Mini-course on GAP – Lecture 4

Leandro Vendramin

Universidad de Buenos Aires

Dalhousie University, Halifax
January 2020

CONICET

Group homomorphisms

Now we work with group homomorphisms. There are several ways to construct group homomorphisms.

The function `GroupHomomorphismByImages` returns the group homomorphism constructed from a list of generators of the domain and the value of the image at each generator. Properties of group homomorphisms can be studied with `Image`, `IsInjective`, `IsSurjective`, `Kernel`, `PreImage`, `PreImages`, etc.

Group homomorphisms

The map $\mathrm{Sym}_4 \to \mathrm{Sym}_3$ that maps each transposition of Sym_4 into (12) extends to a group homomorphism f. This homomorphism f is not injective and it is not surjective.

```
gap> S4 := SymmetricGroup(4);;
gap> S3 := SymmetricGroup(3);;
gap> f := GroupHomomorphismByImages(S4, S3,\
> [(1,2),(1,3),(1,4),(2,3),(2,4),(3,4)],\
> [(1,2),(1,2),(1,2),(1,2),(1,2),(1,2)]);;
gap> Size(Kernel(f));
12
gap> IsInjective(f);
false
gap> Size(Image(f));
2
gap> (1,2,3) in Image(f);
false
```

Group homomorphisms

To construct the canonical canonical map $G \to G/K$ one uses the function `NaturalHomomorphismByNormalSubgroup`. Let us construct $C_{12} = \langle g : g^{12} = 1 \rangle$ as a group of permutations, the subgroup $K = \langle g^6 \rangle$ and the quotient C_{12}/K. We also construct the canonical (surjective) map $C_{12} \to C_{12}/K$:

```
gap> g := (1,2,3,4,5,6,7,8,9,10,11,12);;
gap> C12 := Group(g);;
gap> K := Subgroup(C12, [g^6]);;
gap> f := NaturalHomomorphism\
> ByNormalSubgroup(C12, K);
[ (1,2,3,4,5,6,7,8,9,10,11,12) ] -> [ f1 ]
gap> Image(f, g^6);
<identity> of ...
```

An exercise on group homomorphisms

Verify the correspondence theorem for the groups G and G/K defined in the previous slide: subgroups of G containing K are in bijective correspondence with subgroups of G/K.

Group homomorphisms

The function `AutomorphismGroup` computes the automorphism group of a finite group. If G is a group, the automorphisms of G of the form $x \mapsto g^{-1}xg$, where $g \in G$, are the inner automorphisms of G. The function `IsInnerAutomorphism` checks whether a given automorphism is inner.

Group homomorphisms

Let us check that Aut(Sym_3) is a non-abelian group of six elements:

```
gap> aut := AutomorphismGroup(SymmetricGroup(3));
<group of size 6 with 2 generators>
gap> IsAbelian(aut);
false
```

Group homomorphisms

For $n \in \{2,3,4,5\}$ each automorphism of Sym_n is inner. Here is the code:

```
gap> for n in [2..5] do
> G := SymmetricGroup(n);;
> if ForAll(AutomorphismGroup(G),\
> x->IsInnerAutomorphism(x)) then
> Print("Each automorfism of S",\
> n, " is inner.\n");
> fi;
> od;
Each automorphism of S2 is inner.
Each automorphism of S3 is inner.
Each automorphism of S4 is inner.
Each automorphism of S5 is inner.
```

Group homomorphisms

It is known that in Sym_6 there are non-inner automorphisms:

```
gap> S6 := SymmetricGroup(6);;
gap> Number(AutomorphismGroup(S6),\
> x->IsInnerAutomorphism(x)=false);;
720
```

The automorphism of Sym_6 given by $(123456) \mapsto (162)(35)$ and $(12) \mapsto (12)(34)(56)$ is not inner.

```
gap> f := First(AutomorphismGroup(S6),\
> x->IsInnerAutomorphism(x)=false);
[ (1,2,3,4,5,6), (1,2) ] ->
[ (1,6,2)(3,5), (1,2)(3,4)(5,6) ]
```

Group homomorphisms

Let us compute the image of this homomorphism in some transpositions:

```
gap> (1,2)^f;
(1,2)(3,4)(5,6)
gap> (2,3)^f;
(1,6)(2,3)(4,5)
```

Alternatively:

```
gap> Image(f, (1,2));
(1,2)(3,4)(5,6)
gap> Image(f, (2,3));
(1,6)(2,3)(4,5)
```

Group homomorphisms

With `AllHomomorphisms` one constructs the set of group homomorphisms between two given groups. `AllEndomorphisms` computes all endomorphisms.

There are ten endomorphisms of Sym_3.

```
gap> S3 := SymmetricGroup(3);;
gap> Size(AllEndomorphisms(S3));
10
```

Group homomorphisms

The center of $C_2 \times \mathrm{Sym}_3$ is not stable under endomorphisms of $C_2 \times \mathrm{Sym}_3$. We see that $Z(C_2 \times \mathrm{Sym}_3) = \{\mathrm{id}, (12)\}$ and that there exists at least one endomorphism of $C_2 \times \mathrm{Sym}_3$ that permutes the non-trivial element of the center:

```
gap> C2 := CyclicGroup(IsPermGroup, 2);;
gap> S3 := SymmetricGroup(3);;
gap> C2xS3 := DirectProduct(C2, S3);;
gap> Center(C2xS3);
Group([ (1,2) ])
gap> ForAll(AllEndomorphisms(C2xS3),\
> f->Image(f,(1,2)) in [(), (1,2)]);
false
```

Group homomorphisms

To prove that $\mathrm{Aut}(\mathrm{Sym}_6)/\mathrm{Inn}(\mathrm{Sym}_6) \simeq C_2$ we use the function `InnerAutomorphismsAutomorphismGroup`, which returns the inner automorphism group of a given group.

```
gap> S6 := SymmetricGroup(6);;
gap> A := AutomorphismGroup(S6);;
gap> Size(A);
1440
gap> I := InnerAutomorphismsAutomorphismGroup(A);;
gap> Order(A/I);
2
```

SmallGroups

GAP contains a database with all groups of certain small orders. The groups are sorted by their orders and they are listed up to isomorphism. This database is part of a library named `SmallGroups`. It contains the following groups:

- those of order ≤ 2000 except order 1024,
- those of cube-free order ≤ 50000,
- those of order p^7 for $p \in \{3, 5, 7, 11\}$,
- those of order p^n for $n \leq 6$ and all primes p,
- those of order $q^n p$ for q^n dividing 2^8, 3^6, 5^5 or 7^4 and all primes p with $p \neq q$,
- those of square-free order.

The library was written by H, Besche, B. Eick and E. O'Brien.

SmallGroups

Do you want to see what GAP knows about groups of order twelve?
Just use the function `SmallGroupsInformation`.

SmallGroups

There exist non-abelian groups of odd order and that the smallest of this group has order 21:

```
gap> First(AllSmallGroups(Size, [1, 3..21]),\
> x->not IsAbelian(x));;
gap> Size(last);
21
```

SmallGroups

There are no simple groups of order 84. We use the filter `IsSimple` with the function `AllSmallGroups`:

```
gap> AllSmallGroups(Size, 84, IsSimple, true);
[  ]
```

SmallGroups

With the function `StructureDescription` one explores the structure of a given group. The function returns a short string which gives some insight into the structure of the group. Let us see how the groups of order twelve look like:

```
gap> List(AllSmallGroups(Size, 12),\
> StructureDescription);
[ "C3 : C4", "C12", "A4", "D12", "C6 x C2" ]
```

The group `C3 : C4` denotes the semidirect product $C_3 \rtimes C_4$.

SmallGroups

The string returned by `StructureDescription` is not an isomorphism invariant: non-isomorphic groups can have the same string value and two isomorphic groups in different representations can produce different strings.

SmallGroups

There are two groups of order 20 that can be written as a semidirect product $C_5 \rtimes C_4$. `StructureDescription` will not distinguish such groups:

```
gap> List(AllSmallGroups(Size, 20),\
> StructureDescription);
[ "C5 : C4", "C20", "C5 : C4", "D20", "C10 x C2" ]
```

SmallGroups

To identify groups in the database `SmallGroups` one uses the function `IdGroup`.

```
gap> IdGroup(SymmetricGroup(3));
[ 6, 1 ]
gap> IdGroup(SymmetricGroup(4));
[ 24, 12 ]
gap> IdGroup(AlternatingGroup(4));
[ 12, 3 ]
gap> IdGroup(DihedralGroup(8));
[ 8, 3 ]
gap> IdGroup(QuaternionGroup(8));
[ 8, 4 ]
```

SmallGroups

Lam and Leep[1] proved that each index-two subgroup of Aut(Sym_6) is isomorphic either to Sym_6, $\mathbf{PGL}_2(9)$ or to the Mathieu group M_{10}. Let us check this claim using the function `IdGroup`:

```
gap> autS6 := AutomorphismGroup(SymmetricGroup(6));;
gap> lst := SubgroupsOfIndexTwo(autS6);;
gap> List(lst, IdGroup);
[ [ 720, 764 ], [ 720, 763 ], [ 720, 765 ] ]
gap> IdGroup(PGL(2,9));
[ 720, 764 ]
gap> IdGroup(MathieuGroup(10));
[ 720, 765 ]
gap> IdGroup(SymmetricGroup(6));
[ 720, 763 ]
```

---

[1] Exposition. Math. 11 (1993), no. 4, 289–308

Guralnick's theorem on commutators

Guralnick[2] proved without using computers that the smallest group G such that $[G, G] \neq \{[x, y] : x, y \in G\}$ has order 96. Here is the proof:

```
gap> G := First(AllSmallGroups(Size, [1..100]),\
> x->Order(DerivedSubgroup(x))<>Size(\
> Set(List(Cartesian(x,x), Comm))));;
gap> Order(G);
96
```

---

[2] Adv. in Math., 45(3):319–330, 1982

Guralnick's theorem on commutators

With `IdGroup` (or with `IsomorphismGroups`) we can check that

$$G \simeq \langle (135)(246)(7\,11\,9)(8\,12\,10), (39\,4\,10)(58)(67)(11\,12) \rangle.$$

```
gap> IdGroup(G);
[ 96, 3 ]
gap> a := (1,3,5)(2,4,6)(7,11,9)(8,12,10);;
gap> b := (3,9,4,10)(5,8)(6,7)(11,12);;
gap> IdGroup(Group([a,b]));
[ 96, 3 ]
```

Okay, but how did we find this isomorphism?

Guralnick's theorem on commutators

We have our group G. We use the function `IsomorphismPermGroup` to construct a faithful representation of G as a permutation group. With `SmallerDegreePermutationRepresentation` we construct (if possible) an isomorphic permutation group of smaller degree. Be aware that this new degree may not be minimal. After some attempts, we obtain an isomorphic copy of G inside Sym_{12}. To construct a set of generators we then use `SmallGeneratingSet`. Again, be aware that this set may not be minimal.

Can you try this yourself? Be aware that maybe you will not get the exact same result.

A theorem of Navarro

For a finite group G let $\mathrm{cs}(G)$ denote the set of sizes of the conjugacy classes of G, that is

$$\mathrm{cs}(G) = \{|g^G| : g \in G\}.$$

For example: $\mathrm{cs}(\mathrm{Sym}_3) = \{1, 2, 3\}$ and $cs(\mathbf{SL}_2(3)) = \{1, 4, 6\}$.

```
gap> cs := function(group)
> return Set(List(ConjugacyClasses(group), Size));
> end;
function( group ) ... end
gap> cs(SymmetricGroup(3));
[ 1, 2, 3 ]
gap> cs(SL(2,3));
[ 1, 4, 6 ]
```

A theorem of Navarro

We will write $G_{n,k}$ to denote the k-th group of size n in the database, thus $G_{n,k}$ is a group with `IdGroup` equal to `[ n, k ]`.

A theorem of Navarro

Navarro[3] proved that there exist finite groups G and H such that G is solvable, H is not solvable and $\mathrm{cs}(G) = \mathrm{cs}(H)$. This answers a question of Brauer.

Let $G = G_{240,13} \times G_{960,1019}$ and $H = G_{960,239} \times G_{480,959}$. Then G is solvable, H is not solvable and $\mathrm{cs}(G) = \mathrm{cs}(H)$.

```
gap> U := SmallGroup(960,239);;
gap> V := SmallGroup(480,959);;
gap> L := SmallGroup(960,1019);;
gap> K := SmallGroup(240,13);;
gap> UxV := DirectProduct(U,V);;
gap> KxL := DirectProduct(K,L);;
gap> IsSolvable(UxV);
false
gap> IsSolvable(KxL);
true
```

---

[3] J. Algebra 411 (2014), 47–49.

A theorem of Navarro

One could try to compute $\mathrm{cs}(U \times V)$ directly. However, this calculation seems to be hard. The trick is to use that

$$\mathrm{cs}(U \times V) = \{nm : n \in \mathrm{cs}(U), m \in \mathrm{cs}(V)\}.$$

```
gap> cs(KxL)=Set(List(Cartesian(cs(U),cs(V)),\
> x->x[1]*x[2]));
true
```

Another theorem of Navarro

Navarro proved that there exist finite groups G and H such that G is nilpotent, $Z(H) = 1$ and $\mathrm{cs}(G) = \mathrm{cs}(H)$. This answers another question of Brauer.

The groups are $G = \mathbb{D}_8 \times G_{243,26}$ and $H = G_{486,36}$.

```
gap> K := DihedralGroup(8);;
gap> L := SmallGroup(243,26);;
gap> H := SmallGroup(486,36);;
gap> IsTrivial(Center(H));
true
gap> G := DirectProduct(K,L);;
gap> cs(G)=cs(H);
true
gap> IsNilpotent(G);
true
```

Finitely presented groups

Let us start working with free groups. The function `FreeGroup` construct the free group in a finite number of generators. We create the free group F_2 in two generators and we create some random elements with the function `Random`:

```
gap> f := FreeGroup(2);
<free group on the generators [ f1, f2 ]>
gap> f.1^2;
f1^2
gap> f.1^2*f.1;
f1^3
gap> f.1*f.1^(-1);
<identity ...>
gap> Random(f);
f1^-3
```

Finitely presented groups

The function `Length` can be used to compute the length of words in a free group. In this example we create 10000 random elements in F_2 and compute their lengths.

```
gap> f := FreeGroup(2);;
gap> Collected(List(List([1..10000],\
> x->Random(f)), Length));
[ [ 0, 2270 ], [ 1, 1044 ], [ 2, 1113 ],
  [ 3, 986 ], [ 4, 874 ], [ 5, 737 ],
  [ 6, 642 ], [ 7, 500 ], [ 8, 432 ],
  [ 9, 329 ], [ 10, 248 ], [ 11, 189 ],
  [ 12, 152 ], [ 13, 119 ], [ 14, 93 ],
  [ 15, 68 ], [ 16, 57 ], [ 17, 34 ],
  [ 18, 30 ], [ 19, 23 ], [ 20, 19 ],
  [ 21, 16 ], [ 22, 8 ], [ 23, 3 ], [ 24, 4 ],
  [ 25, 4 ], [ 26, 2 ], [ 27, 2 ], [ 28, 1 ],
  [ 31, 1 ] ]
```

Finitely presented groups

Some of the functions we used before can also be used in free groups. Examples of these functions are `Normalizer`, `RepresentativeAction`, `IsConjugate`, `Intersection`, `IsSubgroup`, `Subgroup`.

The free group F_2

Here we perform some elementary calculations in F_2, the free group with generators a and b.

```
gap> f := FreeGroup("a", "b");;
gap> a := f.1;;
gap> b := f.2;;
gap> Random(f);
b^-1*a^-5
gap> Centralizer(f, a);
Group([ a ])
gap> Index(f, Centralizer(f, a));
infinity
gap> Subgroup(f, [a,b]);
Group([ a, b ])
gap> Order(Subgroup(f, [a,b]));
infinity
```

The free group F_2

We compute the automorphism group of F_2.

```
gap> AutomorphismGroup(f);
<group of size infinity with 3 generators>
gap> GeneratorsOfGroup(AutomorphismGroup(f));
[ [ a, b ] -> [ a^-1, b ],
  [ a, b ] -> [ b, a ],
  [ a, b ] -> [ a*b, b ] ]
```

The free group F_2

We now check that the subgroup S generated by a^2, b and aba^{-1} has index two in F_2. We compute $\mathrm{Aut}(S)$ and check that it is not a free group:

```
gap> S := Subgroup(f, [a^2, b, a*b*a^(-1)]);
Group([ a^2, b, a*b*a^-1 ])
gap> Index(f, S);
2
gap> A := AutomorphismGroup(S);
<group of size infinity with 3 generators>
gap> IsFreeGroup(A);
false
```

Finitely presented groups

The group

$$G = \langle a, b, c : ba = ac, ca = ab, bc = ca \rangle$$

has an infinite number of elements and its center has finite index.

```
gap> f := FreeGroup(3);;
gap> a := f.1;;
gap> b := f.2;;
gap> c := f.3;;
gap> gr := f/[a^b*Inverse(c),\
> a^c*Inverse(b),\
> b^c*Inverse(a)];;
gap> Order(gr);
infinity
gap> Center(gr);
Group([ f2^2 ])
gap> StructureDescription(gr/Center(gr));
"S3"
```

Finitely presented groups

The abelianization of G is isomorphic to $\mathbb{Z}$.

```
gap> gr/DerivedSubgroup(gr);
Group([ f1*f2^-1*f3, f3, f2^-1*f3 ])
gap> AbelianInvariants(gr/DerivedSubgroup(gr));
[ 0 ]
```

Since the index $(G : Z(G))$ is finite, a theorem of Schur implies that the commutator subgroup $[G, G]$ is a finite group. However, GAP cannot prove this!

A theorem of Coxeter

Let $n \geq 3$ and $p \geq 2$ be integers. Coxeter[4] proved that the group generated by $\sigma_1, \ldots, \sigma_{n-1}$ and

$$\begin{aligned} &\sigma_i\sigma_{i+1}\sigma_i = \sigma_{i+1}\sigma_i\sigma_{i+1} && \text{if } i \in \{1, \ldots, n-2\}, \\ &\sigma_i\sigma_j = \sigma_j\sigma_i && \text{if } |i-j| \geq 2, \\ &\sigma_i^p = 1 && \text{if } i \in \{1, \ldots, n-1\}\rangle, \end{aligned}$$

is finite if and only if $(p-2)(n-2) < 4$.

---

[4] Kaleidoscopes. Selected writings of H. S. M. Coxeter.

A theorem of Coxeter

We study the case $n = 3$. Let

$$G = \langle a, b : aba = bab,\ a^p = b^p = 1 \rangle.$$

We claim that

$$G \simeq \begin{cases} \mathrm{Sym}_3 & \text{if } p = 2, \\ \mathbf{SL}_2(3) & \text{if } p = 3, \\ \mathbf{SL}_2(3) \rtimes C_4 & \text{if } p = 4, \\ \mathbf{SL}_2(3) \times C_5 & \text{if } p = 5 : \end{cases}$$

A theorem of Coxeter

Here is the proof:

```
gap> f := FreeGroup(2);;
gap> a := f.1;;
gap> b := f.2;;
gap> p := 2;;
gap> while p-2<4 do
> G := f/[a*b*a*Inverse(b*a*b), a^p, b^p];;
> Display(StructureDescription(G));
> p := p+1;
> od;
S3
SL(2,3)
SL(2,3) : C4
C5 x SL(2,5)
```

A theorem of von Dyck

For $l, m, n \in \mathbb{N}$, we define the von Dyck group (or triangular group) of type (l, m, n) as the group

$$G(l, m, n) = \langle a, b : a^l = b^m = (ab)^n = 1 \rangle.$$

It is known that $G(l, m, n)$ is finite if and only if

$$\frac{1}{l} + \frac{1}{m} + \frac{1}{n} > 1.$$

We claim that

$$G(2, 3, 3) \simeq \mathrm{Alt}_4, \quad G(2, 3, 4) \simeq \mathrm{Sym}_4, \quad G(2, 3, 5) \simeq \mathrm{Alt}_5.$$

A theorem of von Dyck

Here is the proof:

```
gap> f := FreeGroup(2);;
gap> a := f.1;;
gap> b := f.2;;
gap> StructureDescription(f/[a^2,b^3,(a*b)^3]);
"A4"
gap> StructureDescription(f/[a^2,b^3,(a*b)^4]);
"S4"
gap> StructureDescription(f/[a^2,b^3,(a*b)^5]);
"A5"
```

Some presentations of the trivial group

This example is taken from Pierre de la Harpe's book[5]. The group

$$\langle a, b, c : a^3 = b^3 = c^4 = 1,\ ac = ca^{-1},\ aba^{-1} = bcb^{-1} \rangle$$

is trivial.

```
gap> f := FreeGroup(3);;
gap> a := f.1;;
gap> b := f.2;;
gap> c := f.3;;
gap> G := f/[a^3, b^3, c^4, c^(-1)*a*c*a, \
> a*b*a^(-1)*b*c^(-1)*b^(-1)];;
gap> IsTrivial(G);
true
```

---

[5] Topics in geometric group theory.

Some presentations of the trivial group

Miller and Schupp[6] proved that for $n \in \mathbb{N}$,

$$\langle a, b : a^{-1} b^n a = b^{n+1},\ a = a^{i_1} b^{j_1} a^{i_2} b^{j_2} \cdots a^{i_k} b^{j_k} \rangle,$$

is trivial if $i_1 + i_2 + \cdots i_k = 0$. As an example let us see that

$$\langle a, b : a^{-1} b^2 a = b^3,\ a = a^{-1} ba \rangle$$

is the trivial group:

```
gap> f := FreeGroup(2);;
gap> a := f.1;;
gap> b := f.2;;
gap> G := f/[a^(-1)*b^2*a*b^(-3),a*(a^(-1)*b*a)];;
gap> IsTrivial(G);
true
```

---

[6] Groups, languages and geometry, 113–115, Contemp. Math., 250, 1999.

Burnside problem

For each $n \geq 2$ the Burnside group $B(2, n)$ is defined as the group

$$B(2, n) = \langle a, b : w^n = 1 \text{ for all word } w \text{ in the letters } a \text{ and } b \rangle.$$

Is the group $B(2, n)$ finite?

The particular case $B(2, 5)$ remains open.

Burnside problem: A theorem of Burnside

We prove that the group $B(2,3)$ is a finite group of order ≤ 27. Let F be the free group of rank two. We divide F by the normal subgroup generated by $\{w_1^3, \dots, w_{10000}^3\}$, where $w_1, \dots, w_{10000}$ are some randomly chosen words of F. The following code shows that $B(2,3)$ is finite:

```
gap> f := FreeGroup(2);;
gap> rels := Set(List([1..10000],\
> x->Random(f)^3));;
gap> G := f/rels;;
gap> Order(G);
27
```

Burnside problem: A theorem of Sanov

It is known that $B(2,4)$ is a finite group. Here we present here a computational proof. We use the same trick as before to prove that $B(2,4)$ is finite and has order ≤ 4096:

```
gap> f := FreeGroup(2);;
gap> rels := Set(List([1..10000],\
> x->Random(f)^4));;
gap> B24 := f/rels;;
gap> Order(B24);
4096
```

A problem by Djokovic

In 1970 Djokovic posed in the *Canadian Mathematical Bulletin* the following problem: Prove that the alternating groups Alt_n for $n \geq 5$ and $n \neq 8$ can be generated by three conjugate involutions. In his solution, published in the *Canadian Mathematical Bulletin* in 1972, he writes that he does not know what happens if $n = 8$.

A problem by Djokovic

We write a function that finds all possible conjugate involutions that generate the whole group. The code written will be is pretty naive, one just runs (in a clever way) over all subsets of three conjugate involutions and checks whether these three permutation generate the whole group.

A problem by Djokovic

```
gap> Djokovic := function(n)
> local gr, cc, c, t, l;
> l := [];
> gr := AlternatingGroup(n);;
> cc := ConjugacyClasses(gr);;
> for c in cc do
> if Order(Representative(c))=2 then
> for t in IteratorOfCombinations(AsList(c), 3) do
> if Size(Subgroup(gr, t))=Size(gr) then
> Add(l, t);
> fi;
> od;
> fi;
> od;
> return l;
> end;
function( n ) ... end
```

A problem by Djokovic

We see that Alt_5 can be generated by the involutions (23)(45), (24)(35) and (12)(45):

```
gap> Djokovic(5)[1];
[ (2,3)(4,5), (2,4)(3,5), (1,2)(4,5) ]
```

There are 380 generating sets that fit into Djokovic assumtions:

```
gap> Size(Djokovic(5));
380
```

A problem by Djokovic

Finally we prove we cannot find three conjugate involutions of Alt_8 that generate the whole Alt_8. The calculation is straightforward but requires several minutes to be performed:

```
gap> Djokovic(8);
[  ]
```

A theorem of Dixon

The commuting probability of a finite group G is defined as the probability that a randomly chosen pair of elements of G commute, and it is thus equal to $k(G)/|G|$. The following function computes the commuting probability of a given finite group.

```
gap> p := x->NrConjugacyClasses(x)/Order(x);
function( x ) ... end
```

Dixon observed that the commuting probability of a finite non-abelian simple group is $\leq 1/12$. This bound is attained for the alternating simple group Alt_5.

```
gap> p(AlternatingGroup(5));
1/12
```

A theorem of Dixon

One can find Dixon's proof in a 1973 volume of the *Canadian Mathematical Bulletin*. The proof we present here was found by Iván Sadofschi Costa.

We first assume that the commuting probability of G is $> 1/12$. Since G is a non-abelian simple group, the identity is the only central element. Let us assume first that there is a conjugacy class of G of size m, where m is such that $1 < m \leq 12$. Then G is a transitive subgroup of Sym_m.

A transitive group of degree n is a subgroup of Sym_n that acts transitively on $\{1, \ldots, n\}$; in this case, n is the degree of the transitive group. GAP contains a database with all transitive groups of low degree.

Now the problem is easy: we show that there are no non-abelian simple groups that act transitively on sets of size $m \in \{2, \ldots, 12\}$ with commuting probability $> 1/12$.

A theorem of Dixon

```
gap> l := AllTransitiveGroups(NrMovedPoints,\
> [2..12], \
> IsAbelian, false, \
> IsSimple, true);;
gap> List(l, p);
[ 1/12, 1/12, 7/360, 1/28, 1/280, 1/28, 1/1440,
  1/56, 1/10080, 1/12, 7/360, 1/75600, 2/165,
  1/792, 31/19958400, 1/12, 2/165, 1/792, 1/6336,
  43/239500800 ]
gap> ForAny(l, x->p(x)>1/12);
false
```

A theorem of Dixon

Now assume that all non-trivial conjugacy class of G have at least 13 elements. Then the class equation implies that

$$|G| \geq \frac{13}{12}|G| - 12,$$

and therefore $|G| \leq 144$. Thus one needs to check what happens with groups of order ≤ 144. But we know that the only non-abelian simple group of size ≤ 144 is the alternating simple group Alt_5.

```
gap> AllGroups(Size, [2..144], \
> IsAbelian, false, \
> IsSimple, true);
[ Alt( [ 1 .. 5 ] ) ]
```

An exercise on primitive groups

A subgroup G of Sym_n is called primitive of degree n if it is transitive and preserves no nontrivial partition of $\{1, \ldots, n\}$, where nontrivial partition means a partition that is not a partition into singleton sets or partition into one set. GAP contains a database with all primitive groups of degree < 4096.

Two exercises from Peter Cameron's book[7]:

1. There is no sharply 4-transitive group of degree seven or nine.
2. Primitive groups of degree eight are 2-transitive.

---

[7] Permutation groups.