff*

$$(**) \qquad x \cdot y \cdot (x + y + W) \equiv 0 \pmod 2 \ \forall x, y \in H.$$

Lemma 2. *$W \in H$ is a characteristic element for $F \in S^3 H^\vee$ if and only if the function $l_W : H \to \mathbf{Z}$, $l_W(x) := 4x^3 + 6x^2 W + 3x W^2$ is linear in x modulo 24.*

Proof. $l_W(x + y) = l_W(x) + l_W(y) + 12(x^2 y + xy^2 + xyW)$, whence the assertion.

The existence of characteristic elements is a necessary and sufficient condition for a cubic form $F \in S^3 H^\vee$ to be realizable by a manifold. In fact, we have:

Proposition 2. *A given cubic form $F \in S^3 H^\vee$ on a finitely generated free abelian group H is realizable as cup-form of a 1-connected, closed, oriented, 6-dimensional manifold with torsion-free homology if and only if it possesses a characteristic element.*

Proof. If (r, H, w, τ, F, p) is an admissible system of invariants, and $W_\circ \in H$ any integral lift of w, then we have $p(x) \equiv 4x^3 + 6x^2 W_\circ + 3x W_\circ^2 \pmod{24}$ $\forall x \in H$, i.e. the function $l_{W_\circ} : H \to \mathbf{Z}$ is linear modulo 24, and $W_\circ$ is therefore characteristic for F. Conversely, suppose $W_\circ \in H$ is a characteristic element for a cubic form $F \in S^3 H^\vee$; let $w := \bar{W}_\circ \pmod 2$, $r := 0$.

By the main lemma we have to construct linear forms $p, T \in H^\vee$, such that

i) $W_\circ^3 \equiv (p + 24T)(W_\circ) \pmod{48}$

ii) $p(x) \equiv 4x^3 + 6x^2 W_\circ + 3x W_\circ^2 \pmod{24}$ $\forall x \in H$.

The function $l_{W_\circ}: H \to \mathbf{Z}, l_{W_\circ}(x) = 4x^3 + 6x^2 W_\circ + 3x W_\circ^2$ is linear modulo 24 since $W_\circ$ is a characteristic element for F: we therefore choose a linear form $p_\circ \in H^\vee$ with $p_\circ(x) \equiv l_{W_\circ}(x) \pmod{24}$ $\forall x \in H$. Substituting $x = W_\circ$ we find $p_\circ(W_\circ) \equiv 13 W_\circ^3 \pmod{24}$; but since $W_\circ$ is characteristic we have $W_\circ^3 \equiv 0 \pmod 2$, thus $p_\circ(W_\circ) \equiv W_\circ^3 \pmod{24}$. Write $p_\circ(W_\circ) = W_\circ^3 + 24k$ for some $k \in \mathbf{Z}$.

case 1) $k \equiv 0 \pmod 2$: define $p := p_0$, $T := 0$.

case 2) $k \equiv 1 \pmod 2$: we must find a linear form $T_\circ \in H^\vee$ with $T_\circ(W_\circ) \equiv 1 \pmod 2$; clearly this can be done if and only if $W_\circ$ is not divisible by 2. If $W_\circ$ were divisible by 2, $W_\circ = 2V_\circ$ for some $V_\circ \in H$, then $2p_\circ(V_\circ) = p_\circ(W_\circ) = W_\circ^3 + 24k = 8V_\circ^3 + 24k$ would give $p_\circ(V_\circ) = 4V_\circ^3 + 12k$; then, using $p_\circ(V_\circ) \equiv 4V_\circ^3 + 6V_\circ^2 W_\circ + 3V_\circ W_\circ^2 \equiv 4V_\circ^3 \pmod{24}$ we would find $k \equiv 0 \pmod 2$, which is not the case by assumption.

This shows that $F \in S^3 H^\vee$ is realizable by a topological manifold with Pontrjagin class $p_\circ$ and non-vanishing triangulation obstruction $\tau_\circ := \bar{T}_\circ \pmod 2$. In order to realize F by a smooth manifold, one can take $p := p_\circ + 24T_\circ$, and $\tau := 0$.

REMARK 3. The topological counterpart of the existence of a characteristic element for a given cubic form $F \in S^3 H^\vee$ is the existence of a mod-2 Steenrod-algebra structure, which is a necessary condition for a ring to be a cohomology ring.

The existence and the classification of characteristic elements for a given cubic form is essentially a linear algebra problem over $\mathbf{Z}_{/2}$. To see this, let $F \in S^3 H^\vee$ be a fixed cubic form on a finitely generated free abelian group H. Associated with F we have a linear map $F^t: H \to S^2 H^\vee$ sending an element $h \in H$ to the bilinear form $F^t(h): H \otimes H \to \mathbf{Z}, (x, y) \to x \cdot y \cdot h$. Let $\bar{H} := H/_{2H}$. $\bar{F} \in S^3 \bar{H}^\vee$ be the reductions of H and F modulo 2, and let $- : H \to \bar{H}$ be the natural epimorphism. The symmetric trilinear form $\bar{F}$ on the $\mathbf{Z}_{/2}$-module $\bar{H}$ defines a natural symmetric bilinear form $q_{\bar{F}} \in S^2 \bar{H}^\vee$ given by $q_{\bar{F}}(\bar{x}, \bar{y}) := \bar{x} \cdot \bar{y} \cdot (\bar{x} + \bar{y})$.

LEMMA 3. *$F \in S^3 H^\vee$ admits characteristic elements if and only if $q_{\bar{F}}$ lies in the image of $\bar{F}^t \in \mathrm{Hom}_{\mathbf{Z}}(H, S^2 \bar{H}^\vee)$. The set of all characteristic elements for F is a coset of the form $W_\circ + \mathrm{Ker}(\bar{F}^t)$.*

Proof. $W_\circ$ is characteristic for F if and only if $q_{\bar F} = \bar F^t(W_\circ)$.

In terms of a $\mathbf{Z}$-basis $\{e_1, \ldots, e_b\}$ for H the condition $q_{\bar F} \in \operatorname{Im}(\bar F^t)$ translates into a simple rank condition over $\mathbf{Z}_{/2}$: the $\mathbf{Z}_{/2}$-rank of the $b \times \binom{b+1}{2}$-matrix A representing $\bar F^t$ must be equal to the $\mathbf{Z}_{/2}$-rank of the matrix A extended by the column $(\bar e_i \cdot \bar e_j \cdot (\bar e_i + \bar e_j))_{1 \leqslant i \leqslant j \leqslant b}$

EXAMPLE 3. Let $H = \mathbf{Z}e_1 \oplus \mathbf{Z}e_2$ be free of rank 2, $F \in S^3H^\vee$ given by $e_1^3 = a$, $e_1^2e_2 = b$, $e_1e_2^2 = c$, $e_2^3 = d$ with $a, b, c, d \in \mathbf{Z}$. The rank condition becomes

$$rk_2 \begin{bmatrix} \bar a & \bar b \\ \bar c & \bar d \\ \bar b & \bar c \end{bmatrix} = rk_2 \begin{bmatrix} \bar a & \bar b & \bar 0 \\ \bar c & \bar d & \bar 0 \\ \bar b & \bar c & \overline{b+c} \end{bmatrix}$$

2.2 Homotopy types with a given cohomology ring

Our next task is to describe the set of oriented homotopy types of 1-connected, closed, oriented, 6-dimensional manifolds with a fixed torsion-free cohomology ring.

From Žubr's classification theorem we know that in algebraic terms this means the following: fix a non-negative integer $r_\circ$, a finitely generated free abelian group $H_\circ$, and a symmetric trilinear form $F_\circ \in S^3H_\circ^\vee$ which admits characteristic elements.

Let $\mathcal{M}(r_\circ, H_\circ, F_\circ)$ be the set of 1-connected, closed, oriented, 6-dimensional manifolds X with $b_3(X) = 2r_\circ$, such that there exists an isomorphism $\alpha : H_\circ \to H^2(X, \mathbf{Z})$ with $\alpha^* F_X = F_\circ$. Denote by $\operatorname{Aut}(F_\circ)$ the subgroup of $\mathbf{Z}$-automorphisms of $H_\circ$ which leave $F_\circ \in S^3H_\circ^\vee$ invariant; $\operatorname{Aut}(F_\circ)$ acts on pairs $(w, [l]) \in \bar H_\circ \times H_\circ^\vee/_{48H_\circ^\vee}/_{U_{F_\circ}}$ in a natural way:

$$\gamma \cdot (w, [l]) := (\gamma(w), (\gamma^{-1})^* [l]) \ .$$

Let ${}_{\operatorname{Aut}(F_\circ)}\backslash \bar H_\circ \times H_\circ^\vee/_{48H_\circ^\vee}/_{U_{F_\circ}}$ be the set of $\operatorname{Aut}(F_\circ)$-orbits.

A manifold X in $\mathcal{M}(r_\circ, H_\circ, F_\circ)$ and an isomorphism $\alpha : H_\circ \to H^2(X, \mathbf{Z})$ with $\alpha^* F_X = F_\circ$ yields a well-defined $\operatorname{Aut}(F_\circ)$-orbit:

$$(\alpha^{-1}(w_2(X)), \alpha^*[p_1(X) + 24T]) \text{ (modulo } \operatorname{Aut}(F_\circ)) \ ,$$

where $T \in H^4(X, \mathbf{Z})$ is an arbitrary integral lifting of $\tau(X) \in H^4(X, \mathbf{Z}_{/2})$.

The set of oriented homotopy types $\mathcal{M}(r_\circ, H_\circ, F_\circ)/_\simeq$ of manifolds in $\mathcal{M}(r_\circ, H_\circ, F_\circ)$ can now be described in the following way: