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Non-commutative algebra

Notes

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Preface

The notes correspond to the master course *Non-commutative Algebra* of the Vrije Universiteit Brussel, Faculty of Sciences, Department of Mathematics and Data Sciences. The course is divided into thirteen two-hours lectures.

Most of the material is based on standard results on group algebras covered in the VUB course *Associative Algebras*. Lecture notes for this course are freely available at `https://github.com/vendramin/associative`. Basic texts on group algebras are Lam's book [6] and Passman's book [7].

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Lecture 1

§1. Group rings

Let K be a field and G be a group (written multiplicatively). Let $K[G]$ be the vector space with basis $\{g : g \in G\}$. Then $\dim K[G] < \infty$ if and only if G is finite. The vector space $K[G]$ is an algebra with multiplication

$$\left(\sum_{g\in G} \lambda_g g\right)\left(\sum_{h\in G} \mu_h h\right) = \sum_{g,h\in G} \lambda_g \mu_h (gh).$$

Exercise 1.1. Prove that $\mathbb{C}[\mathbb{Z}] \simeq \mathbb{C}[X, X^{-1}]$.

For $n \in \mathbb{Z}_{>1}$ let C_n be the cyclic group of order n.

Exercise 1.2. Let $n \in \mathbb{Z}_{>1}$. Prove that $\mathbb{C}[C_n] \simeq \mathbb{C}[X]/(X^n - 1)$.

Exercise 1.3. Prove that if G and H are isomorphic groups, then $K[G] \simeq K[H]$.

In a similar way, if R is a commutative ring (with 1) and G is a group, then one defines the group ring $R[G]$. More precisely, $R[G]$ is the set of finite linear combinations

$$\sum_{g\in G} \lambda_g g$$

where $\lambda_g \in R$ and $\lambda_g = 0$ for all but finitely many $g \in G$. One easily proves that $R[G]$ is a ring with addition

$$\left(\sum_{g\in G} \lambda_g g\right) + \left(\sum_{g\in G} \mu_g g\right) = \sum_{g\in G} (\lambda_g + \mu_g)(g)$$

and multiplication

$$\left(\sum_{g\in G}\lambda_g g\right)\left(\sum_{h\in G}\mu_h h\right)=\sum_{g,h\in G}\lambda_g\mu_h(gh).$$

Moreover, $R[G]$ is a left R-module with $\lambda(\sum_{g\in G}\lambda_g g)=\sum_{g\in G}(\lambda\lambda_g)g$.

Exercise 1.4. Let G be a group. Prove that if $\mathbb{Z}[G]\simeq\mathbb{Z}[H]$, then $R[G]\simeq R[H]$ for any commutative ring R.

question:IP

Question 1.1 (Isomorphism problem). Let G and H be groups. Does $\mathbb{Z}[G]\simeq\mathbb{Z}[H]$ imply $G\simeq H$?

Despite the fact that there are several cases were the isomorphism problem has an affirmative answer (e.g. abelian groups, metabelian groups, nilpotent groups, nilpotent-by-abelian groups, simple groups, abelian-by-nilpotent groups), it is false in general. In 2001 Hertweck found a counterexample of order $2^{21}97^{28}$, see [5].

question:MIP

Question 1.2 (Modular isomorphism problem). Let p be a prime number. Let G and H be finite p-groups and let K be a field of characteristic p. Does $K[G]\simeq K[H]$ imply $G\simeq H$?

Question 1.2 has an affirmative answer in several cases. However, it is not true in general. This question recently answered by García, Margolis and del Río [2]. They found two non-isomorphic groups G and H both of order 512 such that $K[G]\simeq K[H]$ for all field K of characteristic two.

§2. Kapanskly's problems

Let G be a group and K be a field. If $x\in G\setminus\{1\}$ is such that $x^n=1$, then, since

$$(1-x)(1+x+x^2+\cdots+x^{n-1})=0,$$

it follows that $K[G]$ has non-trivial zero divisors. What happens in the case where G is torsion-free?

example:k[Z]

Example 2.1. Let $G=\langle x\rangle\simeq\mathbb{Z}$. Then $K[G]$ has no zero divisors. Let $\alpha,\beta\in K[G]$ be non-zero elements and write $\alpha=\sum_{i\leq n}a_ix^i$ with $a_n\neq 0$ and $\beta=\sum_{j\leq m}b_jx^j$ with $b_m\neq 0$. Since the coefficient of x^{n+m} of $\alpha\beta$ is non-zero, it follows that $\alpha\beta\neq 0$.

A similar problem concerns units of group algebras. A unit $u\in K[G]$ is said to be **trivial** if $u=\lambda g$ for some $\lambda\in K\setminus\{0\}$ and $g\in G$.

Exercise 2.2. Prove that units of $\mathbb{C}[C_2]$ are trivial.

Exercise 2.3. Prove that $\mathbb{C}[C_5]$ has non-trivial units.

prob:dominio

Open problem 2.1 (Zero divisors). Let G be a torsion-free group. Is it true that $K[G]$ is a domain?

We mention some intriguing problems, generally known as Kaplansky's problems.

prob:units

Open problem 2.2 (Units). Let G be a torsion-free group. Is it true that all units of $K[G]$ are trivial?

The unit problem is still open for fields of characteristic zero. However, it was recently solved by Gardam [3] in the case of K the field of two elements. We will present Gardam's theorem as a computer calculation. We will use GAP [1].

Lemma 2.4. *The group* $G = \langle a, b : a^{-1}b^2a = b^{-2}, b^{-1}a^2b = a^{-2}\rangle$ *is torsion-free. Moreover, the subgroup* $N = \langle a^2, b^2, (ab)^2\rangle$ *is normal in* G*, free-abelian of rank three and* $G/N \simeq C_2 \times C_2$.

Proof. We first construct the group.

```
gap> F := FreeGroup(2);;
gap> A := F.1;;
gap> B := F.2;;
gap> rels := [(B^2)^A*B^2,(A^2)^B*A^2];;
gap> G := F/rels;;
gap> a := G.1;;
gap> b := G.2;;
```

Now we construct the subgroup N generated by a^2, b^2 and $(ab)^2$. It is easy to check that N is normal in G and that $G/N \simeq C_2 \times C_2$. It is even easier to do this with the computer.

```
gap> N := Subgroup(G, [a^2,b^2,(a*b)^2]);;
gap> IsNormal(G,N);
true
gap> StructureDescription(G/N);
"C2 x C2"
```

It is easy to check by hand that N is abelian, and not so easy to do it with the computer. For example,

$$b^{-2}a^2b^{-2} = b^{-1}a^{-2}b = (b^{-1}a^2b)^{-1} = (a^{-2})^{-1} = a^2.$$

We use the computer to show that N is free abelian of rank three.

```
gap> AbelianInvariants(N);
[ 0, 0, 0 ]
```

Let us prove that G is torsion-free. Let $x = a^2$, $y = b^2$ and $z = (ab)^2$. Since $(G : N) = 4$, the group G decomposes as a disjoint union $G = N \cup aN \cup bN \cup (ab)N$. Let $g \in G$ be a non-trivial element of finite order. Since N is torsion-free, $g \in aN \cup bN \cup (ab)N$. Without loss of generality we may assume that $g \in aN$, so $g = an$ for some $n \in N$. Let $\pi\colon G \to G/N$ be the canonical map. Since $g \notin N$ and $\pi(g) \in G/N \simeq C_2 \times C_2$,

$$\pi(g^2) = \pi(g)^2 = 1$$

so $g^2 \in N$ and hence $g^2 = 1$, as N is torsion-free. Thus

$$1 = g^2 = (an)^2 = (an)(an) = a^2(a^{-1}na)n = x(a^{-1}na)n.$$

Write $n = x^i y^j z^k$ for some $i, j, k \in \mathbb{Z}$. Then

$$a^{-1}na = (a^{-1}x^i a)(a^{-1}y^j a)(a^{-1}z^k a) = x^i t^{-j} z^{-k}$$

and hence $(a^{-1}na)n = x^{2i}$. Then it follows that $1 = g^2 = x(a^{-1}na)n = x^{2i+1}$, a contradiction. □

Let P be the group generated by

$$a = \begin{pmatrix} 1 & 0 & 0 & 1/2 \\ 0 & -1 & 0 & 1/2 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad b = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1/2 \\ 0 & 0 & -1 & 1/2 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

The group P appears in the literature with various names. For us P will be the Promislow group. It is easy to check that there exists a surjective group homomorphism $G \to P$. Prove that $G \simeq P$.

thm:Gardam

Theorem 2.5 (Gardam). *Let $\mathbb{F}_2$ be the field of two elements. Consider the elements $x = a^2$, $y = b^2$ and $z = (ab)^2$ of P and let*

$$p = (1+x)(1+y)(1+z^{-1}), \qquad q = x^{-1}y^{-1} + x + y^{-1}z + z,$$
$$r = 1 + x + y^{-1}z + xyz, \qquad s = 1 + (x + x^{-1} + y + y^{-1})z^{-1}.$$

Then $u = p + qa + rb + sab$ is a non-trivial unit in $\mathbb{F}_2[P]$.

Proof. We claim that the inverse of u is the element $v = p_1 + q_1 a + r_1 b + s_1 ab$, where

$$p_1 = x^{-1}(a^{-1}pa), \qquad q_1 = -x^{-1}q, \qquad r_1 = -y^{-1}r, \qquad s_1 = z^{-1}(a^{-1}sa).$$

We only need to show that $uv = vu = 1$. We will perform this calculation with GAP. We first need to create the group $P = \langle a, b \rangle$.

```
gap> a := [[1,0,0,1/2],[0,-1,0,1/2],[0,0,-1,0],[0,0,0,1]];;
gap> b := [[-1,0,0,0],[0,1,0,1/2],[0,0,-1,1/2],[0,0,0,1]];;
gap> P := Group([a,b]);
```

Now we create the group algebra $F[P]$ and the embedding $P \hookrightarrow F[P]$. The field $\mathbb{F}_2$ will be `GF(2)` and the embedding will be denoted by `f`.

```
gap> R := GroupRing(GF(2),P);;
gap> f := Embedding(P, R);;
```

We first need the elements x, y and z that were defined in the statement.

```
gap> x := Image(f, a^2);;
```

```
gap> y := Image(f, b^2);;
gap> z := Image(f, (a*b)^2);;
```

Now we define the elements p, q, r and s. Note that the identity of the group algebra `R` is `One(R)`.

```
gap> p := (One(R)+x)*(One(R)+y)*(One(R)+Inverse(z));;
gap> r := One(R)+x+Inverse(y)*z+x*y*z;;
gap> q := Inverse(x)*Inverse(y)+x+Inverse(y)*z+z;;
gap> s := One(R)+(x+Inverse(x)+y+Inverse(y))*Inverse(z);
```

Rather than trying to compute the inverse of u we will show that $uv = vu = 1$. For that purpose we need to define p_1, q_1, r_1 and s_1.

```
gap> p1 := Inverse(x)*p^Image(f, a);;
gap> q1 := -Inverse(x)*q;;
gap> r1 := -Inverse(y)*r;;
gap> s1 := Inverse(z)*s^Image(f, a);;
```

Now it is time to prove the theorem.

```
gap> u := p+q*a+r*b+s*a*b;;
gap> v := p1+q1*a+r1*b+s1*a*b;;
gap> IsOne(u*v);
true
gap> IsOne(v*u);
true
```

This completes the proof of the theorem. □

Our proof of Theorem 2.5 is exactly as that of [3].

Exercise 2.6. Let p be a prime number and $\mathbb{F}_p$ be the field of size p. Use the technique for proving Gardam's theorem to prove Murray's theorem on the existence on non-trivial units in $\mathbb{F}_p[P]$. Reference: arXiv:2106.02147.

Lecture 2

We now describe some very-well known open problems in the theory of group rings and the connection between them.

Definition 2.7. A ring R is **reduced** if for all $r \in R$ such that $r^2 = 0$ one has $r = 0$.

Integral domains and boolean rings are reduced. $\mathbb{Z}/8$ and $M_2(\mathbb{R})$ are not reduced.

Example 2.8. $\mathbb{Z}^n$ with $(a_1, \dots, a_n)(b_1, \dots, b_n) = (a_1 b_1, \dots, a_n b_n)$ is reduced.

The structure of reduced rings is described by Andrunakevic–Rjabuhin's theorem. It states that a ring is reduced if and only if it is a subdirect products of domains. See [4, 3.20.5] for a proof.

prob:reducido **Open problem 2.3.** Let G be a torsion-free group. Is it true that $K[G]$ is reduced?

Recall that if R is a unitary ring, one proves that the Jacobson radical $J(R)$ is the set of elements x such that $1 + \sum_{i=1}^{n} r_i x s_i$ is invertible for all n and all $r_i, s_i \in R$.

prob:J **Open problem 2.4 (Semisimplicity).** Let G be a torsion-free group. It is true that $J(K[G]) = \{0\}$ if G is non-trivial?

Recall that an element e of a ring is said to be *idempotent* if $e^2 = e$. Examples of idempotents are 0 and 1 and these are known as the trivial idempotents.

pro:idempotente **Open problem 2.5 (Idempotents).** Let G be a torsion-free group and $\alpha \in K[G]$ be an idempotent. Is it true that $\alpha \in \{0, 1\}$?

Exercise 2.9. Prove that if $K[G]$ has no zero-divisors and $\alpha \in K[G]$ is an idempotent, then $\alpha \in \{0, 1\}$.

Exercise 2.10. Prove that $K[C_4]$ contains non-trivial zero divisors and every idempotent of $K[C_4]$ is trivial.

The problems mentioned are all related. Our goal is the prove the following implications:

$$2.4 \Longleftarrow 2.2 \Longrightarrow 2.3 \Longleftrightarrow 2.1$$

We first prove that an affirmative solution to the Units Problem 2.2 yields a solution to Problem 2.3 about the reducibility of group algebras.

Theorem 2.11. *Let K be a field of characteristic $\neq 2$ and G be a non-trivial group. Assume that $K[G]$ has only trivial units. Then $K[G]$ is reduced.*

Proof. Let $\alpha \in K[G]$ be such that $\alpha^2 = 0$. We claim that $\alpha = 0$. Since $\alpha^2 = 0$,

$$(1-\alpha)(1+\alpha) = 1-\alpha^2 = 1,$$

it follows that $1-\alpha$ is a unit of $K[G]$. Since units of $K[G]$ are trivial, there exist $\lambda \in K \setminus \{0\}$ and $g \in G$ such that $1-\alpha = \lambda g$. We claim that $g = 1$. If not,

$$0 = \alpha^2 = (1-\lambda g)^2 = 1 - 2\lambda g + \lambda^2 g^2,$$

a contradiction. Therefore $g = 1$ and hence $\alpha = 1-\lambda \in K$. Since K is a field, one concludes that $\alpha = 0$. $\square$

Exercise 2.12. What happens if K is a field of characteristic two?

We now prove that an affirmative solution to the Units Problem 2.2 also yields a solution to the Jacobson Semisimplicity Problem 2.4.

Theorem 2.13. *Let G be a non-trivial group. Assume that $K[G]$ has only trivial units. If $|K| > 2$ or $|G| > 2$, then $J(K[G]) = \{0\}$.*

Proof. Let $\alpha \in J(K[G])$. There exist $\lambda \in K \setminus \{0\}$ and $g \in G$ such that $1-\alpha = \lambda g$. We claim that $g = 1$. Assume $g \neq 1$. If $|K| \geq 3$, then there exist $\mu \in K \setminus \{0,1\}$ such that

$$1 - \alpha\mu = 1 - \mu + \lambda\mu g$$

is a non-trivial unit, a contradiction. If $|G| \geq 3$, there exists $h \in G \setminus \{1, g^{-1}\}$ such that $1 - \alpha h = 1 - h + \lambda g h$ is a non-trivial unit, a contradiction. Thus $g = 1$ and hence $\alpha = 1 - \lambda \in K$. Therefore $1 + \alpha h$ is a trivial unit for all $h \neq 1$ and hence $\alpha = 0$. $\square$

Exercise 2.14. Prove that if $G = \langle g \rangle \simeq \mathbb{Z}/2$, then $J(\mathbb{F}_2[G]) = \{0, g-1\} \neq \{0\}$.

§3. The transfer map

Now we prove that an affirmative solution to the Units Problem (Open Problem 2.2) yields a solution to Open Problem 2.1 about zero divisors in group algebras. The proof is hard and requires some preliminaries. We first need to discuss a group theoretical tool known as the *transfer map*.

If H is a subgroup of G, a **transversal** of H in G is a complete set of coset representatives of G/H.

lem:d

Lemma 3.1. *Let G be a group and H be a subgroup of G of finite index. Let R and S be transversals of H in G and let $\alpha\colon H \to H/[H,H]$ be the canonical map. Then*

$$d(R,S) = \prod \alpha(rs^{-1}),$$

where the product is taken over all pairs $(r,s) \in R\times S$ such that $Hr = Hs$, is well-defined and satisfies the following properties:

1) $d(R,S)^{-1} = d(S,R)$.
2) $d(R,S)d(S,T) = d(R,T)$ *for all transversal T of H in G.*
3) $d(Rg,Sg) = d(R,S)$ *for all $g \in G$.*
4) $d(Rg,R) = d(Sg,S)$ *for all $g \in G$.*

Proof. The product that defines $d(R,S)$ is well-defined since $H/[H,H]$ is an abelian group. The first three claim are trivial. Let us prove 4). By 2),

$$d(Rg,Sg)d(Sg,S)d(S,R) = d(Rg,S)d(S,R) = d(Rg,R).$$

Since $H/[H,H]$ is abelian, 1) and 3) imply that

$$d(Rg,Sg)d(Sg,S)d(S,R) = d(R,S)d(S,R)d(Sg,S) = d(Sg,S). \qquad \square$$

We are know ready to state and prove the theorem:

thm:transfer

Theorem 3.2. *Let G be a group and H be a finite-index subgroup of G. The map*

$$\nu\colon G \to H/[H,H], \quad g \mapsto d(Rg,R),$$

does not depend on the transversal R of H in G and it is a group homomorphism.

Proof. The lemma implies that the map does not depend on the transversal used. Moreover, ν is a group homomorphism, as

$$\nu(gh) = d(R(gh),R) = d(R(gh),Rh)d(Rh,R) = d(Rg,R)d(Rh,R) = \nu(g)\nu(h). \ \square$$

The theorem justifies the following definition:

Definition 3.3. Let G be a group and H be a finite-index subgroup of G. The **transfer map** of G in H is the group homomorphism

$$\nu\colon G \to H/[H,H], \quad g \mapsto d(Rg,R),$$

of Theorem 3.2, where R is some transversal of H in G.

We need methods for computing the transfer map. If H is a subgroup of G and $(G:H) = n$, let $T = \{x_1,\dots,x_n\}$ be a transversal of H. For $g \in G$ let

$$\nu(g) = \prod \alpha(xy^{-1}),$$

where the product is taken over all pairs $(x,y)\in(Tg)\times T$ such that $Hx=Hy$ and $\alpha\colon H\to H/[H,H]$ is the canonical map. If we write $x=x_ig$ for some $i\in\{1,\dots,n\}$, then $Hx_ig=Hx_{\sigma(i)}$ for some permutation $\sigma\in\mathbb{S}_n$. Thus

$$\nu(g)=\prod_{i=1}^{n}\alpha(x_igx_{\sigma(i)}^{-1}).$$

The cycle structure of σ turns out to be important. For example, if $\sigma=(12)(345)$ and $n=5$, then a direct calculation shows that

$$\prod_{i=1}^{5}\alpha\left(x_igx_{\sigma(i)}^{-1}\right)=\alpha(x_1g^2x_1^{-1})\alpha(x_3g^3x_3^{-1}).$$

This is precisely the content of the following lemma.

lem:transfer

Lemma 3.4. *Let G be a group and H be a subgroup of index n. Let $T=\{t_1,\dots,t_n\}$ be a transversal of H in G. For each $g\in G$ there exist $m\in\mathbb{Z}_{>0}$ and elements $s_1,\dots,s_m\in T$ and positive integers $n_1,\dots,n_m$ such that $s_i^{-1}g^{n_i}s_i\in H$, $n_1+\dots+n_m=n$ and*

$$\nu(g)=\prod_{i=1}^{m}\alpha(s_i^{-1}g^{n_i}s_i).$$

Proof. For each i there exist $h_1,\dots,h_n\in H$ and $\sigma\in\mathbb{S}_n$ such that $gt_i=t_{\sigma(i)}h_i$. Write σ as a product of disjoint cycles, say

$$\sigma=\alpha_1\cdots\alpha_m.$$

Let $i\in\{1,\dots,n\}$ and write $\alpha_i=(j_1\cdots j_{n_i})$. Since

$$gt_{j_k}=t_{\sigma(j_k)}h_{j_k}=\begin{cases}t_{j_1}h_{j_k} & \text{si } k=n_i,\\ t_{j_{k+1}}h_{j_k} & \text{otherwise,}\end{cases}$$

then

$$\begin{aligned}
t_{j_1}^{-1}g^{n_i}t_{j_1}&=t_{j_1}^{-1}g^{n_i-1}gt_{j_1}\\
&=t_{j_1}^{-1}g^{n_i-1}t_{j_2}h_{j_1}\\
&=t_{j_1}^{-1}g^{n_i-2}gt_{j_2}h_{j_1}\\
&=t_{j_1}^{-1}g^{n_i-2}t_{j_3}h_{j_2}h_{j_1}\\
&\;\;\vdots\\
&=t_{j_1}^{-1}gt_{j_{n_i}}h_{n_{i-1}}\cdots h_{j_2}h_{j_1}\\
&=t_{j_1}^{-1}t_{j_1}h_{j_{n_i}}\cdots h_{j_2}h_{j_1}\in H.
\end{aligned}$$

Thus $s_i=t_{j_1}\in T$. It only remains to note that $\nu(g)=h_1\cdots h_n$. □

An application:

pro:center **Proposition 3.5.** *If G is a group such that $Z(G)$ has finite index n, then $(gh)^n = g^n h^n$ for all $g, h \in G$.*

Proof. Note that we may assume that $\alpha = \mathrm{id}$, as $Z(G)$ is abelian. Let $g \in G$. By Lemma 3.4 there are positive integers $n_1, \dots, n_k$ such that $n_1 + \cdots + n_k = n$ and elements $t_1, \dots, t_k$ of a transversal of $Z(G)$ in G such that

$$\nu(g) = \prod_{i=1}^{k} t_i g^{n_1} t_i^{-1}.$$

Since $g^{n_i} \in Z(G)$ for all $i \in \{1, \dots, k\}$ (as $t_i g^{n_i} t_i^{-1} \in Z(G)$), it follows that

$$\nu(g) = g^{n_1 + \cdots + n_k} = g^n.$$

Now Theorem 3.2 implies the claim. □

The same idea implies the following property:

xca:K_central **Exercise 3.6.** If G is a group and K is a central subgroup of finite index n, then $(gh)^n = g^n h^n$ for all $g, h \in G$.

For a group G we consider

$$\Delta(G) = \{g \in G : (G : C_G(g)) < \infty\}.$$

Exercise 3.7. Prove that $\Delta(\Delta(G)) = \Delta(G)$.

A subgroup H of G is a **characteristic** subgroup of G if $f(H) \subseteq H$ for all $f \in \mathrm{Aut}(G)$. The center and the commutator subgroup of a group are characteristic subgroups. Every characteristic subgroup is a normal subgroup.

Exercise 3.8. Prove that if H is characteristic in K and K is normal in G, then H is normal in G.

Proposition 3.9. *If G is a group, then $\Delta(G)$ is a characteristic subgroup of G.*

Proof. We first prove that $\Delta(G)$ is a subgroup of G. If $x, y \in \Delta(G)$ and $g \in G$, then $g(xy^{-1})g^{-1} = (gxg^{-1})(gyg^{-1})^{-1}$. Moreover, $1 \in \Delta(G)$. Let us show now that $\Delta(G)$ is characteristic in G. If $f \in \mathrm{Aut}(G)$ and $x \in G$, then, since

$$f(gxg^{-1}) = f(g)f(x)f(g)^{-1},$$

it follows that $f(x) \in \Delta(G)$. □

Exercise 3.10. Prove that if $G = \langle r, s : s^2 = 1, srs = r^{-1} \rangle$ is the infinite dihedral group, then $\Delta(G) = \langle r \rangle$.

Exercise 3.11. Let H and K be finite-index subgroups of G. Prove that

$$(G : H \cap K) \leq (G : H)(G : K).$$

Lecture 3

§4. Passman's theorem

pro:FCabeliano

Proposition 4.1. *If G is a torsion-free group such that $\Delta(G) = G$, then G is abelian.*

Proof. Let $x, y \in G = \Delta(G)$ and $S = \langle x, y\rangle$. The group $Z(S) = C_S(x) \cap C_S(y)$ has finite index, say n, in S. By Proposition 3.5, the map $S \to Z(S)$, $s \mapsto s^n$, is a group homomorphism. Thus

$$[x, y]^n = (xyx^{-1}y^{-1})^n = x^n y^n x^{-n} y^{-n} = 1$$

as $x^n \in Z(S)$. Since G is torsion-free, $[x, y] = 1$. □

lem:Neumann

Lemma 4.2 (Neumann). *Let $H_1, \dots, H_m$ be subgroups of G. Assume there are finitely many elements $a_{ij} \in G$, $1 \le i \le m$, $1 \le j \le n$, such that*

$$G = \bigcup_{i=1}^{m} \bigcup_{j=1}^{n} H_i a_{ij}.$$

Then some H_i has finite index in G.

Proof. We proceed by induction on m. The case $m = 1$ is trivial. Let us assume that $m \ge 2$. If $(G : H_1) = \infty$, there exists $b \in G$ such that

$$H_1 b \cap \left(\bigcup_{j=1}^{n} H_1 a_{1j} \right) = \emptyset.$$

Since $H_1 b \subseteq \bigcup_{i=2}^{m} \bigcup_{j=1}^{n} H_i a_{ij}$, it follows that

$$H_1 a_{1k} \subseteq \bigcup_{i=2}^{m} \bigcup_{j=1}^{n} H_1 a_{ij} b^{-1} a_{1k}.$$

Hence G can be covered by finitely many cosets of $H_2,\dots,H_m$. By the inductive hypothesis, some of these H_j has finite index in G. $\square$

We now consider a projection operator of group algebras. If G is a group and H is a subgroup of G, let

$$\pi_H\colon K[G]\to K[H],\quad \pi_H\left(\sum_{g\in G}\lambda_g g\right)=\sum_{g\in H}\lambda_g g.$$

If R and S are rings, a (R,S)-bimodule is an abelian group M that is both a left R-module and a right S-module and the compatibility condition

$$(rm)s=r(ms)$$

holds for all $r\in R$, $s\in S$ and $m\in M$.

Exercise 4.3. Let G be a group and H be a subgroup of G. Prove that if $\alpha\in K[G]$, then π_H is a $(K[H],K[H])$-bimodule homomorphism with usual left and right multiplications,

$$\pi_H(\beta\alpha\gamma)=\beta\pi_H(\alpha)\gamma$$

for all $\beta,\gamma\in K[H]$.

lem:escritura

Lemma 4.4. *Let X be a left transversal of H in G. Every $\alpha\in K[G]$ can be written uniquely as*

$$\alpha=\sum_{x\in X}x\alpha_x,$$

where $\alpha_x=\pi_H(x^{-1}\alpha)\in K[H]$.

Proof. Let $\alpha\in K[G]$. Since $\operatorname{supp}\alpha$ is finite, $\operatorname{supp}\alpha$ is contained in finitely many cosets of H, say $x_1H,\dots,x_nH$, where each x_j belongs to X. Write $\alpha=\alpha_1+\dots+\alpha_n$, where $\alpha_i=\sum_{g\in x_iH}\lambda_g g$. If $g\in x_iH$, then $x_i^{-1}g\in H$ and hence

$$\alpha=\sum_{i=1}^n x_i(x_i^{-1}\alpha_i)=\sum_{x\in X}x\alpha_x$$

with $\alpha_x\in K[H]$ for all $x\in X$. For the uniqueness, note that for each $x\in X$ the previous exercise implies that

$$\pi_H(x^{-1}\alpha)=\pi_H\left(\sum_{y\in X}x^{-1}y\alpha_y\right)=\sum_{y\in X}\pi_H(x^{-1}y)\alpha_y=\alpha_x,$$

as

$$\pi_H(x^{-1}y)=\begin{cases}1 & \text{si } x=y,\\ 0 & \text{si } x\neq y.\end{cases}$$ $\square$

lem:ideal_pi

Lemma 4.5. *Let G be a group and H be a subgroup of G. If I is a non-zero left ideal of $K[G]$, then $\pi_H(I) \neq \{0\}$.*

Proof. Let X be a left transversal of H in G and $\alpha \in I \setminus \{0\}$. By Lemma 4.4 we can write $\alpha = \sum_{x \in X} x\alpha_x$ with $\alpha_x = \pi_H(x^{-1}\alpha) \in K[H]$ for all $x \in X$. Since $\alpha \neq 0$, there exists $y \in X$ such that $0 \neq \alpha_y = \pi_H(y^{-1}\alpha) \in \pi_H(I)$ ($y^{-1}\alpha \in I$ since I is a left ideal). □

Another application:

Proposition 4.6. *Let G be a group, H be a subgroup of G and $\alpha \in K[H]$. The following statements hold:*

1) *α is invertible in $K[H]$ if and only if α is invertible in $K[G]$.*
2) *α is a zero divisor of $K[H]$ if and only if α is a zero divisor of $K[G]$.*

Proof. If α is invertible in $K[G]$, there exists $\beta \in K[G]$ such that $\alpha\beta = \beta\alpha = 1$. Apply π_H and use that π_H is a $(K[H], K[H])$-bimodule homomorphism to obtain

$$\alpha\pi_H(\beta) = \pi_H(\alpha\beta) = \pi_H(1) = 1 = \pi_H(1) = \pi_H(\beta\alpha) = \pi_H(\beta)\alpha.$$

Assume now that $\alpha\beta = 0$ for some $\beta \in K[G] \setminus \{0\}$. Let $g \in G$ be such that $1 \in \operatorname{supp}(\beta g)$. Since $\alpha(\beta g) = 0$,

$$0 = \pi_H(0) = \pi_H(\alpha(\beta g)) = \alpha\pi_H(\beta g),$$

where $\pi_H(\beta g) \in K[H] \setminus \{0\}$, as $1 \in \operatorname{supp}(\beta g)$. □

lem:Passman

Lemma 4.7 (Passman). *Let G be a group and $\gamma_1, \gamma_2 \in K[G]$ be such that $\gamma_1 K[G]\gamma_2 = \{0\}$. Then $\pi_{\Delta(G)}(\gamma_1)\pi_{\Delta(G)}(\gamma_2) = \{0\}$.*

Proof. It is enough to show that $\pi_{\Delta(G)}(\gamma_1)\gamma_2 = \{0\}$, as in this case

$$\{0\} = \pi_{\Delta(G)}(\pi_{\Delta(G)}(\gamma_1)\gamma_2) = \pi_{\Delta}(\gamma_1)\pi_{\Delta(G)}(\gamma_2).$$

Write $\gamma_1 = \alpha_1 + \beta_1$, where

$$\begin{aligned} \alpha_1 &= a_1u_1 + \cdots + a_ru_r, && u_1, \dots, u_r \in \Delta(G),\\ \beta_1 &= b_1v_1 + \cdots + b_sv_s, && v_1, \dots, v_s \notin \Delta(G),\\ \gamma_2 &= c_1w_1 + \cdots + c_tw_t, && w_1, \dots, w_t \in G. \end{aligned}$$

The subgroup $C = \bigcap_{i=1}^{r} C_G(u_i)$ has finite index in G. Assume that

$$0 \neq \pi_{\Delta}(\gamma_1)\gamma_2 = \alpha_1\gamma_2.$$

Let $g \in \operatorname{supp}(\alpha_1\gamma_2)$. If v_i is a conjugate in G of some gw_j^{-1}, let $g_{ij} \in G$ be such that $g_{ij}^{-1}v_ig_{ij} = gw_j^{-1}$. If v_i and gw_j^{-1} are not conjugate, we take $g_{ij} = 1$.

For every $x \in C$ it follows that $\alpha_1\gamma_2 = (x^{-1}\alpha_1x)\gamma_2$. Since

$$x^{-1}\gamma_1 x\gamma_2 \in x^{-1}\gamma_1 K[G]\gamma_2 = 0,$$

it follows that

$$\begin{aligned}(a_1u_1+\cdots+a_ru_r)\gamma_2 = \alpha_1\gamma_2 = x^{-1}\alpha_1 x\gamma_2 = -x^{-1}\beta_1 x\gamma_2\\ = -x^{-1}(b_1v_1+\cdots+b_sv_r)x(c_1w_1+\cdots+c_tw_t).\end{aligned}$$

Now $g \in \operatorname{supp}(\alpha_1\gamma_2)$ implies that there exist i,j such that $g = x^{-1}v_ixw_j$. Thus v_i and gw_j^{-1} are conjugate and hence $x^{-1}v_ix = gw_j^{-1} = g_{ij}^{-1}v_ig_{ij}$, that is $x \in C_G(v_i)g_{ij}$. This proves that

$$C \subseteq \bigcup_{i,j} C_G(v_i)g_{ij}.$$

Since C has finite index in G, it follows that G can be covered by finitely many cosets of the $C_G(v_i)$. Every $v_i \notin \Delta(G)$, so each $C_G(v_i)$ has infinite index in G, a contradiction to Neumann's lemma. □

Before proving Passman's theorem, we need to mention that if G is a torsion-free abelian group, then $K[G]$ has no non-zero divisors. We will prove this fact later, as an application of the theory of bi-ordered groups (see Corollary 6.15).

thm:Passman

Theorem 4.8 (Passman). *Let G be a torsion-free group. If $K[G]$ is reduced, then $K[G]$ is a domain.*

Proof. Assume that $K[G]$ is not a domain. Let $\gamma_1,\gamma_2 \in K[G]\setminus\{0\}$ be such that $\gamma_2\gamma_1 = 0$. If $\alpha \in K[G]$, then

$$(\gamma_1\alpha\gamma_2)^2 = \gamma_1\alpha\gamma_2\gamma_1\alpha\gamma_2 = 0$$

and thus $\gamma_1\alpha\gamma_2 = 0$, as $K[G]$ is reduced. In particular, $\gamma_1K[G]\gamma_2 = \{0\}$. Let I be the left ideal of $K[G]$ generated by γ_2. Since $I \neq \{0\}$, it follows from Lemma 4.5 that $\pi_{\Delta(G)}(I) \neq \{0\}$. Hence $\pi_{\Delta(G)}(\beta\gamma_2) \neq \{0\}$ for some $\beta \in K[G]$. Similarly, $\pi_{\Delta(G)}(\gamma_1\alpha) \neq \{0\}$ for some $\alpha \in K[G]$. Since

$$\gamma_1\alpha K[G]\beta\gamma_2 \subseteq \gamma_1 K[G]\gamma_2 = \{0\},$$

it follows that $\pi_{\Delta(G)}(\gamma_1\alpha)\pi_{\Delta(G)}(\beta\gamma_2) = \{0\}$ by Passman's lemma. Hence $K[\Delta(G)]$ has zero divisors, a contradictions since $\Delta(G)$ is an abelian group. □

Lecture 4

§5. More applications of the transfer

Let us start with a group-theoretic application of the transfer map. We start with some applications to the theory of finite groups.

prop:semidirecto **Proposition 5.1.** *Let G be a finite group and H a central subgroup of index n, where n is coprime with $|H|$. Then $G \simeq N \rtimes H$.*

Proof. Since H is abelian, $H = H/[H,H]$. Let $\nu\colon G \to H$ be the transfer map and $h \in H$. By Lemma 3.4,

$$\nu(h) = \prod_{i=1}^{m} s_i^{-1} h^{n_i} s_i,$$

where each $s_i^{-1} h^{n_i} s_i \in H$. Since $h^{n_i} \in H \subseteq Z(G)$ for all i, it follows that $s_i^{-1} h^{n_i} s_i = h^{n_i}$ for all i. Thus

$$\nu(h) = \prod_{i=1}^{m} s_i^{-1} h^{n_i} s_i = \prod_{i=1}^{m} h^{n_i} = h^{\sum_{i=1}^{m} n_i} = h^n.$$

The composition $f\colon H \hookrightarrow G \xrightarrow{\nu} H$ is a group homomorphism. We claim that it is an isomorphism. It is injective: If $h^n = 1$, then $|h|$ divides both $|H|$ and n. Since n and $|H|$ are coprime, $h = 1$. It is surjectice: Since n and $|H|$ are coprime, there exists $m \in \mathbb{Z}$ such that $nm \equiv 1 \bmod |H|$. If $h \in H$, then $h^m \in H$ and $\nu(h^m) = h^{nm} = h$.

Let $N = \ker f$. We claim that $G = N \rtimes H$. By definition, N is normal in G and $N \cap H = \{1\}$. To show that $G = NH$ note that $|NH| = |N||H|$ and $G/N \simeq H$. □

Exercise 5.2. Let H be a central subgroup of a finite group G. If $|H|$ and $|G/H|$ are coprime, then $G \simeq H \times G/H$.

An application to infinite groups taken from Serre's book [8, 7.12].

Theorem 5.3. *Let G be a torsion-free group that contains a finite-index subgroup isomorphic to $\mathbb{Z}$. Then $G \simeq \mathbb{Z}$.*

Proof. We may assume that G contains a finite-index normal subgroup isomorphic to $\mathbb{Z}$. Indeed, if H is a finite-index subgroup of G such that $H \simeq \mathbb{Z}$, then $K = \cap_{x \in G} xHx^{-1}$ is a non-trivial normal subgroup of G (because $K = \mathrm{Core}_G(H)$ and G has no torsion) and hence $K \simeq \mathbb{Z}$ (because $K \subseteq H$) and $(G : K) = (G : H)(H : K)$ is finite. The action of G on K by conjugation induces a group homomorphism $\epsilon \colon G \to \mathrm{Aut}(K)$. Since $\mathrm{Aut}(K) \simeq \mathrm{Aut}(\mathbb{Z}) = \{-1, 1\}$, there are two cases to consider.

Assume first that $\epsilon = \mathrm{id}$. Since $K \subseteq Z(G)$, let $\nu \colon G \to K$ be the transfer homomorphism. By Proposition 3.5 (more precisely, by Exercise 3.6), $\nu(g) = g^n$, where $n = (G : K)$. Since G has no torsion, ν is injective. Thus $G \simeq \mathbb{Z}$ because it is isomorphic to a subgroup of K.

Assume now that $\epsilon \neq \mathrm{id}$. Let $N = \ker \epsilon \neq G$. Since $K \simeq \mathbb{Z}$ is abelian, $K \subseteq N$. The result proved in the previous paragraph applied to $\epsilon|_N = 1$ implies that $N \simeq \mathbb{Z}$, as N contains a finite-index subgroup isomorphic to $\mathbb{Z}$. Let $g \in G \setminus N$. Since N is normal in G, G acts by conjugation on N and hence there exists a group homomorphism $c_g \in \mathrm{Aut}(N) \simeq \{-1, 1\}$. Since $K \subseteq N$ y g acts non-trivially on K,

$$c_g(n) = gng^{-1} = n^{-1}$$

for all $n \in N$. Since $g^2 \in N$,

$$g^2 = gg^2g^{-1} = g^{-2}.$$

Therefore $g^4 = 1$, a contradiction since $g \neq 1$ and G has no torsion. □

Before giving another application of the transfer map, we prove Dietzman's theorem:

theorem:Dietzmann

Theorem 5.4 (Dietzmann). *Let G be a group and $X \subseteq G$ be a finite subset of G closed by conjugation. If there exists n such that $x^n = 1$ for all $x \in X$, then $\langle X \rangle$ is a finite subgroup of G.*

Proof. Let $S = \langle X \rangle$. Since $x^{-1} = x^{n-1}$, every element of S can be written as a finite product of elements of X. Fix $x \in X$. We claim that if $x \in X$ appears $k \geq 1$ times in the word s, then we can write s as a product of m elements of X, where the first k elements are equal to x. Suppose that

$$s = x_1 x_2 \cdots x_{t-1} x x_{t+1} \cdots x_m,$$

where $x_j \neq x$ for all $j \in \{1, \dots, t-1\}$. Then

$$s = x(x^{-1}x_1x)(x^{-1}x_2x) \cdots (x^{-1}x_{t-1}x)x_{t+1} \cdots x_m$$

is a product of m elements of X since X is closed under conjugation and the first element is x. The same argument implies that s can be written as

$$s = x^k y_{k+1} \cdots y_m,$$

where each y_j belongs to $X \setminus \{x\}$.

Let $s \in S$ and write s as a product of m elements of X, where m is minimal. We need to show that $m \leq (n-1)|X|$. If $m > (n-1)|X|$, then at least one $x \in X$ appears exactly n times in the representation of s. Without loss of generality, we write

$$s = x^n x_{n+1} \cdots x_m = x_{n+1} \cdots x_m,$$

a contradiction to the minimality of m. □

The second result goes back to Schur:

thm:Schur

Theorem 5.5 (Schur). *Let G be a group. If $Z(G)$ has finite index in G, then $[G,G]$ is finite.*

Proof. Let $n = (G : Z(G))$ and X be the set of commutators of G. We claim that X is finite, in fact $|X| \leq n^2$. A routine calculation shows that the map

$$\varphi\colon X \to G/Z(G) \times G/Z(G), \quad [x,y] \mapsto (xZ(G), yZ(G)),$$

is well-defined. It is, moreover, injective: if $(xZ(G), yZ(G)) = (uZ(G), vZ(G))$, then $u^{-1}x \in Z(G)$, $v^{-1}y \in Z(G)$. Thus

$$[u,v] = uvu^{-1}v^{-1} = uv(u^{-1}x)x^{-1}v^{-1} = xvx^{-1}(v^{-1}y)y^{-1} = xyx^{-1}y^{-1} = [x,y].$$

Moreover, X is closed under conjugation, as

$$g[x,y]g^{-1} = [gxg^{-1}, gyg^{-1}]$$

for all $g,x,y \in G$. Since $G \to Z(G)$, $g \mapsto g^n$ is a group homomorphism, Proposition 3.5 implies that $[x,y]^n = [x^n, y^n] = 1$ for all $[x,y] \in X$. The theorem follows from applying Dietzmann's theorem. □

Exercise 5.6. Let G be the group with generators a,b,c and relations $ab = ca$, $ac = ba$ and $bc = ab$. Prove the following statements:

1) G is infinite and non-abelian.
2) $Z(G)$ has finite index in G and every conjugacy class of G is finite.
3) $[G,G]$ is finite.
4) The subgroup $N = \langle a^3 \rangle$ of G generated by a^3 is central and G/N is finite.

We conclude the section with some results similar to that of Schur.

thm:Niroomand

Theorem 5.7 (Niroomand). *If the set of commutators of a group G is finite, then $[G,G]$ is finite.*

Proof. Let $C = \{[x_1,y_1], \dots, [x_k,y_k]\}$ be the (finite) set of commutators of G and $H = \langle x_1, x_2, \dots, x_k, y_1, y_2, \dots, y_k \rangle$. Since C is a set of commutators of H, it follows that $[G,G] = \langle C \rangle \subseteq [H,H]$. To simplify the notation we write $H = \langle h_1, \dots, h_{2k} \rangle$. Since $h \in Z(H)$ if and only if $h \in C_H(h_i)$ for all $i \in \{1, \dots, 2k\}$, we conclude that $Z(H) = C_H(h_1) \cap \cdots \cap C_H(h_{2k})$. Moreover, if $h \in H$, then $hh_ih^{-1} = ch_i$ for some

$c \in C$. Thus the conjugacy class of each h_i contains at most as many elements as C. This implies that

$$|H/Z(H)| = |H/\cap_{i=1}^{2k} C_H(h_i)| \leq \prod_{i=1}^{2k} (H : C_H(h_i)) \leq |C|^{2k}.$$

Since $H/Z(H)$ is finite, $[H,H]$ is finite. Hence $[G,G] = \langle C \rangle \subseteq [H,H]$ is a finite group. □

thm:HiltonNiroomand

Theorem 5.8 (Hilton–Niroomand). *Let G be a finitely generated group. If $[G,G]$ is finite and $G/Z(G)$ is generated by n elements, then*

$$|G/Z(G)| \leq |[G,G]|^n.$$

Proof. Assume that $G/Z(G) = \langle x_1 Z(G), \dots, x_n Z(G) \rangle$. Let

$$f \colon G/Z(G) \to [G,G] \times \cdots \times [G,G], \quad y \mapsto ([x_1, y], \dots, [x_n, y]).$$

Note that f is well-defined: If $y \in G$ y $z \in Z(G)$, then $[x_i, y] = [x_i, yz]$ for all i. Then $f(yz) = f(y)$.

The map f is injective. Assume that $f(xZ(G)) = f(yZ(G))$. Then $[x_i, x] = [x_i, y]$ for all $i \in \{1, \dots, n\}$. For each i we compute

$$\begin{aligned}[x^{-1}y, x_i] &= x^{-1}[y, x_i]x[x^{-1}, x_i] \\ &= x^{-1}[y, x_i][x_i, x]x = x^{-1}[x_i, y]^{-1}[x_i, x]x = x^{-1}[x_i, y]^{-1}[x_i, y]x = 1.\end{aligned}$$

This implies that $x^{-1}y \in Z(G)$. Indeed, since every $g \in G$ can be written as $g = x_k z$ for some $k \in \{1, \dots, n\}$ and some $z \in Z(G)$, it follows that

$$[x^{-1}y, g] = [x^{-1}y, x_k z] = [x^{-1}y, x_k] = 1.$$

Since f is injective, $|G/Z(G)| \leq |[G,G]|^n$. □

Exercise 5.9. Prove Theorem 5.8 from Theorem 5.7.

Lecture 5

§6. Bi-ordered groups

Based on Example 2.1 we will study some properties of groups.

Recall that a **total order** is a partial order in which any two elements are comparable. This means that a total order is a binary relation $\leq$ on some set X such that for all $x, y, z \in X$ one has

1) $x \leq x$.
2) $x \leq y$ and $y \leq z$ imply $x \leq z$.
3) $x \leq y$ and $y \leq x$ imply $x = y$.
4) $x \leq y$ or $y \leq x$.

A set equipped with a total order is a **totally ordered set**.

Definition 6.1. A group G is **bi-ordered** if there exists a total order $<$ in G such that $x < y$ implies that $xz < yz$ and $zx < zy$ for all $x, y, z \in G$.

Example 6.2. The group $\mathbb{R}_{>0}$ of positive real numbers is bi-ordered.

The multiplicative group $\mathbb{R} \setminus \{0\}$ is not bi-ordered. Why?

Exercise 6.3. Let G be a bi-ordered group and $x, x_1, y, y_1 \in G$. Prove that $x < y$ and $x_1 < y_1$ imply $xx_1 < yy_1$.

Clearly, bi-orderability is preserved under taking subgroups.

Exercise 6.4. Let G be a bi-ordered group and $g, h \in G$. Prove that $g^n = h^n$ for some $n > 0$ implies $g = h$.

The following result goes back to Neumann.

Exercise 6.5. Let G be a bi-ordered group and $g, h \in G$. Prove that $g^n \in C_G(h)$ if and only if $g \in C_G(h)$.

Bi-ordered groups do not behave nicely under extensions:

xca:BO_sequence **Exercise 6.6.** Let $1 \to K \to G \to Q \to 1$ be an exact sequence of groups. Assume that K and Q are bi-ordered. Prove that G is bi-ordered if and only if $x < y$ implies $gxg^{-1} < gyg^{-1}$ for all $x, y \in K$ and $g \in G$.

Definition 6.7. Let G be a bi-ordered group. The **positive cone** of G is the set $P(G) = \{x \in G : 1 < x\}$.

Let us state some properties of positive cones.

pro:biordenableP1 **Proposition 6.8.** *Let G be a bi-ordered group and let P be its positive cone.*

1) *P is closed under multiplication, i.e. $PP \subseteq P$.*
2) *$G = P \cup P^{-1} \cup \{1\}$ (disjoint union).*
3) *$xPx^{-1} = P$ for all $x \in G$.*

Proof. If $x, y \in P$ and $z \in G$, then, since $1 < x$ and $1 < y$, it follows that $1 < xy$. Thus $1 = z1z^{-1} < zxz^{-1}$. It remains to prove the second claim. If $g \in G$, then $g = 1$ or $g > 1$ or $g < 1$. Note that $g < 1$ if and only if $1 < g^{-1}$, so the claim follows. □

The previous proposition admits a converse statement.

pro:biordenableP2 **Proposition 6.9.** *Let G be a group and P be a subset of G such that P is closed under multiplication, $G = P \cup P^{-1} \cup \{1\}$ (disjoint union) and $xPx^{-1} = P$ for all $x \in G$. Let $x < y$ whenever $yx^{-1} \in P$. Then G is bi-ordered with positive cone is P.*

Proof. Let $x, y \in G$. Since $yx^{-1} \in G$ and $G = P \cup P^{-1} \cup \{1\}$ (disjoint union), either $yx^{-1} \in P$ or $xy^{-1} = (yx^{-1})^{-1} \in P$ or $yx^{-1} = 1$. Thus either $x < y$ or $y < x$ or $x = y$. If $x < y$ and $z \in G$, then $zx < zy$, as $(zy)(zx)^{-1} = z(yx^{-1})z^{-1} \in P$ and $zPz^{-1} = P$. Moreover, $xz < yz$ since $(yz)(xz)^{-1} = yx^{-1} \in P$. To prove that P is the positive cone of G note that $x1^{-1} = x \in P$ if and only if $1 < x$. □

An important property:

pro:BOsintorsion **Proposition 6.10.** *Bi-ordered groups are torsion-free.*

Proof. Let G be a bi-ordered group and $g \in G \setminus \{1\}$. If $g > 1$, then $1 < g < g^2 < \cdots$. If $g < 1$, then $1 > g > g^2 > \cdots$. Hence $g^n \neq 1$ for all $n \neq 0$. □

The converse of the previous proposition does not hold.

Exercise 6.11. Let $G = \langle x, y : yxy^{-1} = x^{-1} \rangle$.

1) Prove that x and y are torsion-free.
2) Prove that G is torsion-free.
3) Prove that $G \simeq \langle a, b : a^2 = b^2 \rangle$.

Example 6.12. The torsion-free group $G = \langle x, y : yxy^{-1} = x^{-1} \rangle$ is not bi-ordered. If not, let P be the positive cone. If $x \in P$, then $yxy^{-1} = x^{-1} \in P$, a contradiction. Hence $x^{-1} \in P$ and $x = y^{-1}x^{-1}y \in P$, a contradiction.

thm:BO **Theorem 6.13.** *Let G be a bi-ordered group. Then $K[G]$ is a domain such that only has trivial units. Moreover, if G is non-trivial, then $J(K[G]) = \{0\}$.*

Proof. Let $\alpha, \beta \in K[G]$ be such that

$$\alpha = \sum_{i=1}^{m} a_i g_i, \qquad g_1 < g_2 < \cdots < g_m, \qquad a_i \neq 0 \qquad \forall i \in \{1,\dots,m\},$$
$$\beta = \sum_{j=1}^{n} b_j h_j, \qquad h_1 < h_2 < \cdots < h_n, \qquad b_j \neq 0 \qquad \forall j \in \{1,\dots,n\}.$$

Then

$$g_1 h_1 \leq g_i h_j \leq g_m h_n$$

for all i, j. Moreover, $g_1 h_1 = g_i h_j$ if and only if $i = j = 1$. The coefficient of $g_1 h_1$ in $\alpha\beta$ is $a_1 b_1 \neq 0$. In particular, $\alpha\beta \neq 0$. If $\alpha\beta = \beta\alpha = 1$, then the coefficient of $g_m h_n$ in $\alpha\beta$ is $a_m b_n$. Hence $m = n = 1$ and therefore $\alpha = a_1 g_1$ and $\beta = b_1 h_1$ with $a_1 b_1 = b_1 a_1 = 1$ in K and $g_1 h_1 = 1$ in G. □

thm:Levi **Theorem 6.14 (Levi).** *Let A be an abelian group. Then A is bi-ordered if and only if A is torsion-free.*

Proof. If A is bi-ordered, then A is torsion-free. Let us prove the non-trivial implication, so assume that A is torsion-free abelian. Let $\mathcal{S}$ be the class of subsets P of A such that $0 \in P$, are closed under the addition of A and satisfy the following property: if $x \in P$ and $-x \in P$, then $x = 0$. Clearly, $\mathcal{S} \neq \emptyset$, as $\{0\} \in \mathcal{S}$. The inclusion turns $\mathcal{S}$ into a partially ordered set and $\bigcup_{i \in I} P_i$ is an upper bound for the chain $\{P_i : i \in I\}$. By Zorn's lemma, $\mathcal{S}$ admits a maximal element $P \in \mathcal{S}$.

Claim. If $x \in A$ is such that $kx \in P$ for some $k > 0$, then $x \in P$.

Let $Q = \{x \in A : kx \in P \text{ for some } k > 0\}$. We will show that $Q \in \mathcal{S}$. Clearly, $0 \in Q$. Moreover, Q is closed under addition, as $k_1 x_1 \in P$ and $k_2 x_2 \in P$ imply $k_1 k_2 (x_1 + x_2) \in P$. Let $x \in A$ be such that $x \in Q$ and $-x \in Q$. Thus $kx \in P$ and $l(-x) \in P$ for some $l > 0$. Since $klx \in P$ and $kl(-x) \in P$, it follows that $klx = 0$, a contradiction since A is torsion-free. Hence $x \in Q \subseteq P$.

Claim. If $x \in A$ is such that $x \notin P$, then $-x \in P$.

Assume that $-x \notin P$ and let $P_1 = \{y + nx : y \in P, n \geq 0\}$. We will show that $P_1 \in \mathcal{S}$. Clearly, $0 \in P_1$ and P_1 is closed under addition. If $P_1 \notin S$, there exists

$$0 \neq y_1 + n_1 x = -(y_2 + n_2 x),$$

where $y_1, y_2 \in P$ and $n_1, n_2 \geq 0$. Thus $y_1 + y_2 = -(n_1 + n_2)x$. If $n_1 = n_2 = 0$, then $y_1 = -y_2 \in P$ and $y_1 = y_2 = 0$, so it follows that $y_1 + n_1 x = 0$, a contradiction. If $n_1 + n_2 > 0$, then, since

$$(n_1 + n_2)(-x) = y_1 + y_2 \in P,$$

it follows from the first claim that $-x \in P$, a contradiction. Let us show that $P_1 \in \mathcal{S}$. Since $P \subseteq P_1$, the maximality of P implies that $x \in P = P_1$.

By Proposition 6.9, $P^* = P \setminus \{0\}$ is the positive cone of a bi-order in A. In fact, P^* is closed under addition, as $x, y \in P^*$ implies that $x + y \in P$ and $x + y = 0$ implies $x = y = 0$, as $x = -y \in P$. Moreover, $G = P^* \cup -P^* \cup \{0\}$ (disjoint union), as the second claim states that $x \notin P^*$ implies $-x \in P$. □

Our proof of Passman's theorem (Theorem 4.8) used the fact that the group algebra $K[G]$ of a torsion-free abelian group G has no non-zero divisors. We now present a proof of this fact.

cor:domain_G_abelian **Corollary 6.15.** *Let A be a non-trivial torsion-free abelian group. Then $K[A]$ is a domain that only admits trivial units and $J(K[A]) = \{0\}$.*

Proof. Apply Levi's theorem and Theorem 6.13. □

Some exercises. The first one is a variation on Exercise 6.6.

Exercise 6.16. Let N be a central subgroup of G. If N and G/N are bi-ordered, then G is bi-ordered. Prove with an example that N needs to be central, normal is not enough.

Exercise 6.17. Let G be a group that admits a sequence

$$\{1\} = G_0 \subseteq G_1 \subseteq \cdots \subseteq G_n = G$$

such that each G_k is normal in G_{k+1} and each quotient G_{k+1}/G_k is torsion-free abelian. Prove that G is bi-ordered.

Exercise 6.18. Prove that torsion-free nilpotent groups are bi-ordered.

§7. Left-ordered groups

Definition 7.1. A group G is **left-ordered** if there is a total order $<$ in G such that $x < y$ implies $xz < yz$ for all $x, y, z \in G$.

If G is left-ordered, the positive cone of G is defined as $P(G) = \{x \in G : 1 < x\}$.

Exercise 7.2. Let G be left-ordered with positive cone P. Prove that P is closed under multiplication and that $G = P \cup P^{-1} \cup \{1\}$ (disjoint union).

xca:LO_cone **Exercise 7.3.** Let G be a group and P be a subset closed under multiplication. Assume that $G = P \cup P^{-1} \cup \{1\}$ (disjoint union). Prove that $x < y$ if and only if $x^{-1}y \in P$ turns G into a left-ordered group with positive cone P.

Left-ordered groups behave nicely with respect to extensions. Let G be a group and N be a left-ordered normal subgroup of G. If $\pi\colon G \to G/N$ is the canonical map and G/N is left-ordered, then G is left-ordered with $x < y$ if and only if either $\pi(x) < \pi(y)$ or $\pi(x) = \pi(y)$ and $1 < x^{-1}y$.

Proposition 7.4. *Let G be a group and N be a normal subgroup of G. If N and G/N are left-ordered, then so is G.*

Proof. Since N and G/N are both left-ordered, there exist positive cones $P(N)$ and $P(G/N)$. Let $\pi\colon G \to G/N$ be the canonical map and

$$P(G) = \{x \in G : \pi(x) \in P(G/N) \text{ or } x \in N\}.$$

A routine calculation shows that $P(G)$ is closed under multiplication and that G decomposes as $G = P(G) \cup P(G)^{-1} \cup \{1\}$ (disjoint union). It follows from Exercise 7.3 that G is left-ordered. □

We now present a criterion for detecting left-ordered groups. We shall need a lemma.

lem:fg

Lemma 7.5. *Let G be a finitely generated group. If H is a finite-index subgroup, then H is finitely generated.*

Proof. Assume that G is generated by $\{g_1, \dots, g_m\}$. Assume that for each i there exists k such that $g_i^{-1} = g_k$. Let $\{t_1, \dots, t_n\}$ be a transversal of H in G. For $i \in \{1, \dots, n\}$ and $j \in \{1, \dots, m\}$ write

$$t_i g_j = h(i,j) t_{k(i,j)}.$$

We claim that H is generated by the $h(i,j)$. For $x \in H$, write

$$\begin{aligned} x &= g_{i_1} \cdots g_{i_s} \\ &= (t_1 g_{i_1}) g_{i_2} \cdots g_{i_s} \\ &= h(1,i_1) t_{k_1} g_{i_2} \cdots g_{i_s} \\ &= h(1,i_1) h(k_1,i_2) t_{k_2} g_{i_3} \cdots g_{i_s} \\ &= h(1,i_1) h(k_1,i_2) \cdots h(k_{s-1}, g_{i_s}) t_{k_s}, \end{aligned}$$

where $k_1, \dots, k_{s-1} \in \{1, \dots, n\}$. Since $t_{k_s} \in H$, it follows that $t_{k_s} = t_1 \in H$ and therefore $x \in H$. □

Now the theorem.

Theorem 7.6. *Let G be a finitely generated torsion-free group. If A is an abelian normal subgroup such that G/A is finite and cyclic, then G is left-ordered.*

Proof. Note that if A is trivial, then so is G. Let us assume that $A \neq \{1\}$. Since $(G:A)$ is finite, A is finitely generated by the previous lemma. We proceed by induction on the number of generators of A. Since G/A is cyclic, there exists $x \in G$ such that $G = \langle A, x\rangle$. Then $[x,A] = \langle [x,a] : a \in A\rangle$ is a normal subgroup of G

such that $A/C_A(x) \simeq [x,A]$ (because $a \mapsto [x,a]$ is a group homomorphism $A \to A$ with image $[x,A]$ and kernel $C_A(x)$). If $\pi\colon G \to G/[x,A]$ is the canonical map, then $G/[x,A] = \langle \pi(A), \pi(x)\rangle$ and thus $G/[x,A]$ is abelian, as $[\pi(x),\pi(A)] = \pi[x,A] = 1$. Moreover, $G/[x,A]$ is finitely generated, as G is finitely generated. Since $(G:A) = n$ and G is torsion-free, it follows that $1 \neq x^n \in A$. Hence $x^n \in C_A(x)$ and therefore $1 \leq \operatorname{rank} C_A(x) < \operatorname{rank} A$ (if $\operatorname{rank} C_A(x) = \operatorname{rank} A$, then $[x,A]$ would be a torsion subgroup of A, a contradiction since $x \notin A$). So

$$\operatorname{rank}[x,A] = \operatorname{rank}(A/C_A(x)) \leq \operatorname{rank} A - 1$$

and hence $\operatorname{rank}(A/[x,A]) \geq 1$. We proved that $A/[x,A]$ is infinite and hence $G/[x,A]$ is infinite.

Since $G/[x,A]$ is infinite, abelian and finitely generated, there exists a normal subgroup H of G such that $[x,A] \subseteq H$ and $G/H \simeq \mathbb{Z}$. The subgroup $B = A \cap H$ is abelian, normal in H and such that H/B is cyclic (because it is isomorphic to a subgroup of G/A). Since $\operatorname{rank} B < \operatorname{rank} A$, the inductive hypothesis implies that H is left-ordered. Hence G is left-ordered. □

Theorem 7.7 (Malcev–Neumann). *Let G be left-ordered group. Then $K[G]$ has no zero divisors and no non-trivial units.*

Proof. If $\alpha = \sum_{i=1}^n a_i g_i \in K[G]$ and $\beta = \sum_{j=1}^m b_j h_j \in K[G]$, then

$$\alpha\beta = \sum_{i=1}^n \sum_{j=1}^m a_i b_j (g_i h_j). \tag{5.1}$$ eq:producto

Without loss of generality we may assume that $a_i \neq 0$ for all i and $b_j \neq 0$ for all j. Moreover, we may assume that $g_1 < g_2 < \cdots < g_n$. Let i,j be such that

$$g_i h_j = \min\{g_i h_j : 1 \leq i \leq n, 1 \leq j \leq m\}.$$

Then $i = 1$, as $i > 1$ implies $g_1 h_j < g_i h_j$, a contradiction. Since $g_1 h_j \neq g_1 h_k$ whenever $k \neq j$, there exists a unique minimal element in the left hand side of Equality (5.1). The same argument shows that there is a unique maximal element in (5.1). Thus $\alpha\beta \neq 0$, as $a_1 b_j \neq 0$, and therefore $K[G]$ has no zero divisors. If, moreover, $n > 1$ or $m > 1$, then (5.1) contains at least two terms than cancel out and thus $\alpha\beta \neq 1$. It follows that units of $K[G]$ are trivial. □

Formanek proved that the zero divisors conjecture is true in the case of torsion-free super solvable. Brown and, independently, Farkas and Snider proved that the conjecture is true in the case of groups algebras (over fields of characteristic zero) of polycyclic-by-finite torsion-free groups. These results can be found in Chapter 13 of Passman's book [7].

§8. The braid group

Definition 8.1. Let $n \geq 1$. The **braid group** $\mathbb{B}_n$ is the group with generators $\sigma_1, \dots, \sigma_{n-1}$ and relations

$$\begin{aligned} \sigma_i \sigma_{i+1} \sigma_i &= \sigma_{i+1} \sigma_i \sigma_{i+1} && \text{if } 1 \leq i \leq n-2, \\ \sigma_i \sigma_j &= \sigma_j \sigma_i && \text{if } |i-j| > 1. \end{aligned}$$

Note that $\mathbb{B}_1 = \{1\}$ and $\mathbb{B}_2 \simeq \mathbb{Z}$. The braid group $\mathbb{B}_3$ is generated by σ_1 and σ_2 with relations $\sigma_1\sigma_2\sigma_1 = \sigma_2\sigma_1\sigma_2$.

Exercise 8.2. Prove that there exists a group homomorphism $\mathbb{B}_n \to \mathbb{S}_n$ given by $\sigma_i \mapsto (i\, i+1)$ for all $i \in \{1, \dots, n-1\}$.

Note that if $n \geq 3$, then $\mathbb{B}_n$ is a non-abelian group, as there exists a surjective group homomorphism $\mathbb{B}_n \to \mathbb{S}_n$.

Exercise 8.3. Let $n \geq 2$. Prove that the map $\deg\colon \mathbb{B}_n \to \mathbb{Z}$, $\sigma_i \mapsto 1$, is a group homomorphism. Moreover, $\ker \deg = [\mathbb{B}_n, \mathbb{B}_n]$.

The previous result implies, in particular, that $\mathbb{B}_n$ is an infinite group for all $n \geq 2$. Moreover, $\sigma_i^m \neq 1$ for all $m \in \mathbb{Z} \setminus \{0\}$ and all i.

Exercise 8.4. Prove that the center $Z(\mathbb{B}_3)$ of $\mathbb{B}_3$ is the cyclic group generated by $(\sigma_1\sigma_2\sigma_1)^2$.

More generally, one can prove that the center of $\mathbb{B}_n$ is generated by Δ_n^2, where

$$\Delta_n = (\sigma_1 \cdots \sigma_{n-1})(\sigma_1 \cdots \sigma_{n-2}) \cdots (\sigma_1\sigma_2)\sigma_1.$$

As a corollary, $\mathbb{B}_n \simeq \mathbb{B}_m$ if and only if $n = m$.

Exercise 8.5. Let $n \geq 3$. Prove that $\mathbb{B}_n$ is not bi-ordered.

One can prove that the natural map $\mathbb{B}_n \to \mathbb{B}_{n+1}$ is an injective group homomorphism, this is not an easy proof. Moreover, the diagram

$$\begin{tikzcd} \mathbb{B}_n \arrow[r, two heads] \arrow[d, hook] & \mathbb{S}_n \arrow[d, hook] \\ \mathbb{B}_{n+1} \arrow[r, two heads] & \mathbb{S}_{n+1} \end{tikzcd}$$

commutes.

xca:derivedB3 **Exercise 8.6.** Use the Reidemeister–Schreier's method to prove that $[\mathbb{B}_3, \mathbb{B}_3]$ is isomorphic to the free group in two letters.

A celebrated theorem of Dehornoy states that the braid group $\mathbb{B}_n$ is left-ordered. The proof of this fact is quite hard. However, there is a nice short proof of the fact that $\mathbb{B}_3$ is left-ordered, see [, ...].

§9. Locally indicable groups

Definition 9.1. A group G is **indicable** if there exists a non-trivial group homomorphism $G \to \mathbb{Z}$.

We know that braid groups are indicable. The free group F_n in n letters is indicable.

Definition 9.2. A group G is **locally indicable** if every non-trivial finitely generated subgroup is indicable.

Burns–Hale's theorem states that a group G is left-ordered if and only if for every non-trivial finitely generated subgroup H of G there exists a left-ordered group L and a non-trivial group homomorphism $H \to L$. As a consequence, locally indicable groups are left-ordered.

Example 9.3. Since subgroups of free groups are free, it follows that F_n is locally indicable.

Proposition 9.4. *Let $1 \to K \to G \to Q \to 1$ be an exact sequence of groups. If K and Q are locally indicable, then G is locally indicable.*

Proof. Let $g_1, \dots, g_n \in G$ and $L = \langle g_1, \dots, g_n \rangle$. Assume that $\beta(L) \neq \{1\}$. Since Q is locally indicable, there exists a non-trivial group homomorphism $\beta(L) \to \mathbb{Z}$. Then the composition $L \to Q \to \mathbb{Z}$ is then a non-trivial group homomorphism. Assume now that $\beta(L) = \{1\}$. Then there exist $k_1, \dots, k_n \in K$ such that $\alpha(k_i) = g_i$ for all $i \in \{1, \dots, n\}$. Note that $\alpha\colon \langle k_1, \dots, k_n \rangle \to L$ is a group isomorphism. Since K is locally indicable, there exits a non-trivial group homomorphism $\langle k_1, \dots, k_n \rangle \to \mathbb{Z}$. Thus the composition $L \to \langle k_1, \dots, k_n \rangle \to \mathbb{Z}$ is a non-trivial group homomorphism and hence G is locally indicable. $\square$

As a consequence of the previous proposition, if G and H are locally indicable groups and $\sigma\colon G \to \operatorname{Aut}(H)$ is a group homomorphism, then $G \rtimes_\sigma H$ is locally indicable. In particular, the direct product of locally indicable groups is locally indicable.

xca:B3_LI **Exercise 9.5.** Prove that $\mathbb{B}_3$ is locally indicable.

The previous exercise uses the fact that $[\mathbb{B}_3, \mathbb{B}_3]$ is isomorphic to the free group in two letters, see Exercise 8.6. An alternative solution to the previous fact goes as follows: $\mathbb{B}_3$ is the fundamental group of the trefoil knot and fundamental groups of knots are locally indicable.

Exercise 9.6. Prove that $\mathbb{B}_4$ is locally indicable.

The previous exercise might be harder than Exercise 9.5. One possible solution is based on using the Reidemeister–Schreier method to prove that $[\mathbb{B}_4, \mathbb{B}_4]$ is a certain semidirect product between free groups in two generators. Another solution: Let $f\colon \mathbb{B}_4 \to \mathbb{B}_3$ be the group homomorphism given by $f(\sigma_1) = f(\sigma_3) = \sigma_1$ and $f(\sigma_2) = \sigma_2$. Then $\ker f = \langle \sigma_1\sigma_3^{-1}, \sigma_2\sigma_1\sigma_3^{-1}\sigma_2^{-1} \rangle$ is isomorphic to the free group in two letters. Now use the exact sequence $1 \to \ker f \to \mathbb{B}_4 \to \mathbb{B}_3 \to 1$.

xca:relations **Exercise 9.7.** Let $n \geq 5$. Consider the elements of $\mathbb{B}_n$ given by

$$\beta_1 = \sigma_1^{-1}\sigma_2, \quad \beta_2 = \sigma_2\sigma_1^{-1}, \quad \beta_3 = \sigma_1\sigma_2\sigma_1^{-2}, \quad \beta_4 = \sigma_3\sigma_1^{-1}, \quad \beta_5 = \sigma_4\sigma_1^{-1}.$$

Prove the following relations:

1) $\beta_1\beta_5 = \beta_5\beta_2$.
2) $\beta_2\beta_5 = \beta_5\beta_3$.
3) $\beta_1\beta_3 = \beta_2$.
4) $\beta_1\beta_4\beta_3 = \beta_4\beta_2\beta_4$.
5) $\beta_4\beta_5\beta_4 = \beta_5\beta_4\beta_5$.

Exercise 9.8. Let $n \geq 5$. Prove that $\mathbb{B}_n$ is not locally indicable.

For the previous exercise one needs to show that every group homomorphism $f\colon \langle \beta_1, \dots, \beta_5 \rangle \to \mathbb{Z}$ is trivial. Hint: consider the abelianization of $\langle \beta_1, \dots, \beta_5 \rangle$.

§10. Unique product groups

Sea G un grupo y sean $A, B \subseteq G$ subconjuntos no vacíos. Diremos que un elemento $g \in G$ es un producto único en AB si $g = ab = a_1b_1$ con $a, a_1 \in A$ y $b, b_1 \in B$ implica que $a = a_1$ y $b = b_1$.

Definition 10.1. Se dice que un grupo G tiene la **propiedad del producto único** si dados dos subconjuntos $A, B \subseteq G$ finitos y no vacíos existe al menos un producto único en AB.

Proposition 10.2. *Si un grupo G es ordenable a derecha, entonces G tiene la propiedad del producto único.*

Proof. Sean $A = \{a_1, \dots, a_n\} \subseteq G$ y $B \subseteq G$ ambos finitos y no vacíos. Supongamos que $a_1 < a_2 < \cdots < a_n$. Sea $c \in B$ tal que a_1c es el mínimo del conjunto $a_1B = \{a_1b : b \in B\}$. Veamos que a_1c admite una única representación de la forma $\alpha\beta$ con $\alpha \in A$ y $\beta \in B$. Si $a_1c = ab$, entonces, como $ab = a_1c \leq a_1b$, se tiene que $a \leq a_1$ y luego $a = a_1$ y $b = c$. ∎

Exercise 10.3. Demuestre que un grupo que satisface la propiedad del producto único es libre de torsión.

The converse does not hold. Promislow's group is a celebrated counterexample.

Theorem 10.4 (Promislow). *The group $G = \langle a, b : a^{-1}b^2a = b^{-2}, b^{-1}a^2b = a^{-2} \rangle$ does not have the unique product property.*

Proof. Let

$$S=\{a^2b,b^2a,aba^{-1},(b^2a)^{-1},(ab)^{-2},b,(ab)^2x,(ab)^2,(aba)^{-1},\\ bab,b^{-1},a,aba,a^{-1}\}. \quad (5.2)$$ eq:Promislow

We use GAP and the representation $G\to\mathbf{GL}(4,\mathbb{Q})$ given by

$$a\mapsto\begin{pmatrix}1&0&0&1/2\\0&-1&0&1/2\\0&0&-1&0\\0&0&0&1\end{pmatrix},\quad b\mapsto\begin{pmatrix}-1&0&0&0\\0&1&0&1/2\\0&0&-1&1/2\\0&0&0&1\end{pmatrix}$$

to check that G does not have unique product property, as each

$$s\in S^2=\{s_1s_2:s_1,s_2\in S\}$$

admits at least two different decompositions of the form $s=xy=uv$ for $x,y,u,v\in S$. We first create the matrix representations of a and b.

```
gap> a := [[1,0,0,1/2],[0,-1,0,1/2],[0,0,-1,0],[0,0,0,1]];;
gap> b := [[-1,0,0,0],[0,1,0,1/2],[0,0,-1,1/2],[0,0,0,1]];;
```

Now we create a function that produces the set S.

```
gap> Promislow := function(x, y)
> return Set([
> x^2*y,
> y^2*x,
> x*y*Inverse(x),
> (y^2*x)^(-1),
> (x*y)^(-2),
> y,
> (x*y)^2*x,
> (x*y)^2,
> (x*y*x)^(-1),
> y*x*y,
> y^(-1),
> x,
> x*y*x,
> x^(-1)
]);
end;;
```

So the set S of (5.2) will be `Promislow(a,b)`. We now create a function that checks whether every element of a Promislow subset admits more than one representation.

```
gap> is_UPP := function(S)
> local l,x,y;
> l := [];
> for x in S do
> for y in S do
> Add(l,x*y);
> od;
> od;
```

```
> if ForAll(Collected(l), x->x[2] <> 1) then
> return false;
> else
> return fail;
> fi;
> end;;
```

Finally, we check whether every element of S admits more than one representation.

```
gap> S := Promislow(a,b);;
gap> is_UPP(S);
false
```

This completes the proof. □

There are other examples.

Definition 10.5. Se dice que un grupo G tiene la **propiedad del doble producto único** si dados dos subconjuntos $A,B \subseteq G$ finitos y no vacíos tales que $|A|+|B|>2$ existen al menos dos productos únicos en AB.

theorem:Strojnowski

Theorem 10.6 (Strojnowski). *Sea G un grupo. Las siguientes afirmaciones son equivalentes:*

1) *G tiene la propiedad del doble producto único.*
2) *Para todo subconjunto $A \subseteq G$ finito y no vacío, existe al menos un producto único en $AA = \{a_1a_2 : a_1, a_2 \in A\}$.*
3) *G tiene la propiedad del producto único.*

Proof. La implicación (1) $\implies$ (2) es trivial. Demostremos que vale (2) $\implies$ (3). Si G no tiene la propiedad del producto único, existen subconjuntos $A,B \subseteq G$ finitos y no vacíos tales que todo elemento de AB admite al menos dos representaciones. Sea $C = AB$. Todo $c \in C$ es de la forma $c = (a_1b_1)(a_2b_2)$ con $a_1,a_2 \in A$ y $b_1,b_2 \in B$. Como $a_2^{-1}b_1^{-1} \in AB$, existen $a_3 \in A \setminus \{a_2\}$ y $b_3 \in B \setminus \{b_1\}$ tales que $a_2^{-1}b_1^{-1} = a_3^{-1}b_3^{-1}$. Luego $b_1a_2 = b_3a_3$ y entonces

$$c = (a_1b_1)(a_2b_2) = (a_1b_3)(a_3b_2)$$

son dos representaciones distintas de c en AB. pues $a_2 \neq a_3$ y $b_1 \neq b_3$.

Demostremos ahora que (3) $\implies$ (1). Si G tiene la propiedad del producto único pero no tiene la propiedad del doble producto único, existen subconjuntos $A,B \subseteq G$ finitos y no vacíos con $|A|+|B|>2$ tales que en AB existe un único elemento ab con una única representación en AB. Sean $C = a^{-1}A$ y $D = Bb^{-1}$. Entonces $1 \in C \cap D$ y el elemento neutro 1 admite una única representación en CD (pues si $1 = cd$ con $c = a^{-1}a_1 \neq 1$ y $d = b_1b^{-1} \neq 1$, entonces $ab = a_1b_1$ con $a \neq a_1$ y $b \neq b_1$). Sean $E = D^{-1}C$ y $F = DC^{-1}$. Todo elemento de EF se escribe como $(d_1^{-1}c_1)(d_2c_2^{-1})$. Si $c_1 \neq 1$ o $d_2 \neq 1$ entonces $c_1d_2 = c_3d_3$ para algún $c_3 \in C \setminus \{c_1\}$ y algún $d_3 \in D \setminus \{d_2\}$. Entonces $(d_1^{-1}c_1)(d_2c_2^{-1}) = (d_1^{-1}c_3)(d_3c_2^{-1})$ son dos representaciones distintas para $(d_1^{-1}c_1)(d_2c_2^{-1})$. Si $c_2 \neq 1$ o $d_1 \neq 1$ entonces

$c_2d_1 = c_4d_4$ para algún $d_4 \in D \setminus \{d_1\}$ y algún $c_4 \in C \setminus \{c_2\}$ y entonces, como $d_1^{-1}c_2^{-1} = d_4^{-1}c_4^{-1}$, $(d_1^{-1}1)(1c_2^{-1}) = (d_4^{-1}1)(1c_4^{-1})$. Como $|C|+|D| > 2$, C o D contienen algún $c \neq 1$, y entonces $(1\cdot 1)(1\cdot 1) = (1\cdot c)(1\cdot c^{-1})$. Demostramos entonces que todo elemento de EF tiene al menos dos representaciones. □

Exercise 10.7. Demuestre que si G es un grupo que satisface la propiedad del producto único, entonces $K[G]$ tiene solamente unidades triviales.

En general es muy difícil verificar si un grupo posee la propiedad del producto único. Una propiedad similar es la de ser un grupo difuso. Si G es un grupo libre de torsión y $A \subseteq G$ es un subconjunto, diremos que A es antisimétrico si $A \cap A^{-1} \subseteq \{1\}$, donde $A^{-1} = \{a^{-1} : a \in A\}$. El conjunto de **elementos extremales** de A se define como $\Delta(A) = \{a \in A : Aa^{-1}$ es antisimétrico$\}$. Luego

$$a \in A \setminus \Delta(A) \Longleftrightarrow \text{existe } g \in G \setminus \{1\} \text{ tal que } ga \in A \text{ y } g^{-1}a \in A.$$

Definition 10.8. Un grupo G se dice **difuso** si para todo subconjunto $A \subseteq G$ tal que $2 \leq |A| < \infty$ se tiene $|\Delta(A)| \geq 2$.

Lemma 10.9. *Si G es ordenable a derecha, entonces G es difuso.*

Proof. Supongamos que $A = \{a_1, \dots, a_n\}$ y $a_1 < a_2 < \cdots < a_n$. Vamos a demostrar que $\{a_1, a_n\} \subseteq \Delta(A)$. Si $a_1 \in A \setminus \Delta(A)$, existe $g \in G \setminus \{1\}$ tal que $ga_1 \in A$ y $g^{-1}a_1 \in A$. Esto implica que $a_1 \leq ga_1$ y $a_1 \leq g^{-1}a_1$, de donde se concluye que $1 \leq g$ y $1 \leq g^{-1}$, una contradicción. De la misma forma se demuestra que $a_n \in \Delta(A)$. □

lemma:difuso=>2up

Lemma 10.10. *Si G es difuso, entonces G tiene la propiedad del doble producto único.*

Proof. Supongamos que G no tiene la propiedad del doble producto único. Existen entonces subconjuntos finitos $A, B \subseteq G$ con $|A|+|B| > 2$ tales que $C = AB$ tiene a lo sumo un producto único. Luego $|C| \geq 2$. Como G es difuso, $|\Delta(C)| \geq 2$. Si $c \in \Delta(C)$, entonces c tiene una única expresión como $c = ab$ con $a \in A$ y $b \in B$ (de lo contrario, si $c = a_0b_0 = a_1b_1$ con $a_0 \neq a_1$ y $b_0 \neq b_1$. Si $g = a_0a_1^{-1}$, entonces $g \neq 1$, $gc = a_0a_1^{-1}a_1b_1 = a_0b_1 \in C$ y además $g^{-1}c = a_1a_0^{-1}a_0b_0 = a_1b_0 \in C$. Luego $c \notin \Delta(c)$, una contradicción. □

Open problem 10.1. Find a non-diffuse group with the unique product property.

§11. Connel's theorem

When $K[G]$ is prime? Connel's theorem gives a full answer to this natural question in the case where K is of characteristic zero.

If S is a finite subset of a group G, then we define $\widehat{S} = \sum_{x \in S} x$.

lemma:sumN **Lemma 11.1.** *Let N be a finite normal subgroup of G. Then $\widehat{N}=\sum_{x\in N} x$ is central in $K[G]$ and $\widehat{N}(\widehat{N}-|N|1)=0$.*

Proof. Assume that $N=\{n_1,\dots,n_k\}$. Let $g\in G$. Since $N\to N$, $n\mapsto gng^{-1}$, is bijective,

$$g\widehat{N}g^{-1}=g(n_1+\cdots+n_k)g^{-1}=gn_1g^{-1}+\cdots+gn_kg^{-1}=\widehat{N}.$$

Since $nN=N$ if $n\in N$, it follows that $n\widehat{N}=\widehat{N}$. Thus $\widehat{N}\widehat{N}=\sum_{j=1}^{k} n_j\widehat{N}=|N|\widehat{N}$. □

Si G es un grupo, consideramos el subconjunto

$$\Delta^+(G)=\{x\in\Delta(G): x \text{ tiene orden finito}\}.$$

lem:DcharG **Lemma 11.2.** *Si G es un grupo, entonces $\Delta^+(G)$ es un subgrupo característico de G.*

Proof. Claramente $1\in\Delta^+(G)$. Sean $x,y\in\Delta^+(G)$ y sea H el subgrupo de G generado por el conjunto C formado por los finitos conjugados de x e y. Si $|x|=n$ y $|y|=m$, entonces $c^{nm}=1$ para todo $c\in C$. Como C es finito y cerrado por conjugación, el teorema de Dietzmann implica que H es finito. Luego $H\subseteq\Delta^+(G)$ y en particular $xy^{-1}\in\Delta^+(G)$. Es evidente que $\Delta^+(G)$ es un subgrupo característico pues para todo $f\in\operatorname{Aut}(G)$ se tiene que $f(x)\in\Delta^+(G)$ si $x\in\Delta^+(G)$. □

La segunda aplicación del teorema de Dietzmann es el siguiente resultado:

lem:Connel **Lemma 11.3.** *Sea G un grupo y sea $x\in\Delta^+(G)$. Existe entonces un subgrupo finito H normal en G tal que $x\in H$.*

Dejamos la demostración como ejercicio ya que el muy similar a lo que hicimos en la demostración del lema 11.2.

thm:Connel **Theorem 11.4 (Connell).** *Supongamos que el cuerpo K es de característica cero. Sea G un grupo. Las siguientes afirmaciones son equivalentes:*

1) *$K[G]$ es primo.*
2) *$Z(K[G])$ es primo.*
3) *G no tiene subgrupos finitos normales no triviales.*
4) *$\Delta^+(G)=1$.*

Proof. Demostremos que (1) $\implies$ (2). Como $Z(K[G])$ es un anillo conmutativo, probar que es primo es equivalente a probar que no existen divisores de cero no triviales. Sean $\alpha,\beta\in Z(K[G])$ tales que $\alpha\beta=0$. Sean $A=\alpha K[G]$ y $B=\beta K[G]$. Como α y β son centrales, A y B son ideales de $K[G]$. Como $AB=0$, entonces $A=\{0\}$ o $B=\{0\}$ pues $K[G]$ es primo. Luego $\alpha=0$ o $\beta=0$.

Demostremos ahora que (2) $\implies$ (3). Sea N un subgrupo normal finito. Por el lema 11.1, $\widehat{N}=\sum_{x\in N} x$ es central en $K[G]$ y $\widehat{N}(\widehat{N}-|N|1)=0$. Como $\widehat{N}\neq 0$ (pues K tiene característica cero) y $Z(K[G])$ es un dominio, $\widehat{N}=|N|1$, es decir: $N=\{1\}$.

Demostremos que (3) $\implies$ (4). Sea $x \in \Delta^+(G)$. Por el lema 11.3 sabemos que existe un subgrupo finito H normal en G que contiene a x. Como por hipótesis H es trivial, se concluye que $x = 1$.

Finalmente demostramos que (4) $\implies$ (1). Sean A y B ideales de $K[G]$ tales que $AB = 0$. Supongamos que $B \neq 0$ y sea $\beta \in B \setminus \{0\}$. Si $\alpha \in A$, entonces, como $\alpha K[G]\beta \subseteq \alpha B \subseteq AB = 0$, el lema 4.7 de Passman implica que $\pi_{\Delta(G)}(\alpha)\pi_{\Delta(G)}(\beta) = 0$. Como por hipótesis $\Delta^+(G)$ es trivial, sabemos que $\Delta(G)$ es libre de torsión y luego $\Delta(G)$ es abeliano por el lema **??**. Esto nos dice que $K[\Delta(G)]$ no tiene divisores de cero y luego $\alpha = 0$. Demostramos entonces que $B \neq 0$ implica que $A = 0$. $\square$

Theorem 11.5 (Connel). *Sea K un cuerpo de característica cero y sea G un grupo. Entonces $K[G]$ es artiniano a izquierda si y sólo si G es finito.*

Proof. Si G es finito, $K[G]$ es un álgebra de dimensión finita y luego es artiniano a izquierda. Supongamos entonces que $K[G]$ es artiniano a izquierda.

Primero observemos que si $K[G]$ es un álgebra prima, entonces por el teorema de Wedderburn $K[G]$ es simple y luego G es el grupo trivial (pues si G no es trivial, $K[G]$ no es simple ya que el ideal de aumentación es un ideal no nulo de $K[G]$).

Como $K[G]$ es artiniano a izquierda, es noetheriano a izquierda por Hopkins–Levitzky y entonces, $K[G]$ admite una serie de composición por el teorema **??**. Para demostrar el teorema procederemos por inducción en la longitud de la serie de composición de $K[G]$. Si la longitud es uno, $\{0\}$ es el único ideal de $K[G]$ y luego $K[G]$ es prima y el resultado está demostrado. Si suponemos que el resultado vale para longitud n y además $K[G]$ no es prima, entonces, por el teorema de Connel, G posee un subgrupo normal H finito y no trivial. Al considerar el morfismo canónico $K[G] \to K[G/H]$ vemos que $K[G/H]$ es artiniano a izquierda y tiene longitud $< n$. Por hipótesis inductiva, G/H es un grupo finito y luego, como H también es finito, G es finito. $\square$

Lecture 6

§12. The Yang–Baxter equation

We now briefly discuss set-theoretic solutions to the Yang–Baxter equation.

Definition 12.1. A *set-theoretic solution* to the Yang–Baxter equation (YBE) is a pair (X,r), where X is a non-empty set and $r\colon X\times X\to X\times X$ is a bijective map that satisfies

$$(r\times\mathrm{id})(\mathrm{id}\times r)(r\times\mathrm{id})=(\mathrm{id}\times r)(r\times\mathrm{id})(\mathrm{id}\times r),$$

where, if $r(x,y)=(\sigma_x(y),\tau_y(x))$, then

$$\begin{aligned} r\times\mathrm{id}\colon X\times X\times X\to X\times X\times X, &\qquad (r\times\mathrm{id})(x,y,z)=(\sigma_x(y),\tau_y(x),z),\\ \mathrm{id}\times r\colon X\times X\times X\to X\times X\times X, &\qquad (\mathrm{id}\times r)(x,y,z)=(x,\sigma_y(z),\tau_z(y)). \end{aligned}$$

The solution (X,r) is said to be *finite* if X is a finite set.

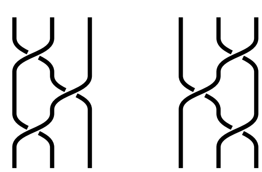

Figure 6.1 The Yang–Baxter equation. fig:braid

Example 12.2. Let X be a non-empty set. Then (X,id) is a set-theoretic solution to the YBE.

Example 12.3. Let X be a non-empty set. Then (X,r), where $r(x,y)=(y,x)$, is a set-theoretic solution to the YBE. This solution is known as the *trivial solution* over the set X.

By convention, we write

$$r(x,y) = (\sigma_x(y), \tau_y(x)).$$

lem:YB **Lemma 12.4.** *Let X be a non-empty set and $r\colon X\times X \to X\times X$ be a bijective map. Then (X,r) is a set-theoretic solution to the YBE if and only if*

$$\sigma_x\sigma_y = \sigma_{\sigma_x(y)}\sigma_{\tau_y(x)}, \quad \sigma_{\tau_{\sigma_y(z)}(x)}\tau_z(y) = \tau_{\sigma_{\tau_y(x)}(z)}\sigma_x(y), \quad \tau_z\tau_y = \tau_{\tau_z(y)}\tau_{\sigma_y(z)}$$

for all $x,y,z\in X$.

Proof. We write $r_1 = r\times\mathrm{id}$ and $r_2 = \mathrm{id}\times r$. We first compute

$$\begin{aligned} r_1r_2r_1(x,y,z) &= r_1r_2(\sigma_x(y),\tau_y(x),z) = r_1(\sigma_x(y),\sigma_{\tau_y(x)}(z),\tau_z\tau_y(x)) \\ &= \left(\sigma_{\sigma_x(y)}\sigma_{\tau_y(x)}(z), \tau_{\sigma_{\tau_y(x)}(z)}\sigma_x(y), \tau_z\tau_y(x)\right). \end{aligned}$$

Then we compute

$$\begin{aligned} r_2r_1r_2(x,y,z) &= r_2r_1(x,\sigma_y(z),\tau_z(y)) = r_2(\sigma_x\sigma_y(z),\tau_{\sigma_y(z)}(x),\tau_z(y)) \\ &= \left(\sigma_x\sigma_y(z), \sigma_{\tau_{\sigma_y(z)}(x)}\tau_z(y), \tau_{\tau_z(y)}\tau_{\sigma_y(z)}(x)\right) \end{aligned}$$

and the claim follows. □

If (X,r) is a set-theoretic solution, by definition the map $r\colon X\times X\to X\times X$ is invertible. By convention, we write

$$r^{-1}(x,y) = (\widehat{\sigma}_x(y), \widehat{\tau}_y(x)).$$

Note that this implies that

$$x = \widehat{\sigma}_{\sigma_x(y)}\tau_y(x), \quad y = \widehat{\tau}_{\tau_y(x)}\sigma_x(y).$$

It is easy to check that (X,r^{-1}) is a set-theoretic solution to the YBE. Thus Lemma 12.4 implies that the following formulas hold:

$$\widehat{\tau}_y\widehat{\tau}_x = \widehat{\tau}_{\tau_y(x)}\widehat{\tau}_{\sigma_x(y)}, \quad \widehat{\sigma}_x\widehat{\sigma_y} = \widehat{\sigma}_{\sigma_x(y)}\widehat{\sigma}_{\tau_y(x)}.$$

Example 12.5. Let $X=\{1,2,3,4\}$ and $r(x,y) = (\sigma_x(y),\tau_y(x))$, where

$$\begin{array}{llll} \sigma_1 = (132), & \sigma_2 = (124), & \sigma_3 = (143), & \sigma_4 = (234), \\ \tau_1 = (12)(34), & \tau_2 = (12)(34), & \tau_3 = (12)(34), & \tau_4 = (12)(34). \end{array}$$

Then r is invertible with $r^{-1}(x,y) = (\widehat{\sigma}_x(y),\widehat{\tau}_y(x))$ given by

$$\begin{array}{llll} \widehat{\sigma}_1 = (12)(34), & \widehat{\sigma}_2 = (12)(34), & \widehat{\sigma}_3 = (12)(34), & \widehat{\sigma}_4 = (12)(34), \\ \widehat{\tau}_1 = (142), & \widehat{\tau}_2 = (123), & \widehat{\tau}_3 = (243), & \widehat{\tau}_4 = (134). \end{array}$$

Definition 12.6. A *homomorphism* between the set-theoretic solutions (X,r) and (Y,s) is a map $f\colon X\to Y$ such that the diagram

$$\begin{tikzcd} X\times X \arrow[r, "r"] \arrow[d, "f\times f"'] & X\times X \arrow[d, "f\times f"] \\ Y\times Y \arrow[r, "s"'] & Y\times Y \end{tikzcd}$$

is commutative, that is $s(f\times f)=(f\times f)r$. An *isomorphism* of solutions is a bijective homomorphism of solutions.

Since we are interested in studying the combinatorics behind set-theoretic solutions to the YBE, it makes sense to study the following family of solutions.

Definition 12.7. We say that a set-theoretic solution (X,r) to the YBE is *non-degenerate* if the maps σ_x and τ_x are permutations of X.

By convention, a *solution* we will mean a non-degenerate **set-theoretic** solution to the YBE.

lem:LYZ **Lemma 12.8.** *Let (X,r) be a solution.*

1) *Given $x,u\in X$, there exist unique $y,v\in X$ such that $r(x,y)=(u,v)$.*
2) *Given $y,v\in X$, there exist unique $x,u\in X$ such that $r(x,y)=(u,v)$.*

Proof. For the first claim take $y=\sigma_x^{-1}(u)$ and $v=\tau_y(x)$. For the second, $x=\tau_y^{-1}(v)$ and $u=\sigma_x(y)$. □

The bijectivity of r means that any row determines the whole square. Lemma 12.8 means that any column also determines the whole square, see Figure 6.2.

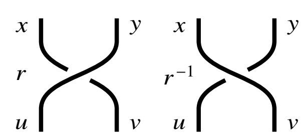

Figure 6.2 Any row or column determines the whole square. fig:braid

Example 12.9. If the map $(x,y)\mapsto(\sigma_x(y),\tau_y(x))$ satisfies the Yang–Baxter equation, then so does $(x,y)\mapsto(\tau_x(y),\sigma_y(x))$.

exa:Lyubashenko **Example 12.10.** Let X be a non-empty set and σ and τ be bijections on X such that $\sigma\circ\tau=\tau\circ\sigma$. Then (X,r), where $r(x,y)=(\sigma(y),\tau(x))$, is a non-degenerate solution. This is known as the *permutation solution* associated with permutations σ and τ.

exa:Venkov **Example 12.11.** Let G be a group. Then (G,r), where $r(x,y)=(xyx^{-1},x)$, is a solution.

Example 12.12. Let $n \geq 2$ and $X = \mathbb{Z}/(n)$ be the ring of integers modulo n. Prove that the map $r(x,y) = (2x-y,x)$ satisfies the the set-theoretic YBE.

The following result was proved by Lu, Yan and Zhu.

thm:LYZ

Theorem 12.13 (Lu–Yan–Zhu). *Let G be a group, $\xi\colon G\times G\to G$, $\xi(x,y) = x \triangleright y$, be a left action of the group G on itself as a set and $\eta\colon G\times G \to G$, $\eta(x,y) = x \triangleleft y$, be a right action of the group G on itself as a set. If the compatibility condition*

$$uv = (u \triangleright v)(u \triangleleft v)$$

holds for all $u, v \in G$, then the pair (G,r), where

$$r\colon G\times G \to G\times G, \quad r(u,v) = (u\triangleright v, u\triangleleft v)$$

is a solution. Moreover, if $r(x,y) = (u,v)$, then

$$r(x^{-1},y^{-1}) = (u^{-1},v^{-1}), \quad r(x^{-1},u) = (y,v^{-1}), \quad r(v,y^{-1}) = (u^{-1},x).$$

Proof. We write $r_1 = r\times \mathrm{id}$ and $r_2 = \mathrm{id}\times r$. Let

$$r_1r_2r_1(u,v,w) = (u_1,v_1,w_1), \quad r_2r_1r_2(u,v,w) = (u_2,v_2,w_2).$$

The compatibility condition implies that $u_1v_1w_1 = u_2v_2w_2$. So we need to prove that $u_1 = u_2$ and $w_1 = w_2$. We note that

$$\begin{aligned} u_1 &= (u\triangleright v)\triangleright((u\triangleleft v)\triangleright w), & w_1 &= (u\triangleleft v)\triangleleft w,\\ u_2 &= u\triangleright(v\triangleright w), & w_2 &= (u\triangleleft(v\triangleright w))\triangleleft(v\triangleleft w).\end{aligned}$$

Using the compatibility condition and the fact that ξ is a left action,

$$u_1 = ((u\triangleright v)(u\triangleleft v))\triangleright w = (uv)\triangleright w = u\triangleright(v\triangleright w) = u_2.$$

Similarly, since η is a right action,

$$w_2 = u\triangleleft((v\triangleright w)(v\triangleleft w)) = u\triangleleft(vw) = (u\triangleleft v)\triangleleft w = w_1.$$

To prove that r is invertible we proceed as follows. Write $r(u,v) = (x,y)$, thus $u\triangleright v = x$, $u\triangleleft v = y$ and $uv = xy$. Since

$$(y\triangleright v^{-1})u = (y\triangleright v^{-1})(y\triangleleft v^{-1}) = yv^{-1} = x^{-1}u,$$

it follows that $y\triangleright v^{-1} = x^{-1}$, i.e. $v^{-1} = y^{-1}\triangleright x^{-1}$. Similarly,

$$v(u^{-1}\triangleleft x) = (u^{-1}\triangleright x)(u^{-1}\triangleleft x) = u^{-1}x = vy^{-1}$$

implies that $u^{-1} = y^{-1}\triangleleft x^{-1}$. Clearly $r^{-1} = \zeta(i\times i)r(i\times i)\zeta$, is the inverse of r, where $\zeta(x,y) = (y,x)$ and $i(x) = x^{-1}$. $\square$

Proposition 12.14. *Under the assumptions of Theorem 12.13, if* $r(x,y)=(u,v)$*, then*

$$r(v^{-1},u^{-1})=(y^{-1},x^{-1}),\quad r(x^{-1},u)=(y,v^{-1}),\quad r(v,y^{-1})=(u^{-1},x).$$

Proof. In the proof of Theorem 12.13 we found that the inverse of the map r is given by $r^{-1}=\zeta(i\times i)r(i\times i)\zeta$, where $\zeta(x,y)=(y,x)$ and $i(x)=x^{-1}$. Hence

$$r^{-1}(y^{-1},x^{-1})=\zeta(i\times i)r(i\times i)\zeta(y^{-1},x^{-1})=\zeta(i\times i)r(x,y)=(v^{-1},u^{-1}).$$

It follows that $r(v^{-1},u^{-1})=(y^{-1},x^{-1})$. To prove the equality $r(x^{-1},u)=(y,v^{-1})$ we proceed as follows. Since $r(x,y)=(u,v)$, it follows that $x\triangleright y=u$. Then $x^{-1}\triangleright u=y$ and hence $r(x^{-1},u)=(y,z)$ for some $z\in G$. Since $xy=uv$ and $x^{-1}u=yz$, it immediately follows that $yt=yv^{-1}$. Then $z=v^{-1}$. Similarly one proves $r(v,y^{-1})=(u^{-1},x)$. □

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