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PERIODIC KNOTS, SMITH THEORY, AND MURASUGI'S CONGRUENCE

by James F. DAVIS and Charles LIVINGSTON

A knot K in a homology 3-sphere Σ has period n if it is invariant under a homeomorphism $h: \Sigma \rightarrow \Sigma$ of order exactly n with fixed set B , a circle disjoint from K . The quotient space $\bar{\Sigma} = \Sigma/h$ is a homology sphere containing \bar{K} , the quotient knot. Kunio Murasugi [Mu] discovered the following congruence involving the Alexander polynomials of the two knots. (See also the proof by J. Hillman [H].)

THEOREM A. *Let K be a knot of prime power period p^r in a homology 3-sphere Σ with fixed set B and quotient knot \bar{K} . Let $\Delta_K(t)$ and $\Delta_{\bar{K}}(t)$ be their Alexander polynomials and let λ be the linking number of K and B . Then*

$$\Delta_K(t) \doteq \Delta_{\bar{K}}(t)^{p^r} (1 + t + \dots + t^{\lambda-1})^{p^r-1} \pmod{p},$$

where \doteq means congruent up to multiplication by $u t^i$ where u and i are integers and u is relatively prime to p .

In another direction it is easily shown that if $G = \mathbf{Z}/p$ acts cellularly on a finite CW complex X , then $\chi(X) + (p-1)\chi(X^G) = p\chi(X/G)$. Using Smith theory, E. Floyd [F] gave a proof of this when X is a finite-dimensional CW complex with $\text{rk } H_*(X; \mathbf{Z}/p) < \infty$. The proof can be generalized easily to the case of semifree actions of a p -group G on X . (An action is semifree if every point in X is either freely permuted by G or fixed by all of G . An action of \mathbf{Z}/p is automatically semifree.) We will prove a multiplicative analogue of Floyd's theorem and use it to deduce Murasugi's congruence.

If X is a space with an action of the infinite cyclic group $C_\infty = \langle t \rangle$ and F is a field with $\text{rk } H_*(X; F) < \infty$, we define a multiplicative Euler characteristic

$$\chi_m(X; F) \in F(t)^*/F[t, t^{-1}]^*$$

to be the alternating product of the generator of the order ideals of $H_i(X; F)$.

(See [Mi] or §1 for definitions). We will be most interested in the case $F = \mathbf{F}_p$, the finite field with p elements.

THEOREM B. *Let G be a p -group. Suppose $C_\infty \times G$ act on a finite-dimensional CW complex X with $\text{rk } H_*(X; \mathbf{F}_p) < \infty$, so that G acts semifreely and cellularly. Then*

$$\chi_m(X; \mathbf{F}_p) \chi_m(X^G; \mathbf{F}_p)^{|G|-1} = \chi_m(X/G; \mathbf{F}_p)^{|G|}.$$

Applying this to the case where X is the infinite cyclic cover of $\Sigma - K$ will immediately yield Murasugi's congruence. One advantage of our approach is that it generalizes to the case of high-dimensional periodic knots.

In §1 we prove Theorem B and derive Theorem A. In §2 we discuss the high-dimensional case and in §3 give the following application of Murasugi's congruence to links.

PROPOSITION C. *Let L be a two-component link in a homology 3-sphere. If the $\mathbf{Z}/2 \times \mathbf{Z}/2$ – cover branched over the link is also a homology 3-sphere, then the linking number of the two components is congruent to ± 1 modulo 8.*

§1. MURASUGI'S CONGRUENCE

We will derive Theorem A from Theorem B and then prove Theorem B, but we first give some homological preliminaries. If R is a commutative Noetherian UFD with quotient field K and M is a finitely generated torsion R -module then we define the *order* of M to be $[M] = E^0(M) \in R/R^*$. Here we take an exact sequence

$$R^k \xrightarrow{A} R^m \rightarrow M \rightarrow 0,$$

and we let $E^0(M)$ be a greatest common divisor of the determinants of the $m \times m$ -submatrices of A . If M is a torsion f.g. R -module then $[M] \neq 0$, and we consider the order $[M]$ as an element of K^*/R^* . If

$$0 \rightarrow M' \rightarrow M \rightarrow M'' \rightarrow 0$$

is an exact sequence of torsion f.g. R -modules, then J. Levine [L, lemma 5] shows $[M] = [M'] [M'']$. It follows for formal reasons that if $C_* = \{C_n \rightarrow \dots \rightarrow C_0\}$ is a chain complex of torsion f.g. R -modules then

$$\chi_m(C_*) := \prod [C_i]^{(-1)^i}$$

equals $\chi_m(H_*(C_*))$. In particular if C_* is exact, then $\chi_m(C_*) = 1$.

Next we turn to Alexander polynomials. By Alexander duality $H_1(\Sigma - K) \cong \mathbf{Z}$. Let $\pi: X \rightarrow \Sigma - K$ be the infinite cyclic cover of the knot complement. The infinite cyclic group $C_\infty = \langle t \rangle$ acts on X and $H_1(X; \mathbf{Z})$ is a f.g. torsion module over the group ring $\mathbf{Z}[C_\infty] = \mathbf{Z}[t, t^{-1}]$. The Alexander polynomial $\Delta_K(t)$ is its associated order. (Note that $\mathbf{Z}[t, t^{-1}]^*$ consists of $\pm t^i$ and the quotient field of $\mathbf{Z}[t, t^{-1}]$ is the field of rational functions $\mathbf{Q}(t)$.) As usual we normalize so that $\Delta_K(t)$ is a polynomial with integer coefficients and non-zero constant term.

If K has period p^r , let $\bar{\pi}: \bar{X} \rightarrow \bar{\Sigma} - \bar{K}$ be the infinite cyclic cover of the quotient knot. The $G = \mathbf{Z}/p^r$ -action on $\Sigma - K$ lifts to a G -action on X with quotient \bar{X} and fixed set $\bar{B} = \pi^{-1}(B)$. Indeed, let g be a generator of G . Then $g \circ \pi: X \rightarrow \Sigma - K$ induces the trivial map on H_1 and so lifts to $\tilde{g}: X \rightarrow X$. Since g has a non-empty, path-connected fixed-point set there is a unique lift \tilde{g} with fixed points and the fixed point set is \bar{B} . Since \tilde{g}^{p^r} is a lift of the identity which has fixed points, it itself is the identity and hence \tilde{g} is a map of period p^r . This gives an action of $C_\infty \times G$ on X . It further follows that $X/G \rightarrow \bar{\Sigma} - \bar{K}$ is an abelian cover inducing the trivial map on H_1 , so that we can identify this cover with $\bar{\pi}$ and X/G with \bar{X} .

The cover π is classified by a map $c: \Sigma - K \rightarrow S^1 = K(\mathbf{Z}, 1)$ inducing an isomorphism on H_1 . The inclusion map $B \rightarrow \Sigma - K$ induces multiplication by the linking number λ on H_1 . Thus by considering $c|_B$ which classifies $\pi: \bar{B} \rightarrow B$, we see \bar{B} is homeomorphic to λ disjoint copies of \mathbf{R} , cyclically permuted by the action of C_∞ .

Now $H_i(X)$ and $H_i(\bar{X})$ are zero for $i > 1$ and $H_0(X)$ and $H_0(\bar{X})$ are isomorphic to $\mathbf{F}_p \cong \mathbf{F}_p[t, t^{-1}]/(t - 1)\mathbf{F}_p[t, t^{-1}]$, so $\chi_m(X) = (t - 1)/\Delta_K(t)$ and $\chi_m(\bar{X}) = (t - 1)/\Delta_{\bar{K}}(t)$. Since $X^G = \bar{B}$ consists of λ arcs cyclically permuted by $C_\infty = \langle t \rangle$, $\chi(X^G) = t^\lambda - 1$. Putting this together with Theorem B we see

$$[(t - 1)/\Delta_K(t)] [t^\lambda - 1]^{p^r - 1} = [(t - 1)/\Delta_{\bar{K}}(t)]^{p^r}$$

or $\Delta_K(t) = \Delta_{\bar{K}}(t)^{p^r} (1 + t + \dots + t^{\lambda-1})^{p^r - 1}$ with the equality taking place in $\mathbf{F}_p(t)/\mathbf{F}_p[t, t^{-1}]^*$. This gives Murasugi's congruence.

Proof of Theorem B. We prove the theorem by induction on the order of G . Let G be a group of prime order p with generator g . Let

$$\sigma = 1 + g + g^2 + \dots + g^{p-1}$$

$$\delta = 1 - g$$

be elements of the group ring $\mathbf{F}_p[G]$. Note that $\delta\sigma = 0 = \sigma\delta$ and $\delta^{p-1} = \sigma$. We consider the following chain complexes of $\mathbf{F}_p[t, t^{-1}]$ -modules (all homology is with \mathbf{F}_p -coefficients).

$$\begin{aligned} , 0 &\rightarrow C_*(X^G) \rightarrow C_*(\bar{X}) \xrightarrow{\text{tr}} \sigma C_*(X) \rightarrow 0 \\ 0 &\rightarrow \delta C_*(X) \oplus C_*(X^G) \rightarrow C_*(X) \xrightarrow{\sigma} \sigma C_*(X) \rightarrow 0 \\ 0 &\rightarrow \sigma C_*(X) \rightarrow \delta C_*(X) \xrightarrow{\delta} \delta^2 C_*(X) \rightarrow 0 \\ &\vdots \\ &\vdots \\ 0 &\rightarrow \sigma C_*(X) \rightarrow \delta^{p-2} C_*(X) \xrightarrow{\delta} \delta^{p-1} C_*(X) \rightarrow 0 . \end{aligned}$$

These induce long exact sequences in homology. All homology is finitely generated and torsion over the PID $\mathbf{F}_p[t, t^{-1}]$. We use shorthand notation – if $\rho \in \mathbf{F}_p[G]$, we write $\chi^\rho(X)$ instead of $\chi(H_*(\rho C_*(X)))$. The above homological considerations show

$$\begin{aligned} \chi(\bar{X}) &= \chi(X^G)\chi^\sigma(X) \\ \chi(X) &= \chi^\delta(X)\chi(X^G)\chi^\sigma(X) \\ \chi^\delta(X) &= \chi^\sigma(X)\chi^{\delta^2}(X) \\ &\vdots \\ &\vdots \\ \chi^{\delta^{p-2}}(X) &= \chi^\sigma(X)\chi^\sigma(X) . \end{aligned}$$

Multiplying all equations but the first together and cancelling terms we see

$$\chi(X) = \chi(X^G) \cdot \chi^\sigma(X)^p .$$

Using the first equation to substitute for $\chi^\sigma(X)$ one finds

$$\chi(X) = \chi(\bar{X})^p / \chi(X^G)^{p-1} .$$

Finally suppose G has order p^r . Let G_1 be a normal subgroup of index p . By the exact sequences above $\text{rk } H_*(X/G_1; \mathbf{F}_p) < \infty$. By applying inductively the result for the G_1 -action on X and the G/G_1 action on X/G_1 , Theorem B follows.

§ 2. HIGH-DIMENSIONAL PERIODIC KNOTS

One advantage of our approach to Murasugi's congruence is that it applies equally well to a more general situation. Higher-dimensional periodic knots

were introduced in the thesis of R. Cruz [C]. He showed that if there is a semifree \mathbf{Z}/q -action on S^n with non-empty fixed set and an invariant knot K^{n-2} disjoint from the fixed set, then the fixed set is S^1 if $q \neq 2$, and is S^1 or S^0 if $q = 2$.

For our purposes a knot K in a homology n -sphere Σ is an embedded $(n-2)$ -dimensional homology sphere. Let G be a finite group. The knot K is G -periodic if it is invariant under a semifree G -action on Σ with fixed set $B \cong S^1$ disjoint from K . To simplify technicalities we assume the action is smooth. Several complications arise: the group need not be cyclic, the action need not be linear and the quotient $\bar{\Sigma} = \Sigma/G$ will not be a manifold. (Even in the linear case the quotient looks like a double suspension of a spherical space form.) However we can still make sense of Alexander polynomials.

PROPOSITION 2.1. $H_*(\bar{\Sigma} - \bar{K}) \cong H_*(S^1)$.

First we need a lemma.

LEMMA 2.2. *The linking number $\lambda = \text{lk}(B, K)$ is relatively prime to the order of G .*

Proof. (See also [C, 2.1.1]). By restricting the action to a subgroup \mathbf{Z}/p of G , we will assume $G = \mathbf{Z}/p$, and show $(\lambda, p) = 1$. By applying the Lefschetz Fixed-Point Theorem to a generator g of \mathbf{Z}/p , we see that if n is odd, the action on K is orientation-preserving, while if n is even, then $p = 2$ and the action is orientation-reversing. For local coefficients we will use \mathbf{Z}^t , the integers with the $\mathbf{Z}[\mathbf{Z}/p]$ -module structure given by $(\sum a_i g^i) \cdot k = \sum a_i (-1)^{i(n+1)} k$.

Let $\bar{\Sigma} - B \rightarrow K(\mathbf{Z}/p, 1)$ classify the G -cover. We will consider the commutative diagram:

$$\begin{array}{ccccccc}
 H_{n-2}(K; \mathbf{Z}) & \xrightarrow{\alpha} & H_{n-2}(\bar{K}; \mathbf{Z}^t) & \rightarrow & H_{n-2}(K(\mathbf{Z}/p, 1); \mathbf{Z}^t) & & \\
 (*) & \downarrow & \downarrow & & \parallel & & \\
 H_{n-2}(\Sigma - B; \mathbf{Z}) & \rightarrow & H_{n-2}(\bar{\Sigma} - B; \mathbf{Z}^t) & \rightarrow & H_{n-2}(K(\mathbf{Z}/p, 1); \mathbf{Z}^t) & & .
 \end{array}$$

The two groups on the left are infinite cyclic and the left vertical map is multiplication by λ . A diagram chase shows we will be done if we can show both horizontal exact sequences are isomorphic to the short exact sequence $0 \rightarrow \mathbf{Z} \rightarrow \mathbf{Z} \rightarrow \mathbf{Z}/p \rightarrow 0$.

The map α is isomorphic to $\mathbf{Z} \xrightarrow{\times p} \mathbf{Z}$ because it comes from a p -fold cover of $(n-2)$ -dimensional closed manifolds. The map

$$H_{n-2}(\bar{K}; \mathbf{Z}^t) \rightarrow H_{n-2}(\mathbf{Z}/p; \mathbf{Z}^t)$$

we compute algebraically by using a free $\mathbf{Z}G$ -resolution of \mathbf{Z} as a substitute for the Eilenberg-MacLane space. By lifting a CW structure on \bar{K} to K ,

$$C_*(K) = \{C_{n-2} \rightarrow \dots \rightarrow C_0\}$$

with the i -chains C_i free $\mathbf{Z}G$ -modules. By mapping a free $\mathbf{Z}G$ -module onto $\ker(C_{n-2} \rightarrow C_{n-3})$ and continuing inductively, one constructs a free $\mathbf{Z}G$ -resolution of \mathbf{Z}

$$D_* = \{\dots \rightarrow D_n \rightarrow D_{n-1} \rightarrow C_{n-2} \rightarrow \dots \rightarrow C_0\}.$$

It follows that

$$H_{n-2}(\bar{K}; \mathbf{Z}^t) = H_{n-2}(C_*(K) \otimes_{\mathbf{Z}G} \mathbf{Z}^t)$$

maps onto $H_{n-2}(D_* \otimes_{\mathbf{Z}G} \mathbf{Z}^t) = H_{n-2}(\mathbf{Z}/p; \mathbf{Z}^t)$. Furthermore by using the standard $\mathbf{Z}G$ -resolution of \mathbf{Z} (see e.g. [Mac]), one easily computes that $H_{n-2}(\mathbf{Z}/p; \mathbf{Z}^t) \cong \mathbf{Z}/p$.

Choose a G -invariant normal disk to B in Σ and let S^{n-2} be its boundary. Then the inclusion $S^{n-2} \rightarrow \Sigma - B$ is a homology equivalence. By the comparison theorem applied to the spectral sequence of the G -coverings (see [Mac]), the bottom row of $(*)$ is isomorphic to

$$H_{n-2}(S^{n-2}; \mathbf{Z}) \rightarrow H_{n-2}(S^{n-2}/G; \mathbf{Z}^t) \rightarrow H_{n-2}(G; \mathbf{Z}^t),$$

and hence by the previous paragraph to $0 \rightarrow \mathbf{Z} \rightarrow \mathbf{Z} \rightarrow \mathbf{Z}/p \rightarrow 0$. Thus $(\lambda, p) = 1$.

Proof of 2.1. Let N be an equivariant tubular neighborhood of B . Then

$$0 = H_*(\Sigma - K, N; \mathbf{Z}[1/\lambda]) = H_*(\Sigma - K - B, N - B; \mathbf{Z}[1/\lambda])$$

where the first equality holds by the definition of linking number and the second by excision. Then

$$\begin{aligned} 0 &= H_*((\Sigma - K - B)/G, (N - B)/G; \mathbf{Z}[1/\lambda]) = H_*((\Sigma - K)/G, N/G; \mathbf{Z}[1/\lambda]) \\ &= H_*((\Sigma - K)/G, B; \mathbf{Z}[1/\lambda]), \end{aligned}$$

where the first equality follows from the spectral sequence of a covering, the second by excision and the third by the homotopy equivalence $B \rightarrow N/G$. Thus $H_*(\bar{\Sigma} - \bar{K})$ looks like $H_*(S^1)$ except possibly for some λ -torsion. But by 2.1, λ is prime to the order of G , so for all primes q dividing λ , the transfer map $\text{tr}: H_*(\bar{\Sigma} - \bar{K}; \mathbf{Z}/q) \rightarrow H_*(\Sigma - K; \mathbf{Z}/q)$ is injective so there is no extra λ -torsion.

To state Murasugi's congruence in higher dimensions is it necessary to find a substitute for the Alexander polynomial. Let X and \bar{X} be the infinite cyclic

covers of $\Sigma - K$ and $\bar{\Sigma} - \bar{K}$ respectively. Let $\Delta_K(t) = \prod_{i>0} [H_i(X)]^{(-1)^{i+1}}$ and $\Delta_{\bar{K}}(t) = \prod_{i>0} [H_i(\bar{X})]^{(-1)^{i+1}}$. The Wang sequence shows that multiplication by $t - 1$ induces an isomorphism on $H_i(X)$ for $i > 0$, so that if we take the polynomial represented by $[H_i(X)]$ and plug in $t = 1$ we get ± 1 . (Indeed if we consider the ring homomorphism $\varphi: \mathbf{Z}[t, t^{-1}] \rightarrow \mathbf{Z}$ defined by $\varphi(t) = 1$, then $\varphi([H_i(X)])$ is a divisor of $[H_i(X) \otimes_{\mathbf{Z}[t, t^{-1}]} \mathbf{Z}] = [0] = 1 \in \mathbf{Z}/\mathbf{Z}^*$.) Thus $[H_i(X)]$ represents a non-zero element in $\mathbf{F}_p[t, t^{-1}]$, and hence $\Delta_K(t)$ and $\Delta_{\bar{K}}(t)$ give well-defined elements of $\mathbf{F}_p(t)^*/\mathbf{F}_p[t, t^{-1}]^*$. Then the considerations of §1 show:

THEOREM 2.3. *Let K be a G -periodic knot in a homology q -sphere Σ with fixed set B , where G is a group of prime power order p^r . Let λ be the linking number of K and B . Then*

$$\Delta_K(t) \cong \Delta_{\bar{K}}(t)^{p^r} (1 + t + \dots + t^{\lambda-1})^{p^r-1} \pmod{p}.$$

§3. AN APPLICATION OF MURASUGI'S CONGRUENCE

For any $\lambda \equiv \pm 1 \pmod{8}$, T. tom Dieck and J. Davis [D-D] constructed a 2-component link with linking number λ in a homology 3-sphere Ω whose $C_2 \times C_2$ -cover branched over the link is a homology 3-sphere Σ . We will show that this congruence condition is necessary. Equivalently, we show

THEOREM 3.1. *Suppose the Klein 4-group $G \times H \cong C_2 \times C_2$ acts on a homology 3-sphere Σ so that the fixed sets Σ^G and Σ^H are disjoint circles. Then their linking number λ is congruent to ± 1 modulo 8.*

Proof. We have

$$\begin{array}{ccc} \Sigma & \rightarrow & \Sigma/G \\ \downarrow & & \downarrow \\ \Sigma/H & \rightarrow & \Sigma/(G \times H) \end{array}.$$

All four of these manifolds are homology 3-spheres and each has two disjoint circles given by the images of the fixed sets. The linking numbers of each pair of circles are all equal.

Let $K = \Sigma^G/G \subset \Sigma/G$ and $\bar{K} = K/H \subset \Sigma/(G \times H)$. Then K is a knot of period 2. Renormalize $\Delta_K(t)$ and $\Delta_{\bar{K}}(t) \in \mathbf{Z}[t, t^{-1}]$ so that $\Delta_K(t) = \Delta_K(t^{-1})$, $\Delta_{\bar{K}}(t) = \Delta_{\bar{K}}(t^{-1})$, and $\Delta_K(1) = 1 = \Delta_{\bar{K}}(1)$. Murasugi's congruence shows

$$(**) \quad \Delta_K(t) = \Delta_{\bar{K}}(t)^2(t^{(1-\lambda)/2} + \dots + 1 + \dots + t^{(\lambda-1)/2}) + 2f(t),$$

where $f(t) \in \mathbf{Z}[t, t^{-1}]$ satisfies $f(t) = f(t^{-1})$. Writing

$$f(t) = a_n t^{-n} + \dots + a_0 + \dots + a_n t^n,$$

we see $f(1) \equiv f(-1) \pmod{4}$. Since $\Sigma \rightarrow \Sigma/G$ is a 2-fold cover branched over K , $|\Delta_K(-1)| = |H_1(\Sigma)| = 1$. So $1 = \Delta_K(1) \equiv \Delta_K(-1) \pmod{4}$, and we see $\Delta_K(-1) = 1$. Take equation $(**)$ and plug in $t = 1$ and $t = -1$:

$$\begin{aligned} 1 &= 1 \cdot \lambda + 2 \cdot f(1) \\ 1 &= 1 \cdot (-1)^{(\lambda-1)/2} + 2 \cdot f(-1). \end{aligned}$$

Thus $\lambda \equiv (-1)^{(\lambda-1)/2} \pmod{8}$ so $\lambda \equiv \pm 1 \pmod{8}$.

Applying the high-dimensional version of Murasugi's congruence ones sees that if $G \times H \cong C_2 \times C_2$ acts on a homology q -sphere Σ so that Σ^G is a homology $q-2$ sphere and Σ^H is a circle disjoint from Σ^G , then their linking number λ is congruent to ± 1 modulo 8. This and considerations from L -theory lead us to conjecture that if $G \times H \cong C_2 \times C_2$ acts on a homology q -sphere Σ so that Σ^G is a homology k -sphere and Σ^H is a homology $q-k-1$ -sphere disjoint from Σ^G , then their linking number λ is congruent to ± 1 modulo 8.

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