EXOTIC COHOMOLOGY FOR $GL_n(\mathbb{Z}[1/2])$

W. G. DWYER

(Communicated by Thomas Goodwillie)

Abstract. We show that for $n = 32$ the mod 2 group cohomology of $GL_n(\mathbb{Z}[1/2])$ is not detected on diagonal matrices.

§1. Introduction

Let $\Lambda$ denote the ring $\mathbb{Z}[1/2]$, $G_n$ the group $GL_n(\Lambda)$ of invertible $n \times n$ matrices over $\Lambda$, and $D_n$ the group of diagonal matrices in $G_n$. The inclusion $D_n \to G_n$ induces a classifying space map $\iota_n : BD_n \to BG_n$ and a cohomology homomorphism

$$\iota_n^* : H^*(BG_n; \mathbb{F}_2) \to H^*(BD_n; \mathbb{F}_2).$$

Say that the mod 2 cohomology of $G_n$ is detected on diagonal matrices if $\iota_n^*$ is injective. In [15, 14.7] Quillen made a conjecture which specializes in the case of the ring $\Lambda$ to the following statement (see [9, p. 51]):

1.1 Conjecture. For any $n \geq 1$ the mod 2 cohomology of $G_n$ is detected on diagonal matrices.

There is some evidence for this conjecture. Mitchell [14] and Henn [10] have proved it for $n \leq 3$. Voevodsky has announced a proof of the mod 2 Quillen-Lichtenbaum Conjecture for $\mathbb{Z}$, and from [5] and [14] it follows that $\iota_n^*$ is injective on the image of $H^*(BGL(\Lambda); \mathbb{F}_2) \to H^*(BG_n; \mathbb{F}_2)$. In particular, 1.1 is true in the stable range.

The aim of this paper, though, is to give a disproof of Conjecture 1.1.

1.2 Theorem. The mod 2 cohomology of $G_{32}$ is not detected on diagonal matrices.

Given the remarks above, it is a consequence of 1.2 that there exists an element in the cohomology of $G_{32}$ which is not in the image of $H^*(BGL(\Lambda); \mathbb{F}_2)$. In fact, 1.2 is proved by a technique distantly related to the one which Quillen uses in [15, p. 592] to show that for various other number rings $S$ and primes $p$ the restriction map $H^*(BGL(S); \mathbb{F}_p) \to H^*(BGL_n(S); \mathbb{F}_p)$ is not surjective.

Further developments. Very recently, Henn and Lannes have improved upon 1.2 by showing that the mod 2 cohomology of $G_{14}$ is not detected on diagonal matrices. Moreover, Henn proves in [11, 0.6] that the Poincaré series $p_n(t)$ of the kernel of $\iota_n^*$ has a pole at $t = 1$ of order $n - n_0 + 1$, where $n_0$ is the smallest natural number.

Received by the editors November 14, 1996 and, in revised form, December 20, 1996.


This research was partially supported by National Science Foundation Grant DMS95-05024.

©1998 American Mathematical Society

2159
such that \( \iota_n^* \) is not injective. Combining these results shows that for any \( n \geq 14 \) the cohomology of \( G_n \) is far from being detected on diagonal matrices.

**A generalization.** Theorem 1.2 is a consequence of a result which is slightly more general. Recall that if \( P \) and \( G \) are groups and \( \alpha, \beta : P \to G \) are homomorphisms, then \( \alpha \) is said to be \textit{conjugate} to \( \beta \) if there is an element \( g \in G \) such that \( g\alpha g^{-1} = \beta \). Let \( \rho_R : G_n \to \text{GL}_n(\mathbb{R}) \) and \( \rho_{F_3} : G_n \to \text{GL}_n(\mathbb{F}_3) \) be the obvious homomorphisms. Two homomorphisms \( \alpha, \beta : P \to G_n \) are said to become \textit{conjugate over} \( \mathbb{R} \) (resp. \textit{become conjugate over} \( \mathbb{F}_3 \)) if \( \rho_R \alpha \) and \( \rho_R \beta \) (resp. \( \rho_{F_3} \alpha \) and \( \rho_{F_3} \beta \)) are conjugate.

**1.3 Theorem.** Suppose that the mod 2 cohomology of \( G_n \) is detected on diagonal matrices. Let \( P \) be a finite 2-group with homomorphisms \( \alpha, \beta : P \to G_n \). Then \( \alpha \) is conjugate to \( \beta \) if and only if \( \alpha \) becomes conjugate to \( \beta \) over \( \mathbb{R} \) and over \( \mathbb{F}_3 \).

To obtain 1.2 from 1.3 let \( \mu_n \) denote the group of \( 2^n \)-th roots of unity. The smallest \( n \) with the property that the ideal class group of \( \Lambda(\mu_n) \) is nontrivial is 6, and the degree of \( \Lambda(\mu_6) \) over \( \Lambda \) (equivalently, the rank of \( \Lambda(\mu_6) \) as a \( \Lambda \)-module) is \( \phi(2^6) = 2^3 = 32 \). Let \( P = \mu_n \), considered as a subgroup of \( \Lambda(\mu_6)^\times \), and let \( \mathcal{I} \) be a nonprincipal ideal in \( \Lambda(\mu_6) \). It is then not hard to use the multiplicative actions of \( P \) on \( \mathcal{I} \) and on \( \Lambda(\mu_n) \) itself to construct two nonconjugate homomorphisms \( P \to G_{32} \) which become conjugate over \( \mathbb{R} \) and over \( \mathbb{F}_3 \).

The proof of 1.3 is homotopy theoretic. If \( X \) and \( Y \) are spaces, let \( [X,Y] \) denote the set of (unpointed) homotopy classes of maps \( X \to Y \); if \( P \) and \( G \) are groups, let \( \{P,G\} \) denote the set of conjugacy classes of homomorphisms \( P \to G \). The classifying space functor gives a bijection \( \{P,G\} \cong [BP,BG] \). For each \( n \geq 1 \) we construct a space \( X_n \) together with a map

\[
\chi_n : BG_n \to X_n
\]

such that the following three statements hold.

**1.4 Proposition.** If the mod 2 cohomology of \( G_n \) is detected on diagonal matrices, then \( \chi_n^* : H^*(X_n;\mathbb{F}_2) \to H^*(BG_n;\mathbb{F}_2) \) is an isomorphism.

**1.5 Proposition.** If \( \chi_n^* \) is an isomorphism, then for any finite 2-group \( P \) the map \( \chi_n \cdot (-) : [BP,BG_n] \to [BP,X_n] \) is a bijection.

**1.6 Proposition.** Let \( P \) be a finite 2-group with homomorphisms \( \alpha, \beta : P \to G_n \). Then \( \chi_n \cdot (\alpha) \) is homotopic to \( \chi_n \cdot (\beta) \) if and only if \( \alpha \) becomes conjugate to \( \beta \) over \( \mathbb{R} \) and over \( \mathbb{F}_3 \).

Together, these imply 1.3.

Section 2 contains a description of the machinery which is used to construct the space \( X_n \). §3 has proofs of the above three propositions, and §4 contains the derivation of 1.2 from 1.3. Throughout the paper, unspecified homology and cohomology is to be taken with mod 2 coefficients. The symbol \( BG \) denotes the 2-completion [1] of the classifying space of \( G \). The usual topological groups \( \text{GL}_n(\mathbb{R}) \) and \( \text{GL}_n(\mathbb{C}) \) are denoted \( \text{GL}_n^{\text{top}}(\mathbb{R}) \) and \( \text{GL}_n^{\text{top}}(\mathbb{C}) \).

The idea for this paper originated in conversations with S. Mitchell, and the approach depends heavily on his calculations from [14]. The construction of \( X_n \) goes back to work with E. Friedlander [4]. Some of the arguments below can be generalized, but we have decided to concentrate on proving 1.2.
§2. Étale homotopy theory

The space $X_n$ promised in §1 is constructed using étale homotopy theory [8], which gives a covariant mechanism for assigning a space (more accurately a pro-space) $A_{\text{ét}}$ to any reasonable scheme or simplicial scheme $A$. We build $X_n$ as a certain space of maps between two étale homotopy types (2.6), in imitation of the way in which $\text{GL}_n(\Lambda)$ can be described as a certain set of maps between schemes.

Étale homotopy types. Here are some examples of étale homotopy types. In the examples, the symbol $\ell$ stands for a prime number.

2.1 Fields and complete local rings. If $k$ is a field, then $\text{Spec}(k)_{\text{ét}}$ is a pro-space of type $K(\pi, 1)$, where $\pi$ is the Galois group over $k$ of the separable algebraic closure of $k$. If $S$ is a complete local ring with residue class field $k$, then the map $\text{Spec}(k)_{\text{ét}} \to \text{Spec}(S)_{\text{ét}}$ induced by $S \to k$ is an equivalence. For instance, $\text{Spec}(\mathbb{C})_{\text{ét}}$ is contractible, $\text{Spec}(R)_{\text{ét}}$ is equivalent to $B\mathbb{Z}/2$, and both $\text{Spec}(\mathbb{F}_3)_{\text{ét}}$ and $\text{Spec}(\mathbb{Z}_3)_{\text{ét}}$ are equivalent to the profinite completion of a circle.

If $S$ is a commutative ring, let $\text{GL}_{n,S}$ denote the rank $n$ general linear group scheme over $S$. Applying the usual bar construction to $\text{GL}_{n,S}$ gives a classifying object $B\text{GL}_{n,S}$ [8, 1.2], which is a simplicial scheme. See [8, §8] for the following three examples.

2.2 General linear groups over algebraically closed fields. If $k$ is an algebraically closed field of characteristic zero, the pro-space $(B\text{GL}_{n,k})_{\text{ét}}$ is equivalent to the profinite completion of the space $B\text{GL}_{n,\text{top}}(\mathbb{C})$. If $k$ is the algebraic closure of a finite field, then the $\ell$-completion of $(B\text{GL}_{n,k})_{\text{ét}}$ at any prime $\ell$ not equal to $\text{char}(k)$ is equivalent to the Bousfield-Kan $\ell$-completion tower $\{(\mathbb{Z}/\ell)^s_{\text{ét}}(B\text{GL}_{n,\text{top}}(\mathbb{C}))\}_s$.

2.3 General linear groups over other fields. If $k$ is a field of characteristic zero with algebraic closure $\overline{k}$, then the natural sequence

$$(B\text{GL}_{n,\overline{k}})_{\text{ét}} \to (B\text{GL}_{n,k})_{\text{ét}} \to \text{Spec}(k)_{\text{ét}}$$

is a fibration sequence of pro-spaces. In effect, if $\pi$ is the Galois group of $\overline{k}$ over $k$, $(B\text{GL}_{n,k})_{\text{ét}}$ is the Borel construction of the natural action of $\pi$ on $(B\text{GL}_{n,\overline{k}})_{\text{ét}}$. If $k$ is a finite field with algebraic closure $\overline{k}$ and $\ell \neq \text{char}(k)$, there is a similar fibration sequence

$$\{(\mathbb{Z}/\ell)^s_{\text{ét}}(B\text{GL}_{n,\overline{k}})\}_s \to \{(\mathbb{Z}/\ell)^s_{\text{ét}}(B\text{GL}_{n,k})\}_s \to \text{Spec}(k)_{\text{ét}},$$

where $\{(\mathbb{Z}/\ell)^s_{\text{ét}}(-)\}_s$ denotes fibrewise $\ell$-completion over $\text{Spec}(k)_{\text{ét}}$.

2.4 General linear groups over number rings. Suppose that $R$ is a number ring, and that $S$ is the ring $R[1/\ell]$. Let $\overline{k}$ denote either the algebraic closure of the quotient field of $S$, or the algebraic closure of one of the residue class fields of $S$ (note that none of these residue fields have characteristic $\ell$). Then the natural sequence

$$\{(\mathbb{Z}/\ell)^s_{\text{ét}}(B\text{GL}_{n,\overline{k}})\}_s \to \{(\mathbb{Z}/\ell)^s_{\text{ét}}(B\text{GL}_{n,S})\}_s \to \text{Spec}(S)_{\text{ét}},$$

is a fibration sequence. There are identical fibration sequences if $S$ is replaced by a complete local ring of residue characteristic different from $\ell$. 


2.5 Number rings. The étale homotopy type of a number ring is not easy to pin down; see [5, 2.1] for a description of its untwisted “integral” homology. We will settle for a partial description of Spec(Λ)\text{\text{ét}}, where, as usual, Λ = Z[1/2]. Choose an embedding Z_3 → C. There are induced commutative diagrams of rings and of pro-spaces
\[
\begin{array}{ccc}
C & \xrightarrow{\text{R}} & \text{Spec}(C)\text{\text{ét}} \\
\uparrow & & \downarrow \\
Z_3 & \xleftarrow{\Lambda} & \text{Spec}(Z_3)\text{\text{ét}}
\end{array}
\]
Since Spec(C)\text{\text{ét}} is contractible, the diagram induces a map
\[
\text{Spec}(Z_3)\text{\text{ét}} \lor \text{Spec}(R)\text{\text{ét}} \rightarrow \text{Spec}(Λ)\text{\text{ét}}.
\]
Pick an equivalence B\text{\text{Z}}/2 → Spec(R)\text{\text{ét}}, and a map S^1 → Spec(Z_3) which sends the generator of \pi_1 S^1 to the Frobenius automorphism of \overline{F}_3 over F_3. What results is a map
\[
S^1 \lor B\text{\text{Z}}/2 \rightarrow \text{Spec}(Λ)\text{\text{ét}}.
\]
By [5], this map induces an isomorphism on mod 2 cohomology (cf. [6, §2]).

2.6 Étale approximations to BGL_n(S). Let S be an algebra over Λ. The homomorphism Λ → S induces a map Spec(S)\text{\text{ét}} → Spec(Λ)\text{\text{ét}}. We set ℓ = 2 and let BGL_\ell,n(S) denote the basepoint component of the space which in [4, 2.3] is called \text{Hom}_\ell(S)\text{\text{ét}}, (BGL_{\ell,n,Λ})_\text{ét}; in other words, BGL_\ell,n(S) is the basepoint component of the function space of maps over Spec(Λ)\text{\text{ét}} from Spec(S)\text{\text{ét}} to the fibre-wise 2-completion of (BGL_{\ell,n,Λ})_\text{ét}. (The function space is pointed because the map BGL_{\ell,Λ} → Spec(Λ) has a natural section provided by the basepoint of the fibrewise bar construction.) Since BGL_\ell,n(S) can be identified as the basepoint component of the space of maps Spec(S) → BGL_{\ell,n,Λ} over Spec(Λ) [4, 4.2], functoriality gives a map
\[
\chi_{n,S} : \text{BGL}_n(S) \rightarrow \text{BGL}_{\ell,n}(S)
\]
(see [4, 2.5, pf. of 4.2]). We will describe this map below in some particular cases.

2.7 Remark. Suppose that B is a space (i.e. a trivial pro-space) together with a map B → Spec(Λ)\text{\text{ét}}. Let “holim” denote the homotopy inverse limit functor from pro-spaces to spaces [8, §6], and E be the fibration over B obtained by the following homotopy pullback diagram:
\[
\begin{array}{ccc}
E & \xrightarrow{} & \text{holim}\{\text{(Z}/2)^{\bullet}(BGL_{\ell,n,Λ})_\text{ét}\}_s \\
\downarrow & & \downarrow \\
B & \xrightarrow{} & \text{holim Spec}(Λ)\text{\text{ét}}
\end{array}
\]
The homotopy fibre of E → B is \text{BGL}^{\text{top}}_n(C). Essentially by definition, the space \text{Hom}_\ell(B, (BGL_{\ell,n,Λ})_\text{ét})_Λ is equivalent to the space of sections of the map E → B.

It follows from a spectral sequence argument [4, 2.11] that if S is a Λ-algebra and f : B → Spec(S)\text{\text{ét}} is a map of pro-spaces which induces an isomorphism on mod 2 cohomology, then f induces an equivalence
\[
\text{BGL}_{\ell,n}(S) \xrightarrow{\simeq} \text{Hom}_\ell(B, (BGL_{\ell,n,Λ})_\text{ét})_Λ.
\]
2.8 The complex numbers. Since Spec(\(\mathbb{C}\))\(_{\text{ét}}\) is contractible, it follows from 2.7 that \(\text{BGL}_n(\mathbb{C})\) is equivalent to \(\tilde{\text{BGL}}_n^{\text{top}}(\mathbb{C})\). The same calculation works for any separably closed field of characteristic not 2. The map \(\chi_{n,\mathbb{C}}\) is essentially the composite of the usual map \(\text{BGL}_n(\mathbb{C}) \to \text{BGL}_n^{\text{top}}(\mathbb{C})\) with the 2-completion map.

2.9 The real numbers. Since Spec(\(\mathbb{R}\))\(_{\text{ét}}\) is equivalent to \(\mathbb{BZ}/2\), it follows from 2.7 that \(\text{BGL}_n^{\text{ét}}(\mathbb{R})\) is equivalent to the basepoint component of the space of sections of a fibration over \(\mathbb{BZ}/2\) with \(\tilde{\text{BGL}}_n^{\text{top}}(\mathbb{C})\) as the fibre. By naturality, this fibration is the one associated to the action of \(\mathbb{Z}/2\) on \(\tilde{\text{BGL}}_n^{\text{top}}(\mathbb{C})\) by complex conjugation.

It follows from [7] that the natural map from \(\text{BGL}_n^{\text{top}}(\mathbb{R})\) to this space of sections is an equivalence. The map \(\chi_{n,\mathbb{R}}\) is the essentially the composite of the usual map \(\text{BGL}_n(\mathbb{R}) \to \text{BGL}_n^{\text{top}}(\mathbb{R})\) with the 2-completion map.

2.10 The field \(\bar{\mathbb{F}}_3\). Consider the commutative diagram

\[
\begin{array}{ccc}
\text{BGL}_n(\bar{\mathbb{F}}_3) & \longrightarrow & \colim_n \text{BGL}_n(\bar{\mathbb{F}}_3) = \text{BGL}(\bar{\mathbb{F}}_3) \\
\chi_{n,\bar{\mathbb{F}}_3} \downarrow & & \downarrow \colim_n (\chi_{n,\bar{\mathbb{F}}_3}) \\
\text{BGL}_n^{\text{ét}}(\bar{\mathbb{F}}_3) & \longrightarrow & \colim_n \text{BGL}_n^{\text{ét}}(\bar{\mathbb{F}}_3)
\end{array}
\]

in which the colimit maps are induced by the usual matrix block inclusions. The right hand vertical arrow induces an isomorphism on mod 2 cohomology (see [4, 4.5, 8.6]). The horizontal maps induce surjections on mod 2 cohomology; for the upper one see [16] and for the lower one 2.7. By diagram chasing, \(\chi_{n,\bar{\mathbb{F}}_3}\) induces a surjection on mod 2 cohomology. Since \(\text{BGL}_n(\bar{\mathbb{F}}_3)\) and \(\text{BGL}_n^{\text{ét}}(\bar{\mathbb{F}}_3)\) have mod 2 cohomology rings which are abstractly isomorphic ([16], 2.7) and finite in each dimension, \(\chi_{n,\bar{\mathbb{F}}_3}\) must be an isomorphism on mod 2 cohomology. It follows that \(\text{BGL}_n^{\text{ét}}(\bar{\mathbb{F}}_3)\) is equivalent to \(\tilde{\text{BGL}}_n(\bar{\mathbb{F}}_3)\).

2.11 The field \(\mathbb{F}_3\). There is a map \(S^1 \to \text{Spec}(\mathbb{F}_3)_{\text{ét}}\) which sends a generator of \(\pi_1(S^1)\) to the Frobenius automorphism \(\psi\) of \(\mathbb{F}_3\) over \(\mathbb{F}_3\). This map is an isomorphism on cohomology with finite coefficients, in particular, on mod 2 cohomology. It follows from 2.7 that \(\text{BGL}_n^{\text{ét}}(\mathbb{F}_3)\) is equivalent to the space of sections of a fibration over \(S^1\) with fibre \(\text{BGL}_n^{\text{top}}(\mathbb{C}) \simeq \text{BGL}_n^{\text{ét}}(\mathbb{F}_3)\) (2.8). By naturality, this is the fibration associated to the action of \(\psi\) on \(\text{BGL}_n^{\text{ét}}(\mathbb{F}_3)\), and so its space of sections is (by definition) the homotopy fixed point set (\(\text{BGL}_n^{\text{ét}}(\mathbb{F}_3)\))\(^{h\psi}\). Consider the commutative diagram of spaces with an action of \(\psi\) (the action in the left hand column is trivial):

\[
\begin{array}{ccc}
\text{BGL}_n(\mathbb{F}_3) & \longrightarrow & \text{BGL}_n(\bar{\mathbb{F}}_3) \\
\chi_{n,\mathbb{F}_3} \downarrow & & \chi_{n,\bar{\mathbb{F}}_3} \downarrow \\
\text{BGL}_n^{\text{ét}}(\mathbb{F}_3) & \longrightarrow & \text{BGL}_n^{\text{ét}}(\bar{\mathbb{F}}_3)
\end{array}
\]

The space \(\text{BGL}_n^{\text{ét}}(\bar{\mathbb{F}}_3)\) is 2-complete (2.7). The map \(\chi_{n,\bar{\mathbb{F}}_3}\) induces an equivalence \(\tilde{\text{BGL}}_n(\mathbb{F}_3) \to \text{BGL}_n^{\text{ét}}(\mathbb{F}_3)\) (2.10). Quillen [16] shows that the map \(\text{BGL}_n(\mathbb{F}_3) \to (\text{BGL}_n^{\text{ét}}(\mathbb{F}_3))^{h\psi}\) induced by the map \(u\) gives an isomorphism on mod 2 cohomology. It follows that the map

\[
\begin{array}{ccc}
\text{BGL}_n(\mathbb{F}_3) & \xrightarrow{\chi_{n,\mathbb{F}_3}} & \text{BGL}_n^{\text{ét}}(\mathbb{F}_3) & \xrightarrow{\cong} & \text{(BGL}_n^{\text{ét}}(\bar{\mathbb{F}}_3))^{h\psi}
\end{array}
\]
also induces an isomorphism on mod 2 cohomology, and that $\text{BGL}_n^\ell(F_3)$ is equivalent to $\text{BGL}_n(F_3)$.

**Remark.** The conjecture that $\chi_n,S$ induces an isomorphism on mod 2 cohomology is a very strong unstable analogue of the mod 2 Quillen-Lichtenbaum Conjecture for the ring $S$. This conjecture is true for a finite field (cf. 2.11) or the algebraic closure of a finite field (cf. 2.10). It is unknown whether or not it is true for the fields $\mathbf{R}$ and $\mathbf{C}$. The results in this paper show that it is false for the ring $\Lambda$.

§3. The space $X_n$ and its properties

We define $X_n$ to be the space $\text{BGL}_n^\ell(\Lambda)$ from 2.6, and $\chi_n : \text{BG}_n \to X_n$ the map $\chi_{n,\Lambda} : \text{BGL}_n(\Lambda) \to \text{BGL}_n^\ell(\Lambda)$. In this section we prove 1.4, 1.5 and 1.6.

(Co)homology of $X_n$. Let $BD_\bullet$, $BG_\bullet$ and $X_\bullet$ denote respectively the spaces $\prod B\text{D}_n$, $\prod B\text{G}_n$ and $\prod X_n$. The index $n$ in these coproducts runs over all non-negative integers, where for $n = 0$ the spaces involved are contractible. There are maps

$$BD_\bullet \xrightarrow{\iota} BG_\bullet \xrightarrow{\chi} X_\bullet.$$ 

Under matrix block sum all three of these spaces are homotopy associative $H$-spaces; $BG_\bullet$ and $X_\bullet$ are homotopy commutative. The maps $\iota$ and $\chi$ respect the multiplications.

There is a natural identification

$$BD_1 \simeq B(\mathbf{Z} \times \mathbf{Z}/2) \simeq S^1 \times B\mathbf{Z}/2.$$ 

Let $e \in H_1 S^1$ and $\beta_k \in H_k B\mathbf{Z}/2$ be generators. We denote the classes $e \otimes \beta_{k-1}$ and $1 \otimes \beta_k$ in $H_k BD_1$ by $a_k$ and $b_k$ respectively. Let $a_k^G = \iota_*(a_k)$, $b_k^G = \iota_*(b_k)$, $a_k^X = (\chi \iota)_*(a_k)$, $b_k^X = (\chi \iota)_*(b_k)$. Since $H_* BD_\bullet$ is the free $F_2$-algebra on the elements $a_k (k \geq 1)$ and $b_k (k \geq 0)$, it follows that the image of $\iota_*$ is the subalgebra of $H_* BG_\bullet$ generated by the classes $a_k^G$ and $b_k^G$, while the image of $(\chi \iota)_*$ is generated by the classes $a_k^X$ and $b_k^X$.

**3.1 Proposition.** The algebra $H_* X_\bullet$ is the free commutative $F_2$-algebra on the classes $a_k^X (k \geq 1)$ and $b_k^X (k \geq 0)$ subject to the following relations:

1. $(a_k^X)^2 = 0$ for $k$ odd, and
2. $a_k^X b_k^X + a_{k-1}^X b_{k-1}^X + \cdots + a_0^X b_{k-1}^X = 0$ for $k$ even.

**3.2 Lemma.** There is a homotopy fibre square

$$
\begin{array}{ccc}
X_n & \longrightarrow & \text{BGL}_n^\ell(\mathbf{R}) \\
\downarrow & & \downarrow \\
\text{BGL}_n^\ell(\mathbf{Z}_3) & \longrightarrow & \text{BGL}_n^\ell(\mathbf{C})
\end{array}
$$

**Proof.** This is a consequence of 2.5 and 2.7. 

**3.3 Remark.** The square from 3.2 can up to homotopy be rewritten in the following way:

$$
\begin{array}{ccc}
X_n & \longrightarrow & \hat{\text{BGL}}_n^{\text{top}}(\mathbf{R}) \\
\downarrow & & \downarrow \\
\hat{\text{BGL}}_n(\mathbf{F}_3) & \longrightarrow & \hat{\text{BGL}}_n^{\text{top}}(\mathbf{C})
\end{array}
$$
The rewriting is justified by 2.9, 2.8, 2.1 and 2.7. By naturality the map $u$ is the usual one induced by the map $\mathbb{R} \to \mathbb{C}$. The map $v$ is a little more problematical, but it is clear from 2.5 that the restriction of $v$ to the diagonal matrices in $\text{GL}_n(\mathbb{F}_3)$ is induced by the ordinary diagonal inclusion $\{\pm 1\}^n \to \text{BGL}_n(\mathbb{C})$. The fact that the mod 2 cohomology of $\text{BGL}_n(\mathbb{F}_3)$ is detected on diagonal matrices [14, §3] [16] means that it is easy to compute the map induced by $v$ on mod 2 homology or cohomology.

Proof of 3.1. This is essentially given by Mitchell in [14, 4.6]; his space $JK(\mathbb{Z})$ can be identified with colim$_n X_n$, where the maps in the colimit are the block inclusions given by product with a point in $X_1$. The role of diagram [14, 4.1] is played by the homotopy fibre square from 3.3 above. □

3.4 Proposition. The classes $a^G_k$, $k \geq 1$, and $b^G_k$, $k \geq 0$, in $H_* \text{BG}_*$ satisfy the analogs of relations 1 and 2 from 3.1.

Proof. See [14, pf. of 7.1]. The place to look for these relations is in $H_2 \text{BGL}_2(\mathbb{A})$, and Mitchell computes this homology explicitly [14, §6]. □

Proof of 1.4. By 3.1 and 3.4, the homology map $(\chi_n \iota_n)^*$ is surjective and its kernel is equal to the kernel of $(\iota_n)^*$. By duality, the cohomology map $(\chi_n \iota_n)^*$ is injective and its image is equal to the image of $\iota_n^*$. This implies that $\iota_n^*$ is injective if and only if $\chi_n^*$ is an isomorphism. □

Maps into $X_n$. Let $P$ be a finite 2-group. We are interested in studying the set $[BP,X_n]$ of unbased homotopy classes of maps from $BP$ to $X_n$. The homotopy fibre square from 3.3 gives a map

$$[BP,X_n] \to [BP,\hat{\text{BGL}}_n(\mathbb{F}_3)] \times [BP,\hat{\text{BGL}}_n^{\text{top}}(\mathbb{R})].$$

3.5 Lemma. The map 3.5 is injective.

Proof. It follows from 3.3 that there is a homotopy fibre square of mapping spaces

$$
\begin{array}{ccc}
\text{Map}(BP,X_n) & \longrightarrow & \text{Map}(BP,\hat{\text{BGL}}_n^{\text{top}}(\mathbb{R})) \\
\downarrow & & \downarrow \\
\text{Map}(BP,\hat{\text{BGL}}_n(\mathbb{F}_3)) & \longrightarrow & \text{Map}(BP,\hat{\text{BGL}}_n^{\text{top}}(\mathbb{C}))
\end{array}
$$

By an elementary argument, it is enough to show that each component of the space $\text{Map}(BP,\hat{\text{BGL}}_n^{\text{top}}(\mathbb{C}))$ is 1-connected. By [7] the space $\text{Map}(BP,\hat{\text{BGL}}_n^{\text{top}}(\mathbb{C}))$ is equivalent to the 2-completion of the disjoint union $\coprod_{\rho} \text{BC}(\rho(P))$, where $\rho$ runs through a set of representatives for the conjugacy classes of homomorphisms $P \to \text{GL}_n(\mathbb{C})$, and $C(\rho(P))$ is the centralizer of $\rho(P)$. By elementary representation theory each one of these centralizers is isomorphic to a product of complex general linear groups, and so is connected. □

The following theorem is derived in [13, §1] from Carlsson's work in [2] and [3]. We state it only for the prime 2, although it holds for any prime.

3.7 Theorem. Let $\Gamma$ be a group of virtually finite cohomological dimension, and let $P$ be a finite 2-group. Then the natural map

$$\{P,\Gamma\} \cong [BP,\text{BG}] \to [BP,\hat{\text{BG}}]$$

is a bijection.
Proof of 1.5. The space $X_n$ is 2-complete (3.3), so the fact that $\chi_n^*$ is an isomorphism implies that $X_n$ is equivalent to $\hat{B}G_n$. Since $G_n$ is a group of virtually finite cohomological dimension [17, p. 124], the result follows from 3.7.

Proof of 1.6. Consider the commutative diagram

$$
\begin{array}{ccc}
[BP, BGL_n(R)] & \xleftarrow{\text{BP}} & [BP, BG_n] \\
\downarrow & & \downarrow \\
[BP, BGL_n^\ell(F)] & \xleftarrow{\text{BP}_{F_3}} & [BP, BGL_n(F_3)]
\end{array}
$$

By 2.9, 2.11, 3.7 and [7], the right and left vertical arrows are bijections. The result follows from 3.6.

§4. Exploiting the class group

In this section we derive 1.2 from 1.3 by showing how class groups of cyclotomic extensions of $\Lambda$ can be used to construct the necessary homomorphisms from finite 2-groups into $\text{GL}_{2\phi(2^n)}(\Lambda)$.

Recall that $\mu_n$ denotes the multiplicative group of $2^n$-th roots of unity. We make a distinction between $\Lambda[\mu_n]$, which is the group ring of $\mu_n$ over $\Lambda$, and $\Lambda(\mu_n)$, which is the integral closure of $\Lambda$ in the field obtained from $\mathbb{Q}$ by adjoining $\mu_n$. There is a surjection $\Lambda[\mu_n] \to \Lambda(\mu_n)$ (cf. [18, 2.6]) which is not an isomorphism unless $n = 0$. Because of this surjection, though, two modules over $\Lambda(\mu_n)$ are isomorphic as $\Lambda(\mu_n)$-modules if and only if they are isomorphic as $\Lambda[\mu_n]$-modules.

4.1 Remark. If $M$ is a $\Lambda$-module and $\alpha : \mu_n \to \text{Aut}(M)$ is a homomorphism, let $M_\alpha$ denote the $\Lambda[\mu_n]$-module obtained by letting $\mu_n$ act on $M$ via $\alpha$. Given two homomorphisms $\alpha, \beta : \mu_n \to \text{Aut}(M)$, it is clear that $\alpha$ is conjugate to $\beta$ if and only if the $\Lambda[\mu_n]$-modules $M_\alpha$ and $M_\beta$ are isomorphic.

4.2 Lemma. Suppose that $\mathcal{I}$ is a nonzero ideal in $\Lambda(\mu_n)$. Then there are isomorphisms of $\Lambda(\mu_n)$-modules

$$
\begin{align*}
R \otimes_\Lambda \mathcal{I} & \cong R \otimes_\Lambda \Lambda(\mu_n), \\
F_3 \otimes_\Lambda \mathcal{I} & \cong F_3 \otimes_\Lambda \Lambda(\mu_n).
\end{align*}
$$

Proof. Since the quotient $\Lambda(\mu_n)/\mathcal{I}$ is a torsion group, the first isomorphism results from taking the inclusion $\mathcal{I} \to \Lambda(\mu_n)$ and tensoring with $R$. For the second, note that by the Chebotarev density theorem there are an infinite number of prime ideals in $\Lambda(\mu_n)$ isomorphic (as modules) to $\mathcal{I}$. Up to isomorphism, then, $\mathcal{I}$ can be taken to be a prime ideal of residue characteristic different from 3. Tensoring the inclusion $\mathcal{I} \to \Lambda(\mu_n)$ with $F_3$ again gives the required isomorphism.

Recall that $\Lambda(\mu_n)$ is free as a module over $\Lambda$ of rank $\phi(2^n) = 2^{n-1} [18, 2.5]$. The same is true of any nonzero ideal in $\Lambda(\mu_n)$.

4.3 Lemma. If $\Lambda(\mu_n)$ has a nonzero ideal which is not principal, then there exist two nonconjugate homomorphisms $\alpha, \beta : \mu_n \to G_{\phi(2^n)}$ which become conjugate both over $R$ and over $F_3$.

Proof. Let $\mathcal{I}$ be such a nonzero ideal. Choosing bases for $\mathcal{I}$ and for $\Lambda(\mu_n)$ allows both to be identified (as $\Lambda$-modules) with $\Lambda^{\phi(2^n)}$. The multiplicative actions of $\mu_n$ on $\mathcal{I}$ and on $\Lambda(\mu_n)$ thus give two homomorphisms $\alpha, \beta : \mu_n \to \text{GL}_{\phi(2^n)}(\Lambda)$. These
homomorphisms are not conjugate, because \( I \) and \( \Lambda(\mu_n) \) are not isomorphic as \( \Lambda[\mu_n] \)-modules (equivalently, as \( \Lambda(\mu_n) \)-modules). The homomorphisms are conjugate over \( \mathbb{R} \) or over \( \mathbb{F}_3 \), because (4.2) the two modules become isomorphic when tensored with \( \mathbb{R} \) or with \( \mathbb{F}_3 \).

\[ \square \]

**Proof of 1.2.** According to 4.3, it is enough to show that \( \Lambda(\mu_6) \) is not a principal ideal domain. By [18, p. 353] the ideal class group of \( \mathbb{Z}(\mu_6) \) is cyclic of order 17. Since the ideal class group of \( \Lambda(\mu_6) \) is the quotient of the ideal class group of \( \mathbb{Z}(\mu_6) \) by the subgroup generated by the prime ideals of \( \mathbb{Z}(\mu_6) \) which lie above 2, it is enough to show that there is only one prime \( \mathcal{P} \) in \( \mathbb{Z}(\mu_6) \) above 2, and that \( \mathcal{P} \) is principal. This is a standard calculation; see [18, 1.4] or [12, p. 73].

\[ \square \]

**References**

10. H.-W. Henn, _The cohomology of SL(3, \mathbb{Z}[1/2])_, preprint (Universität Heidelberg) 1996.

Department of Mathematics, University of Notre Dame, Notre Dame, Indiana 46556

_E-mail address: dwyer.1@nd.edu_