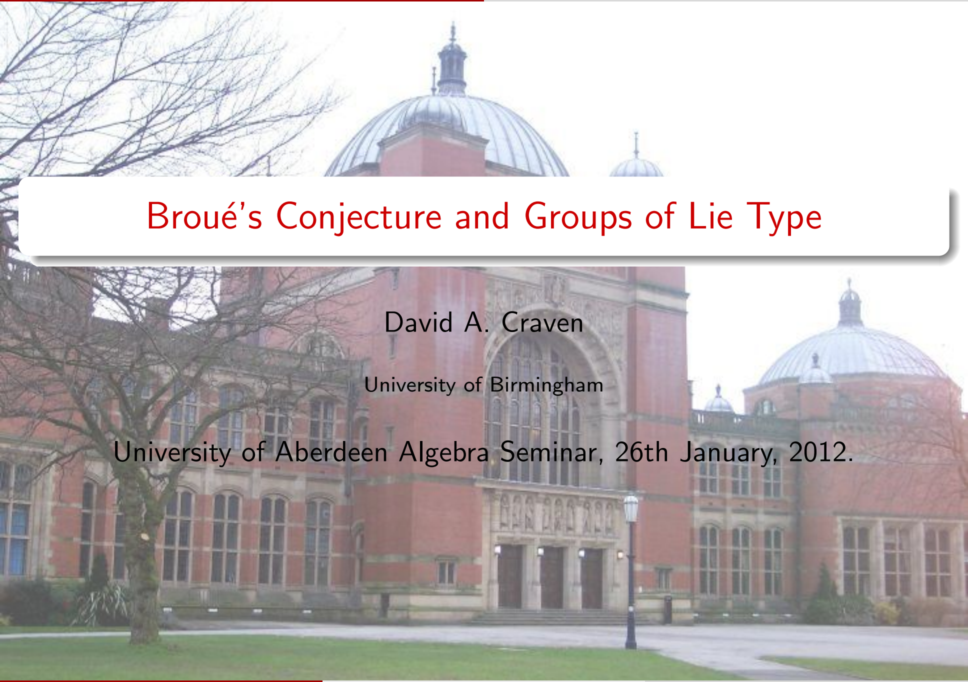

Broué's Conjecture and Groups of Lie Type

David A. Craven

University of Birmingham

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Notation and Conventions

Throughout this talk,

- G is a finite group,
- ℓ is a prime,
- k is a field of characteristic ℓ,
- B is a block of kG, with defect group D and Brauer correspondent b;
- P is a Sylow ℓ-subgroup of G.

I will (try to) use red for definitions and green for technical bits that can be ignored.

About the first half of this talk is joint work with Raphaël Rouquier.

Representation Theory is Local

Many features of the modular representation of a finite group are conjectural, some not even conjectural. Broadly, they fall into three categories:

- finiteness conditions;
- numerical conditions;
- structural conditions.

As an example of the first, we have Donovan's conjecture.

As examples of the second, we have the Alperin–McKay conjecture, Alperin's weight conjecture, and Brauer's height-zero conjecture.

As an example of the third, we have Broué's conjecture.

Representation Theory is Local

Some of the conjectures before (Alperin–McKay, Alperin's weight, Broué) relate the structure of a block B of kG to the structure of its Brauer correspondent b, a block of $k\mathrm{N}_G(D)$, where D is a defect group of B. Write $\ell(B)$ for the number of simple B-modules.

Alperin's weight conjecture gives a precise conjecture about $\ell(B)$ in terms of local information (normalizers of ℓ-subgroups). If D is abelian, the conjecture reduces to

$$\ell(B) = \ell(b).$$

Broué's conjecture gives a structural understanding of Alperin's weight conjecture.

Conjecture (Broué, 1988)

Let G be a finite group, and let B be a ℓ-block of G with abelian defect group D. If b is the Brauer correspondent of B in $\mathrm{N}_G(D)$, then B and b are derived equivalent.

When Is Broué's Conjecture Known?

Broué's conjecture is known for quite a few groups:

- G soluble
- A_n, S_n (Chuang–Rouquier, Marcus)
- $\mathrm{GL}_n(q)$, $\ell \nmid q$ (Chuang–Rouquier)
- D cyclic, $C_2 \times C_2$ (Rouquier, Erdmann, Rickard)
- G finite, $\ell = 2$, B principal
- G finite, $\ell = 3$, $|P| < 81$, B principal (Koshitani, Kunugi, Miyachi, Okuyama, Waki)
- $\mathrm{SL}_2(q)$, $\ell \mid q$ (Chuang, Kessar, Okuyama)
- various low-rank Lie type groups $L(q)$ with $\ell \nmid q$ and sporadic groups. (Okuyama, Holloway, etc.)

Principal Blocks Are Good

In representation theory, one standard method of proof is to reduce a conjecture to finite simple groups and then use their classification.

In general, there is no (known) reduction of Broué's conjecture to simple groups, but for principal blocks there is.

Theorem

Let G be a finite group. If P is abelian, then there are normal subgroups $H \leq L$ of G such that

- $\ell \nmid |H|$,
- $\ell \nmid |G : L|$, *and*
- L/H *is a direct product of simple groups and an abelian* ℓ*-group.*

For **principal** blocks, we may assume that $H = 1$. A derived equivalence for L (compatible with automorphisms of the simple components) passes up to G. Thus if Broué's conjecture for principal blocks holds for all simple groups (with automorphisms), it holds for all groups.

How Do You Find Derived Equivalences?

There are four main methods to prove that B and b are derived equivalent.

1. Okuyama deformations: using many steps, deform the Green correspondents of the simple modules for B into the simple modules for b. This works well for small groups.
2. Rickard's Theorem: randomly find complexes in the derived category of b related to the Green correspondents of the simple modules for B, and if they 'look' like simple modules (i.e., Homs and Exts behave nicely) then there is a derived equivalence $B \to b$.
3. More structure: if B and b are more closely related (say Morita equivalent) then they are derived equivalent. More generally, find another block B' for some other group, an equivalence $B \to B'$, and a (previously known) equivalence $B' \to b$.
4. Perverse equivalence: build a derived equivalence up step by step in an algorithmic way.

What is a Perverse Equivalence?

Let A and B be finite-dimensional algebras, $\mathcal{A} = \textit{mod-}A$, $\mathcal{B} = \textit{mod-}B$.

An equivalence $F : D^b(\mathcal{A}) \to D^b(\mathcal{B})$ is perverse if there exist

- orderings on the simple modules $S_1, S_2, \dots, S_r$, T_1, $T_2, \dots$, T_r, and
- a function $\pi : \{1, \dots, r\} \to \mathbb{Z}$

such that, for all i, the cohomology of $F(S_i)$ only involves T_j for $j < i$, except for one copy of T_i in degree $-\pi(i)$, and T_j can only appear in degrees less than $-\pi(j)$.

Benefits of a Perverse Equivalence

A perverse equivalence is 'better' than a general derived equivalence.

- Has an underlying geometric interpretation for Lie-type groups, coming from the cohomology of Deligne–Lusztig varieties.
- The π-function has even been determined for these groups, at least conjecturally. See later!
- There is an algorithm that gives us a perverse equivalence from $B_0(kN)$ to **some** algebra, so only need to check that the target is $B_0(kG)$. (This is simply checking that the Green correspondents are the last terms in the complexes.) This algorithm is very useful!

An Example: M_{11}, $\ell = 3$

π	Ord. Char.	S_1	S_3	S_7	S_2	S_4	S_6	S_5
0	1	1						
2	10		1					
3	10			1				
4	16	1	1		1			
5	11	1			1	1		
6	44			1	1	1	1	
7	55	1	1		1	1	1	1
	10							1
	16	1				1		1

The cohomology of the complexes gives the rows of the decomposition matrix.

An Example: $\mathrm{PSL}_4(q)$, $\ell = 3$, $3 \mid (q+1)$, $P = C_3 \times C_3$

π	Ord. Char.	S_1	S_2	S_5	S_3	S_4
0	1	1				
3	$q(q^2+q+1)$	1	1			
4	$q^2(q^2+1)$		1	1		
5	$q^3(q^2+q+1)$	1	1	1	1	
6	q^6	1			1	1

$$\begin{aligned}
X_2 &: \quad 0 \to \mathcal{P}(2) \to \mathcal{P}(5) \to \mathcal{P}(3) \oplus M_{1,2} \to C_2 \to 0. \\
X_5 &: \quad 0 \to \mathcal{P}(5) \to \mathcal{P}(345) \to \mathcal{P}(234) \oplus M_{4,1} \to M_{4,1} \oplus M_{4,2} \to C_5 \to 0. \\
X_3 &: \quad 0 \to \mathcal{P}(3) \to \mathcal{P}(34) \to \mathcal{P}(45) \to \mathcal{P}(5) \oplus M_{1,1} \to M_{1,1} \oplus M_{1,2} \to C_3 \to 0. \\
X_4 &: \quad 0 \to \mathcal{P}(4) \to \mathcal{P}(4) \to \mathcal{P}(3) \to \mathcal{P}(3) \to \mathcal{P}(4) \to M_{4,2} \to C_4 \to 0.
\end{aligned}$$

Which Groups Have Perverse Equivalences?

- All groups, D cyclic or $C_2 \times C_2$
- $\mathrm{PSL}_3(q)$, $\ell = 3 \mid (q-1)$, P abelian
- $\mathrm{PSL}_4(q)$, $\mathrm{PSL}_5(q)$, $\ell = 3 \mid (q+1)$, $P = C_3 \times C_3$
- $\mathrm{PSU}_3(q)$, $\ell = 3 \mid (q+1)$, P abelian
- $\mathrm{PSU}_4(q)$, $\mathrm{PSU}_5(q)$, $\ell = 3 \mid (q-1)$
- b a block of $\mathrm{PSU}_n(q)$, $\ell = 5 \mid (q+1)$, b has defect group $C_5 \times C_5$
- $\mathrm{PSp}_4(q)$, $\ell = 3 \mid (q-1)$ or $(q+1)$, $P = C_3 \times C_3$
- (almost) $\Omega_8^+(q)$, $\ell = 5 \mid (q^2+1)$, $P = C_5 \times C_5$
- (almost) ${}^3D_4(q)$, $\ell = 7 \mid (q^2+q+1)$, $P = C_7 \times C_7$
- $G_2(q)$, $\ell = 5 \mid (q+1)$, $P = C_5 \times C_5$
- S_6, A_7, A_8, $\ell = 3$ (A_6 does not)
- M_{11}, $M_{22}.2$, M_{23}, HS, $\ell = 3$ (M_{22} does not)
- $\mathrm{SL}_2(8)$, J_1, ${}^2G_2(q)$, $\ell = 2$ in two steps
- S_n, A_n, $\mathrm{GL}_n(q)$ in multiple steps

Some Remarks

- Since $\pi(-)$, the ordering and the first category determine the perverse equivalence, it is a very compact way of defining a (type of) derived equivalence.
- Computationally, this reduces finding a derived equivalence to finding the Green correspondents of the simple modules for G, a much simpler task.
- For groups of Lie type, it seems as though the complexes above do not really depend on ℓ, and only on d, where $\ell \mid \Phi_d(q)$. It is possible to use these perverse equivalences to prove real results in this direction.

Groups of Lie Type

Let $G = G(q)$ be a group of Lie type (e.g., $\mathrm{GL}_n(q)$, $\mathrm{SL}_n(q)$, $\mathrm{Sp}_{2n}(q)$): the order of G is

$$|G| = q^N \prod_{i \in I} \Phi_i(q).$$

Suppose that $\ell \nmid q$ divides exactly one of the cyclotomic polynomials $\Phi_d(q)$ in the product. Then the Sylow ℓ-subgroup is abelian, and contained in a Φ_d-torus.

The unipotent characters of G are certain irreducible characters of G, not depending on q. A unipotent block of G is one containing a unipotent character, such as the principal block, which contains the trivial character.

Geometric Broué

Broué's conjecture has a special version for unipotent blocks of groups of Lie type, called the geometric form. The derived equivalence in this case comes from the cohomology of a Deligne–Lusztig variety Y_ζ, where ζ is any primitive dth root of unity. (The variety changes depending on ζ.)

This derived equivalence is supposed to be perverse, with perversity function $\pi(-)$ being the (unique) degree in the cohomology of Y_ζ in which a given unipotent character appears.

A big open problem since the late 70s is: What is this degree?

The Parameter π

Let $\ell \mid \Phi_d(q)$ and let χ be a unipotent character in the principal ℓ-block of kG. The generic degree of χ is a polynomial in q, that is a product of q and cyclotomic polynomials $\Phi_i(q)$. The relative degree is the generic degree of χ divided by the relative degree of the unipotent character of the d-cuspidal pair associated to χ.

Define $\zeta = e^{2k\pi i/d}$, and for f a polynomial in q write $\phi_\zeta(f)$ for the number of non-zero zeroes of f (with multiplicity) of argument at most that of ζ (with argument in $[0, 2\pi)$), with the exception that positive reals count for $1/2$ (as their argument is 'both' 0 and 2π). Write $a(f)$ for the multiplicity of the zero at 0. Write $\pi_\zeta(f) = k(\deg f + a(f))/d + \phi_\zeta(f)$. It should be that if f denotes the relative degree of χ, then $\pi_\zeta(f)$ is the parameter π for χ.
This conjecture has been shown to hold in a variety of situations, both for the perverse equivalences and for the Deligne–Lusztig variety Y_ζ.

Pulling π Downstairs

The quantity $\pi_\zeta(\chi)$ is defined for unipotent characters in B, but for the algorithm computing perverse equivalences it needs to be defined on the simple b-modules, which can be thought of as the ordinary characters of the automizer $E = N_G(P)/PC_G(P)$ if B is the principal block and in general $E = \mathrm{N}_G(D, b)/\mathrm{C}_G(D)$.

This means we need a bijection between the unipotent characters of B and the ordinary characters of E. Recall that E is a complex reflection group, and its action on the torus T is as complex reflections.

The object we need for this is the cyclotomic Hecke algebra, which in one specialization gives the characters of B and in another gives the characters of b.

The Cyclic Case, I

The case where the defect group is cyclic is one where we can say the most. Here the π-function and bijection are both fully understood.

Theorem

Suppose that G is of Lie type, B is a unipotent block, and D is cyclic. If G does not have type E_7 or E_8 (and even then in many cases) the 'combinatorial form' of Broué's conjecture is true, with $\pi(-) = \pi_\zeta(-)$ and bijection given by mapping χ to $\omega_\chi \zeta^{(a(\chi)+A(\chi))/\ell(b)}$ (ω_χ is a root of unity, normally ± 1), with the Brauer tree of b (a star) being represented on the complex plane.

In order for this theorem to make sense, for non-principal blocks anyway, we have to fix a rotation of the Brauer tree of b, to decide which non-exceptional b-character is placed at the position 1 (in $\mathbb{C}$). This can be done by taking Green correspondents of simple B-modules in almost all cases.

The Cyclic Case, II

The theorem suggests that we should think of a Brauer tree as being embedded in $\mathbb{C}$, not in $\mathbb{R}^2$: one of the important directions this research might take is a generalization of the Brauer tree to (some other) abelian defect groups.

The method of proof of the theorem is fairly simple: using the π-function and bijection, we construct the Brauer tree of the block, and compare it to the known one (when it is known, i.e., not for some blocks of E_7 and E_8). Combinatorial Broué's conjecture holds if and only if the Brauer tree is correct.

Notice that this allows us to make conjectures as to the shape of the Brauer tree in the remaining cases, and this has lead some outstanding cases being resolved.

ℓ-Extended Finite Groups

Let H be a finite group, and let ρ be a faithful complex representation of H. It is well known that there exists an algebraic number field K, with ring of integers $\mathcal{O} = \mathcal{O}_K$, such that $H \leq \mathrm{GL}_n(\mathcal{O})$ and this embedding induces ρ.

Let ℓ be an integer with $\gcd(\ell, |H|) = 1$, such that the map $\mathcal{O} \to \mathbb{Z}/\ell\mathbb{Z}$ induces a faithful representation of H over $\mathbb{Z}/\ell\mathbb{Z}$ via ρ. Write M for the $\mathbb{Z}/\ell\mathbb{Z}H$-module, and $G_\ell = M \rtimes H$.

- $k(G_\ell)$ is a polynomial in ℓ, and $k(G_\ell) \cdot |H|$ is a monic polynomial in ℓ with integer coefficients.
- If H is a reflection group and ρ is its natural representation over $\mathbb{Z}$, then the second coefficient of $k(G_\ell) \cdot |H|$ is $3N$, where N is the number of reflections in H. (A similar formula exists for complex reflection groups.)

Being Generic: An Example

Let $G = \mathrm{PSU}_3(q)$, $\ell \mid (q+1)$. There are three simple modules in the principal block, as $\mathrm{N}_G(P)/\mathrm{C}_G(P) \cong S_3$. G has a permutation representation on q^3+1 points, let Q be a Sylow ℓ-subgroup of the point stabilizer, so that $|Q| = \ell$.

π	Ord. Char.	1_1	2_1	1_2
0	1	1		
2	$q(q-1)$		1	
3	q^3	1	2	1

Let M_1 be the trivial source module $23/13/23/\cdots/23$ with vertex Q, $\dim M_1 = 3\ell$. Let M_2 be the relatively projective summand of $(1/1/1)\uparrow_Q^N$ with head 23, $\dim M_2 = 9\ell$. For $\ell = 5, 7, 17$ we have the following:

$$\begin{array}{ll} X_3: & 0 \to \mathcal{P}(3) \to \Omega(M_1) \to C_3 \to 0. \\ X_2: & 0 \to \mathcal{P}(2) \to \mathcal{P}(22) \to \mathcal{P}(2) \oplus M_2 \to C_2 \to 0. \end{array}$$