Group Theory

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A **group** $(G, \star)$ is a set G with a binary operation $\star$: $G \times G \to G$ satisfying

G1. $\star$ is associative: For all $a, b, c \in G$, $\quad (a \star b) \star c = a \star (b \star c)$.

G2. $\star$ has a two-sided identity e: For all $a \in G$, $\quad a \star e = e \star a = a$.

G3. $\star$ has two-sided inverses: For all $a \in G$, there is an $i(a)$ with $a \star i(a) = i(a) \star a = e$.

A group is **abelian** if also

G4. $\star$ is commutative: For all $a, b \in G$, $\quad a \star b = b \star a$.

A **monoid** is a set which satisfies G1 and G2 (associative with two-sided identity).
A **semigroup** is a set which satisfies G1 (associative with no other assumptions).
We usually just write G for $(G, \star)$.

The **order** $|G|$ of a group (monoid, semigroup) G is the cardinality of the set G.

Examples

1. The set of maps $X \to X$ forms a monoid X^X under composition.
2. The set of permutations $X \to X$ forms a group S_X under composition.
   (If the set is $X = \{1, \dots, n\}$ we write this group as S_n.)
3. The set $M_n(\mathbb{R})$ of $n \times n$ matrices with entries in $\mathbb{R}$ forms a monoid under matrix multiplication (and a group under matrix addition).
4. The set $GL_n(\mathbb{R})$ of invertible $n \times n$ matrices forms a group under multiplication.
5. The set of linear maps (resp. invertible linear maps) from a vector space V to itself form a monoid (resp. group) under composition.
6. $(\mathbb{N}, +)$, $(\mathbb{N}, \times)$, $(\mathbb{Z}, \times)$, $(\mathbb{Q}, \times)$, $(\mathbb{Z}/n\mathbb{Z}, \times)$ are monoids (but not groups).
7. $(\mathbb{Z}, +)$, $(\mathbb{Z}/n\mathbb{Z}, +)$, $(\mathbb{Q} \setminus \{0\}, \times)$ are groups.
8. The vector cross product on $\mathbb{R}^3$ is not associative, so $(\mathbb{R}^3, \times)$ is not a semigroup.
9. The *trivial group* $1 = \{e\}$ with just one element (the identity) is a group.

Lemma 1.1 *In a semigroup, the identity and inverses are uniquely determined by* $\star$ *when they exist.*

Proof. If e and e' are identities, then $e = e \star e' = e'$. Now assume e is a two-sided identity and b and b' are inverses of a. Then $b = b \star e = b \star (a \star b') = (b \star a) \star b' = e \star b' = b'$. $\square$

Note that this actually shows that any left identity is equal to any right identity and any left inverse is equal to any right inverse, so when looking for identities and inverses in a group we need only check one side (but we need to know G is a group first!). It is possible for an element of a monoid to have a left inverse (and possibly more than one) but not a right inverse (e.g., X^X for infinite X) and a semigroup may have a left identity (and possibly more than one) but not a right identity, (e.g., the semigroup defined by $a \star b = b$ for all a, b).

We shall usually write G multiplicatively: $a \star b = ab$, $e = 1$, $i(a) = a^{-1}$.
Sometimes for Abelian groups we shall write G additively: $a \star b = a + b$, $e = 0$, $i(a) = -a$.

Lemma 1.2 *If G is a group and $x, y \in G$ then $(xy)^{-1} = y^{-1}x^{-1}$.*

Proof. $(xy)(y^{-1}x^{-1}) = ((xy)y^{-1})y = (x(yy^{-1}))x^{-1} = (x1)x^{-1} = xx^{-1} = 1$, so $y^{-1}x^{-1}$ is a (right) inverse to xy, and by Lemma 1.1 it is the unique inverse. □

Lemma 1.3 (Cancelation laws) *Suppose G is a group and $a, x, y \in G$.*
If $ax = ay$ then $x = y$. If $xa = ya$ then $x = y$.

Proof. Multiply on left (respectively right) by a^{-1}. □

Lemma 1.4 (Generalized associativity) *If $a_1, \dots, a_r$ are elements of a semigroup then any two products of $a_1, \dots, a_r$ in that order are equal.*

Proof. Show any such product $= ((\dots(a_1a_2)a_3)\dots)a_n$ by induction on n. To do this, use induction on the number of terms on the right of the highest level multiply: If $(\dots)a_n$, use induction to rewrite $(\dots)$. If $(\dots)((\dots)(\dots))$, rewrite as $((\dots)(\dots))(\dots)$. □

Lemma 1.5 (Generalized commutativity) *If $a_1, \dots, a_r$ are elements of a semigroup and $a_ia_j = a_ja_i$ for each i, j, then any two products of $a_1, \dots, a_r$ in any order are equal.*

For $n \in \mathbb{Z}$ define

$$a^n = \begin{cases} a.a\dots a \ (n \text{ times}) & \text{if } n > 0, \\ 1 & \text{if } n = 0, \\ a^{-1}a^{-1}\dots a^{-1} \ (-n \text{ times}) & \text{if } n < 0. \end{cases}$$

Define na similarly if G is written additively. Using Lemmas 1.4 and 1.5 it is clear that $a^{n+m} = a^na^m$ (or $(n+m)a = na + ma$) for any $n, m \in \mathbb{Z}$. For abelian groups $(ab)^n = a^nb^n$, but this is not true in general for non-abelian groups.

The **order** $|x|$ of $x \in G$ is the minimum $n > 0$ such that $x^n = 1$ (or ∞ if no such n exists).

Lemma 1.6 *If G is a group and $x \in G$ then*

(a) $x^n = 1$ *iff* $|x| \mid n$,

(b) $x^n = x^m$ *iff* $n \equiv m \bmod |x|$,

(c) $|x^r| = |x| / \gcd(r, |x|)$.

Proof. (a): Write $n = q|x| + r$, $0 \le r < |x|$. Then $x^n = (x^{|x|})^q x^r = x^r$, so $x^n = 1$ iff $r = 0$ iff $|x| \mid n$. (b): Multiply by x^{-m} and use (a). (c): Clearly $(x^r)^{|x|} = 1$ so $|x^r| \mid |x|$ and $|x^r| = |x|/d$ for some d. Now $(x^r)^{|x|/d} = 1$ iff $|x| \mid r|x|/d$ iff $d \mid r$ iff $d \mid \gcd(r, |x|)$. Largest d is clearly $\gcd(r, |x|)$. □

Subobjects

A **subgroup** of the group $(G,\star)$ is a subset $H \subseteq G$ which is a group under the restriction of $\star$ to H and has the same identity and inverses. We write $H \le G$. Similarly for submonoids and subsemigroups. A subgroup (or submonoid / subsemigroup) is **proper** if $H \ne G$, and **non-trivial** if $H \ne \{e\}$.

For a subgroup, H automatically must have the same identity and inverses, but for a submonoid you need to check that H has the same identity as G, e.g., $\{0\}$ is not a submonoid of $(\mathbb{N},\times)$. In all cases, a subobject of a subobject is a subobject.

Example Let $O_2(\mathbb{R})$ be the set of linear maps on $\mathbb{R}^2$ which preserve distances (**orthogonal** maps). Then $O_2(\mathbb{R})$ is the set of rotations and reflections about the origin in $\mathbb{R}^2$. Let D_n be the set of such maps in the plane that leave a given regular n-gon centered at the origin unchanged and let C_n be the set of these that are rotations. Then $O_n(\mathbb{R})$, D_n, and C_n are all groups, and (writing I_2 for the 2×2 identity matrix)

$$\{I_2\} \le C_n \le D_n \le O_2(\mathbb{R}) \le GL_2(\mathbb{R}) \le S_{\mathbb{R}^2}.$$

Lemma 2.1 *A subset $H \subseteq G$ is a subgroup of G if and only if*
(i) $H \ne \emptyset$ and (ii) $\forall x,y \in H : xy^{-1} \in H$.

Lemma 2.2 *If $\{H_i : i \in I\}$ is a (possibly infinite) collection of subgroups of G then $\bigcap_{i\in I} H_i \le G$.*

If S is any subset of a group G, the **subgroup generated by** S is $\langle S\rangle = \bigcap_{S\subseteq H\le G} H$, the intersection of all subgroups of G containing S. By Lemma 2.2 this is a subgroup, and it is the smallest subgroup of G containing the set S.

Lemma 2.3 $\langle S\rangle = \{x_1^{\pm1}x_2^{\pm1}\dots x_k^{\pm1} : x_i \in S, k\in\mathbb{N}\}$*, where this set contains all (finite) products of elements and inverses of elements of S (possibly with repetitions).*

A group G is **finitely generated** if $G = \langle S\rangle$ for some finite subset $S \subseteq G$. A group is **cyclic** if $G = \langle x\rangle = \langle\{x\}\rangle = \{x^n : n\in\mathbb{Z}\}$ for some $x \in G$. Note $|\langle x\rangle| = |x|$.

Example The group C_n defined above is cyclic.

Lemma 2.4 *If $x,y \in G$ commute and $\gcd(|x|,|y|) = 1$ then $|xy| = |x||y|$.*

Proof. Let $n = |xy|$. Now $(xy)^{|x||y|} = (x^{|x|})^{|y|}(y^{|y|})^{|x|} = 1$, so $n \mid |x||y|$. Conversely, $(xy)^n = 1$, so $x^ny^n = 1$ and $z = x^n = y^{-n} \in \langle x\rangle \cap \langle y\rangle$. But $|z|$ is then a factor of both $|x|$ and $|y|$. Thus $|z| = 1$, so $z = 1$. Now $|x| \mid n$ and $|y| \mid n$, so $\operatorname{lcm}(|x|,|y|) \mid n$, but $\operatorname{lcm}(|x|,|y|) = |x||y|/\gcd(|x|,|y|) = |x||y|$ so $|x||y| \mid n$. Hence $n = |x||y|$. □

In general, if x and y commute then $|xy|$ is a factor of $\operatorname{lcm}(|x|,|y|)$, but need not be equal to the lcm. If x and y do not commute then $|xy|$ can be almost anything.

Cosets

If S and T are two subsets of G, write $ST = \{st : s \in S, t \in T\}$. Similarly, if $x \in G$, $xS = \{x\}S = \{xs : s \in S\}$ and $Sx = S\{x\} = \{sx : s \in S\}$. This "product" is associative: $S(TU) = (ST)U = \{stu : s \in S, t \in T, u \in U\}$. Also, if $H \leq G$ then $HH \subseteq H = 1H \subseteq HH$, so $H = HH$.

A **left coset** of a subgroup H is a set of the form xH. A **right coset** of H is a set of the form Hx. The set of left cosets is written G/H. The **index** of H in G is the number of left cosets: $[G{:}H] = |G/H|$.

Sometimes the set of right cosets is written $H \setminus G$.

Lemma 2.5 *Let G be a group and $H \leq G$. Define $x \sim y$ iff $y^{-1}x \in H$. Then $\sim$ is an equivalence relation with equivalence classes xH, $x \in G$. Hence left cosets xH and yH are always either equal or disjoint and $G/H = G/{\sim}$.*

Lemma 2.6 *The number of left cosets of H in G is the same as the number of right cosets of H in G.*

Proof. The bijection $G \to G$ given by $x \mapsto x^{-1}$ maps right cosets Hx to left cosets $x^{-1}H$ and vice versa. □

Theorem (Lagrange) *If $H \leq G$ then $|G| = [G{:}H]|H|$.*

Proof. G is the disjoint union of the cosets xH since these are just the equivalence classes of an equivalence relation. But $|H| = |xH|$ (the map $h \mapsto xh$ is a bijection between H and xH), so $|G| = \sum_{xH \in G/H} |xH| = [G{:}H]|H|$. □

Example If $x \in G$ then $|x| = |\langle x \rangle|$ so $|x| \mid |G|$. In particular, $x^{|G|} = 1$ for any $x \in G$.

Quotient groups

A subgroup $H \leq G$ is **normal** ($H \trianglelefteq G$) iff for all $x \in G$, $xH = Hx$.

Note: If G is abelian and $H \leq G$ then $H \trianglelefteq G$.

Lemma 2.7 *A subgroup H of G is normal iff the equivalence relation $\sim$ above satisfies the condition $x \sim x'$, $y \sim y'$ implies $xy \sim x'y'$.*

Lemma 2.8 *If $H \leq G$ then $H \trianglelefteq G$ iff $xhx^{-1} \in H$ for all $x \in G$, $h \in H$.*

Proof. Condition is equivalent to $xHx^{-1} \subseteq H$. But then $H = x(x^{-1})H(x^{-1})^{-1}x^{-1} \subseteq xHx^{-1} \subseteq H$, so $xHx^{-1} = H$, which is equivalent to $xH = Hx$. □

If $H \trianglelefteq G$ then we can define multiplication on G/H by $\bar{x}\bar{y} = \overline{xy}$ (i.e., $(xH)(yH) = xyH$). Note that this "multiplication" is the same as the multiplication defined on sets above since $(xH)(yH) = x(Hy)H = x(yH)H = xyH$. Under this multiplication G/H is a group and is called the **quotient group** of G by H.

If $H \leq G$ then the **normalizer** of H in G is the set $N_G(H) = \{x \in G : xHx^{-1} = H\} = \{x \in G : xH = Hx\}$.

Lemma 3.1 *If $H \leq G$ then $H \trianglelefteq N_G(H) \leq G$, conversely, if $H \trianglelefteq H' \leq G$ then $H' \leq N_G(H)$. In particular $H \trianglelefteq G$ iff $N_G(H) = G$.*

Proof. $1 \in N_G(H)$, so $N_G(H) \neq \emptyset$. If $x, y \in N_G(H)$, $xyH = xHy = Hxy$, so $xy \in N_G(H)$, and $x^{-1}H = (Hx)^{-1} = (xH)^{-1} = Hx^{-1}$, so $x^{-1} \in N_G(H)$. Thus $N_G(H) \leq G$. The other statements are clear. ☐

As a consequence, if $xH = Hx$ for all $x \in S$ and $\langle S \rangle = G$ then $H \trianglelefteq G$.
Also, If $K \trianglelefteq G$ and $K \leq H \leq G$ then $K \trianglelefteq H$.

Warning: If $K \trianglelefteq H \trianglelefteq G$ then it does *not* follow that $K \trianglelefteq G$.

A (semigroup) **homomorphism** from a semigroup G to another semigroup H is a map $f\colon G \to H$ with the property $f(x \star_G y) = f(x) \star_H f(y)$. A monoid homomorphism between two monoids also requires $f(e_G) = e_H$. A group homomorphism between two groups requires this and also $f(i_G(x)) = i_H(f(x))$.

For groups the last two conditions are automatic: $f(e_G)f(e_G) = f(e_G \star_G e_G) = f(e_G)$, so $f(e_G) = e_H$; $f(i_G(x))f(x) = f(e_G) = e_H$, so $f(i_G(x)) = i_H(f(x))$. Thus one only needs to check $f(xy) = f(x)f(y)$. For monoids $f(e_G) = e_H$ is *not* automatic, e.g., inclusion $\{0\} \to (\mathbb{N}, \times)$.

Note: H is a sub-'object' of G iff the inclusion map $H \to G$ is an 'object'-homomorphism.

Examples The determinant map $\det\colon GL_n(\mathbb{R}) \to \mathbb{R}^\times$. The exponential map $(\mathbb{C}, +) \to (\mathbb{C}^\times, \times)$. For $H \trianglelefteq G$, the quotient map $\pi\colon G \to G/H$; $\pi(x) = xH$.

A (semigroup/monoid/group) **isomorphism** is a (semigroup/monoid/group) homomorphism $f\colon G \to H$ which has a 2-sided inverse (semigroup/monoid/group) homomorphism $g\colon H \to G$. If an isomorphism exists we say G and H are **isomorphic** and write $G \cong H$. Note that isomorphism is an 'equivalence relation'.

Example Exponential map $\exp\colon (\mathbb{R}, +) \to (\mathbb{R}_{>0}, \times)$ has inverse $\log\colon (\mathbb{R}_{>0}, \times) \to (\mathbb{R}, +)$.

Lemma 3.2 *For semigroups, monoids, or groups, $f\colon G \to H$ is an isomorphism iff it is a bijective homomorphism.*

Proof. An isomorphism has an inverse, so must be bijective. Conversely, a bijective homomorphism f has an inverse g. Now $f(g(x)g(y)) = f(g(x))f(g(y)) = xy = f(g(xy))$, so by injectivity of f, $g(x)g(y) = g(xy)$. (And for monoids, $f(g(1)) = 1 = f(1)$, so $g(1) = 1$.) Thus g is a homomorphism. ☐

The **kernel**, $\operatorname{Ker} f$, of a group homomorphism $f\colon G \to H$ is the set of elements of G mapped to $1 \in H$; $\operatorname{Ker} f = \{x : f(x) = 1\}$.

Lemma 3.3 *A homomorphism f is injective iff $\operatorname{Ker} f = \{1\}$.*

Proof. Use $f(x) = f(x') \Leftrightarrow f(x^{-1}x') = 1$. □

Lemma 3.4 *If $f\colon G \to H$ is a homomorphism then $\operatorname{Im} f \le H$ and $\operatorname{Ker} f \trianglelefteq G$.*

Proof. If $x \in G$ and $k \in \operatorname{Ker} f$, then $f(xkx^{-1}) = f(x)1f(x)^{-1} = 1$, so $xhx^{-1} \in \operatorname{Ker} f$. Rest is easy. □

Conversely, if $K \trianglelefteq G$ then $K = \operatorname{Ker} f$ for some f (take $f = \pi\colon G \to G/K$), and if $H \le G$ then $H = \operatorname{Im} f$ for some f (e.g., inclusion $H \to G$).

Theorem (1st Isomorphism Theorem) *If $f\colon G \to H$ is a homomorphism then we can write $f = i \circ \tilde{f} \circ \pi$ where*

- *$\pi\colon G \to G/\operatorname{Ker} f$ is the (surjective) projection homomorphism.*
- *$\tilde{f}\colon G/\operatorname{Ker} f \to \operatorname{Im} f$ is a (bijective) isomorphism.*
- *$i\colon \operatorname{Im} f \to H$ is the (injective) inclusion homomorphism.*

$$\begin{array}{ccc} G & \xrightarrow{f} & H \\ {\scriptstyle\pi}\downarrow & & \uparrow{\scriptstyle i} \\ G/\operatorname{Ker} f & \xrightarrow{\tilde{f}} & \operatorname{Im} f \end{array}$$

Proof. We know such a decomposition exists as maps, we only need to show $\tilde{f}$ is a homomorphism. But $\tilde{f}(xHyH) = \tilde{f}(xyH) = f(xy) = f(x)f(y) = \tilde{f}(xH)\tilde{f}(yH)$. □

Important consequence: For any homomorphism $f\colon G \to H$, $G/\operatorname{Ker} f \cong \operatorname{Im} f$.

Theorem (2nd Isomorphism Theorem) *Let $K \trianglelefteq G$. Then there is a bijection between the subgroups of G containing K and the subgroups of G/K. The correspondence is given by H, $K \le H \le G$, maps to $H/K \le G/K$ and $\mathcal{H} \le \mathcal{G}/\mathcal{K}$ maps to $\cup_{xK\in\mathcal{H}}\, xK \le G$. Moreover, in this correspondence, $H \trianglelefteq G$ iff $H/K \trianglelefteq G/K$, and if this occurs then $(G/K)/(H/K) \cong G/H$.*

Proof of last part. Apply 1st Isomorphism Theorem to $f\colon G/K \to G/H$; $f(xK) = xH$. □

Theorem (3rd Isomorphism Theorem) *If $H \le G$ and $K \trianglelefteq G$ then $K \cap H \trianglelefteq H$, $K \trianglelefteq HK$, and $HK/K \cong H/(K \cap H)$.*

Proof. Apply 1st Isomorphism Theorem to $f\colon H \to G/K$; $f(x) = xK$. □

Theorem (Cayley) *Any group is isomorphic to a subgroup of a permutation group.*

Proof. Let G be a group and S_G be the group of bijections $G \to G$. Construct a map $\phi\colon G \to S_G$ by defining for $x \in G$ a map $\phi(x)\colon G \to G$ by $\phi(x)(y) = xy$. Then $\phi(x) \in S_G$ (inverse is $\phi(x^{-1})$) and ϕ is a homomorphism ($\phi(x) \circ \phi(y) = \phi(xy)$). If $\phi(x) = 1$ then $xy = y$ for all y and so $x = 1$. Hence $\operatorname{Ker}\phi = \{1\}$. By the 1st Isomorphism Theorem, $G \cong \operatorname{Im}\phi$, so G is isomorphic to a subgroup of S_G. □

Write S_n for the **Symmetric group** on set $X = \{1, \dots, n\}$, i.e., the group of permutations (bijections $X \to X$) with group operation given by composition. Note that $|S_n| = n!$.

A k**-cycle** $(a_1, \dots, a_k)$ is a permutation in S_n that maps a_j to a_{j+1} and a_k to a_1 but leaves every other element fixed. A 2-cycle is also called a **transposition**.

Note: A k-cycle has order k in S_n. A k-cycle can be written in k different ways, $(a_1, a_2, \dots, a_k) = (a_2, a_3, \dots, a_k, a_1) = \dots = (a_k, a_1, \dots, a_{k-1})$.

The **support** of a permutation, $\operatorname{supp}\pi = \{i : \pi(i) \neq i\}$, is the set of elements that it moves. As an example, $\operatorname{supp}(a_1, \dots, a_k) = \{a_1, \dots, a_k\}$ for $k \geq 2$. Two permutations are **disjoint** if their supports are disjoint.

Lemma 4.1 *Disjoint permutations commute.*

Permutations, or even just cycles, that are not disjoint do not in general commute, e.g., $(12)(13) = (132)$, $(13)(12) = (123)$.

Lemma 4.2 *Any permutation $\pi \in S_n$ can be written as a product of disjoint cycles (of lengths ≥ 2), and this representation is unique up to the order of the cycles. Moreover the support of these cycles are subsets of* $\operatorname{supp}\pi$*.*

Proof. Induction on $|\operatorname{supp}\pi|$. If $\operatorname{supp}\pi = \emptyset$ then $\pi = 1$ is the empty product, otherwise pick $a_1 \in \operatorname{supp}\pi$ and inductively define $a_{i+1} = \pi(a_i)$. Eventually we must have a repeat $a_i = a_j$, and the first such repeat must be of the form $a_1 = a_{k+1}$ (apply π^{1-i} to $a_i = a_j$). Let $\sigma = (a_1, \dots, a_k)$. Then $\operatorname{supp}\sigma^{-1}\pi = \operatorname{supp}\pi \setminus \operatorname{supp}\sigma$, so $\sigma^{-1}\pi = \sigma_1 \dots \sigma_r$, and thus $\pi = \sigma\sigma_1 \dots \sigma_r$. Also $\operatorname{supp}\sigma$ is disjoint from each $\operatorname{supp}\sigma_i \subseteq \operatorname{supp}\pi \setminus \operatorname{supp}\sigma$. □

A permutation π has **cycle type** $(k_1)^{a_1} \dots (k_r)^{a_r}$ if π is the product of disjoint cycles σ_i of length k_i.

Exercise: The order of a permutation of type $(k_1)^{a_1} \dots (k_r)^{a_r}$ is $\operatorname{lcm}\{k_1, \dots, k_r\}$.

Lemma 4.3 *Any permutation can be written as a product of transpositions, i.e, the set of transpositions generates S_n.*

Proof. Any cycle is a product of transpositions, since we can write $(a_1, \dots, a_k) = (a_1, a_k)(a_1, a_{k-1}) \dots (a_1, a_2)$, and the set of all cycles generate S_n by Lemma 4.2 □

Note: The transpositions in Lemma 4.3 are not in general disjoint, nor is the representation unique.

Lemma 4.4 *There exists a group homomorphism* $\operatorname{sgn}\colon S_n \to \{\pm 1\}$ *which sends every transposition to* -1*. (*$\{\pm 1\}$ *is group under multiplication.)*

One definition of sgn is $\operatorname{sgn}\pi = (-1)^n$ where n is the number of transpositions used to express π in Lemma 3. This is clearly a homomorphism, but it requires proof that it is well defined. (It is enough to show that if a product of transpositions is the identity then there must be an even number of them.) Another is $\operatorname{sgn}\pi = \prod_{i<j}\frac{\pi(i)-\pi(j)}{i-j}$. This is clearly well defined, but it requires proof that it is a homomorphism.

The **Alternating group** A_n is the kernel of sgn. A permutation π is called **even** if $\operatorname{sgn}\pi = 1$ and **odd** if $\operatorname{sgn}\pi = -1$. A_n is therefore the set of even permutations.

Note: A k-cycle is even iff k is *odd*.

Lemma 4.5 *The group* A_n *is generated by 3-cycles.*

Proof. The product of two transpositions is always a product of 3-cycles. □

Two elements x, y in a group G are **conjugate** if $x = zyz^{-1}$ for some $z \in G$. Conjugacy is an equivalence relation on G and the equivalence classes C_x, $x \in G$, are called **conjugacy classes**.

Note: A subgroup is normal iff it is the union of conjugacy classes.

Lemma 4.6 $\pi(a_1,\dots,a_r)(b_1,\dots,b_s)\dots\pi^{-1} = (\pi(a_1),\dots,\pi(a_r))(\pi(b_1),\dots,\pi(b_s))\dots$. *In particular two permutations are conjugate in* S_n *iff they have the same cycle type.*

A group G is called **simple** if $|G| > 1$ and the only normal subgroups of G are $\{1\}$ and G.

Theorem 4.7 A_n *is simple for* $n \geq 5$.

Proof. Assume $1 < H \trianglelefteq G$. First show that H contains a 3-cycle. Pick $\sigma \in H$, $\sigma \neq 1$.
If $\sigma = (123)(456)\dots \in H$, then $(124)\sigma(124)^{-1}\sigma^{-1} = (124)(235)^{-1} = (12534) \in H$.
If $\sigma = (123\dots k)(\dots)\dots \in H$ with $k \geq 4$ then $(123)\sigma(123)^{-1}\sigma^{-1} = (124) \in H$.
Hence we may assume σ is of type $(2)^r$ or $(3)(2)^r$. But since $\sigma \in A_n$, r is even.
If $\sigma = (12)(34)\dots \in H$ then $(123)\sigma(123)^{-1}\sigma^{-1} = (13)(24) \in H$.
If $\sigma = (12)(34) \in H$ then $(125)\sigma(125)^{-1}\sigma^{-1} = (152) \in H$.
Once we have one 3-cycle, say (123), we get all the others by conjugation $\pi(123)\pi^{-1}$ (or $(\pi(45))(123)(\pi(45))^{-1}$ if π odd). Then $H = A_n$ since A_n is generated by 3-cycles. □

Note: The subgroup $V = \{1, (12)(34), (13)(24), (14)(23)\}$ is a normal subgroup of A_4.

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The **direct product** $G_1 \times G_2$ of groups G_1 and G_2 is the cartesian product of the sets with product defined componentwise $(g_1, g_2)(h_1, h_2) = (g_1h_1, g_2h_2)$. Similarly for direct products $\prod_{i \in I} G_i$ of a collection of groups G_i, $i \in I$.

Note: $G_1 \times G_2$ has normal subgroups $G_1' = G_1 \times \{1\}$ and $G_2' = \{1\} \times G_2$ isomorphic to G_1 and G_2 respectively. This can be seen by considering the kernel of the **projection** homomorphism $\pi_i : G \to G_i$ obtained by taking the i'th coordinate of an element of G. Elements of G_1' commute with elements of G_2'.

Lemma 5.1 *If $H_i \leq G$, $i = 1, \dots, n$, are subgroups such that $h_ih_j = h_jh_i$ for all $h_i \in H_i$, $h_j \in H_j$, and if $\langle \cup_i H_i \rangle = G$ and $H_i \cap \langle \cup_{j \neq i} H_j \rangle = 1$ for all i, then $G \cong \prod_i H_i$.*

Proof. Define $f \colon \prod_i H_i \to G$ by $f(h_1, \dots, h_n) = h_1h_2 \dots h_n$. Since elements of H_i commute with those of H_j for $j \neq i$ it can be shown that f is a homomorphism. Let $(h_1, \dots, h_n) \in \operatorname{Ker} f$. Then $h_i = (\prod_{j \neq i} h_j)^{-1} \in H_i \cap \langle \cup_{j \neq i} H_j \rangle = 1$ so $h_i = 1$ and f is injective. The image contains each H_i so contains $\langle \cup H_i \rangle = G$. Hence f is surjective. Therefore f is an isomorphism. □

Lemma 5.2 *If $H_i \trianglelefteq G$, $i = 1, \dots, n$, are normal subgroups such that $\langle \cup_i H_i \rangle = G$ and $H_i \cap \langle \cup_{j \neq i} H_j \rangle = 1$ for all i, then $G \cong \prod_i H_i$.*

Proof. If $h_i \in H_i$ and $h_j \in H_j$ then $(h_ih_jh_i^{-1})h_j^{-1} = h_i(h_jh_i^{-1}h_j^{-1}) \in H_i \cap H_j = \{1\}$, so $h_ih_j = h_jh_i$. Now apply Lemma 5.1. □

Theorem (Chinese Remainder Theorem) *If $\gcd(n, m) = 1$ then $C_{nm} \cong C_n \times C_m$.*

Proof. Let $C_{nm} = \langle a \rangle$ and consider the (cyclic) subgroups $\langle a^m \rangle$ and $\langle a^n \rangle$. □

Universal property of direct products.
If H is any group and $f_i \colon H \to G_i$ are homomorphisms then there exists a unique homomorphism $f \colon H \to G$ such that $\pi_i \circ f = f_i$. Conversely, if G and $\pi_i \colon G \to G_i$ have this property then $G \cong \prod_i G_i$.

$$\begin{tikzcd} H \arrow[r, "f_i"] \arrow[dr, "f"'] & G_i \\ & G \arrow[u, "\pi_i"'] \end{tikzcd}$$

There is a "dual" concept of **free product** (see later) in which the arrows in the universal product are reversed. This is a more complicated construction. However, if we restrict our attention to abelian groups we have the following.

The **direct sum** $\bigoplus_i G_i$ of *abelian* groups G_i is the subgroup of $\prod_i G_i$ consisting of the elements (g_i) with all but finitely many g_i equal to the identity. Note this it the same as the direct product if there are only finitely many G_i. Let $i_j \colon G_i \to G$ be the map which sends g_i to $(1, \dots, 1, g_i, 1, \dots, 1) \in G$.

Universal property of direct sums.
If H and G_j are abelian groups and $f_j \colon G_j \to H$ are homomorphisms then there exists a unique homomorphism $f \colon G \to H$ such that $f \circ i_j = f_j$. Conversely, if G and $i_j \colon G_j \to G$ have this property with G abelian then $G \cong \bigoplus_j G_j$.

$$\begin{tikzcd} H & G_j \arrow[l, "f_j"'] \arrow[d, "i_j"] \\ & G \arrow[ul, "f"] \end{tikzcd}$$

Theorem (Classification of Finite Abelian Groups) *Any finite abelian group is a product of cyclic groups $C_{d_1}\times\cdots\times C_{d_r}$ with $d_{i+1}\mid d_i$, $d_i>1$. Moreover, this representation is unique.*

Note: In the representation $C_{d_1}\times\cdots\times C_{d_r}$, the subgroups corresponding to the factors C_{d_i} are not unique in general.

Proof. Let $C=\langle x\rangle$ be a cyclic subgroup of G of maximal order $|C|=d$. Let H be a maximal subgroup of G such that $H\cap C=1$. Such subgroups exist (e.g., $1\cap C=1$) and G is finite so there must be at least one H of maximal size. We wish to show $G\cong C\times H$. Since $H,C\trianglelefteq G$ and $H\cap C=1$, it only remains to prove $HC=G$. Assume otherwise and let $y\notin HC$. Let s be the order of yHC in G/HC, so $y^s\in HC$ and $y^i\notin HC$ for $0<i<s$. Write $y^s=hx^r$, $h\in H$. By replacing y by yx^{-q} we can assume $0\le r<s$. Note that $yHC=yx^{-q}HC$ so the value of s above is the same for y as for yx^{-q}. Now the order of y is divisible by s (since $y^n=1$ implies $(yHC)^n=1$ in G/HC). Thus if $y^n=1$ then $y^n=h^{n/s}x^{rn/s}=1$ and $x^{rn/s}=h^{-n/s}\in H\cap C=1$. But then rn/s is a multiple of d and $r<s$ so either $r=0$ or $rn/s\ge d$ which gives $n>d$, contradicting the choice of C. Hence $r=0$ and $y^s=h$. Now consider $H'=\langle y,H\rangle$. If $z\in H'\cap C$ then $y^ih'=z=x^j$ for some $i,j\in\mathbb{Z}$, $h\in H$. But then $y^i\in HC$, so $s\mid i$, $z=y^ih'=h^{i/s}h'\in H\cap C=1$, Thus $H'\cap C=1$ and $H'>H$ contradicting the choice of H.

Hence $HC=G$ and $G\cong C\times H$. Since $H\cap C=1$, if $h\in H$ is of order d' then the order of xh is $\operatorname{lcm}(d,d')$. But by the choice of C this is $\le d$. Hence $d'\mid d$, and so all elements of H have orders dividing d. By induction on $|G|$ we can write $H\cong C_{d_2}\times\cdots\times C_{d_r}$, so $G\cong C_{d_1}\times\cdots\times C_{d_r}$ with $d_1=d$ and $d_{i+1}\mid d_i$ for $i>1$. But H has an element of order d_2 so $d_2\mid d_1$ as well.

For uniqueness, assume $G\cong C_{d_1}\times\cdots\times C_{d_r}\cong C_{d'_1}\times\cdots\times C_{d'_s}$. By dropping the requirement that $d_i,d'_i>1$ and including C_1 factors, we may assume $r=s$. Let i be the smallest integer such that $d_i\ne d'_i$. Consider the subgroup $G^{d_i}=\{g^{d_i}:g\in G\}$. (This is a subgroup since G is abelian). Now $C_d^{d_i}\cong C_{d/d_i}$ for $d_i\mid d$ and $C_d^{d_i}=1$ if $d\mid d_i$, so $G^{d_i}\cong C_{d_1/d_i}\times\cdots\times C_{d_{i-1}/d_i}$. But $d_j=d'_j$ for $j<i$, so $G^{d_i}\cong C_{d_1/d_i}\times\cdots\times C_{d_{i-1}/d_i}\times H$, where $H=(C_{d'_i}\times\cdots\times C_{d'_s})^{d_i}$. By comparing orders, $|H|=1$, so in particular $d'_i\mid d_i$. Similarly $d_i\mid d'_i$, so $d_i=d'_i$, contradicting the choice of i. $\square$

Note that the requirement that $d_{i+1}\mid d_i$ is important for uniqueness. Indeed, $C_r\times C_s\cong C_{rs}$ if $\gcd(r,s)=1$. As a consequence of this, if $d_i=p_1^{a_{i,1}}\dots p_s^{a_{i,s}}$ is the prime factorization of d_i, then $C_{d_i}\cong C_{p_1^{a_{i,1}}}\times\cdots\times C_{p_s^{a_{i,s}}}$. Hence we may write any finite abelian group as

$$G\cong(C_{p_1^{a_{1,1}}}\times C_{p_1^{a_{1,2}}}\times\dots)\times(C_{p_2^{a_{2,1}}}\times C_{p_2^{a_{2,2}}}\times\dots)\times\dots$$

where $a_{i,1}\ge a_{i,2}\ge\cdots\ge 1$ and p_i are distinct primes. This representation is unique up to rearrangement of the p_i.

Example: $C_{360}\times C_{24}\times C_2\cong(C_8\times C_8\times C_2)\times(C_9\times C_3)\times(C_5)$.

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A group F is **free** on a subset $S \subseteq F$ if for any group G and any function $\phi\colon S \to G$, there exists a unique homomorphism $f\colon F \to G$ with $f_{|S} = \phi$.

$$\begin{tikzcd} S \arrow[r, "\phi"] \arrow[dr, "i"'] & G \\ & F \arrow[u, "f"'] \end{tikzcd}$$

Example: $(\mathbb{Z}, +)$ is a free group on $S = \{1\}$ with $f(n) = (\phi(1))^n$.

Idea: Existence of f implies that there are no relations between the elements of S which hold in F but do not hold in a general group G. Uniqueness of f implies that F is generated by S.

The universal property states that any map on S can be extended uniquely to a homomorphism on F. Compare this with a basis in a vector space — any map on the basis can be extended uniquely to a linear map on the space.

Construction: Let S be a set of symbols and let T be the set of 'terms' $\{x, x^{-1} : x \in S\}$. Let $W_S = \cup_{i=0}^{\infty} T^i$ be the set of all finite 'words' or 'strings' made up from elements of T. We can define multiplication $\star$ on W_S by concatenation. This makes W_S into a monoid with identity equal to the empty string '' $\in T^0$. However, W_S is not a group since there are no inverses. Somehow we must modify the construction so that 'xx^{-1}' = ''. To do this, define an equivalence relation $\sim$ on W_S as the smallest equivalence relation that makes $sx^a x^{-a} t$ equivalent to st for any $s, t \in W_S$, $x \in S$, $a \in \{\pm 1\}$. We check that $s \sim s'$ and $t \sim t'$ imply $s \star t \sim s' \star t'$ so that $\star$ is well defined on $F_S = W_S/\sim$. Since $W_S/\sim$ has inverses, it is a group. Now check the universal property.

Group presentations: The group presentation $\langle S \mid t_i = 1,\ i \in I\rangle$ where S is a set of symbols and t_i are words in W_S, is the group F_S/K where K is the smallest normal subgroup of F_S containing (the equivalence classes of) t_i for all $i \in I$. More specifically

$$K = \left\langle \{z t_i z^{-1} : i \in I,\ z \in F_S\} \right\rangle$$

The group F_S/K is a group generated by S in which the equations $t_i = 1$ hold, and is the largest group for which this is true, as the following lemma shows.

Lemma 7.1 *Let $F_S/K = \langle S \mid t_i = 1,\ i \in I\rangle$ be a group presentation and G a group generated by S in which the equations $t_i = 1$ hold. Then G is isomorphic to a quotient of F_S/K.*

Proof. Define $f\colon F_S \to G$ by sending each $x \in S$ to $x \in G$ and extending to a homomorphism by the universal property. Now $f(z t_i z^{-1}) = f(z) f(t_i) f(z)^{-1} = 1$ since $f(t_i) = 1$. Thus $\ker f$ contains all $z t_i z^{-1}$, and hence contains K. Thus f induces a map $\tilde{f}\colon F_S/K \to G$ but $\operatorname{Im} \tilde{f} = \operatorname{Im} f = G$ since G is generated by S and $S \subseteq \operatorname{Im} f$. Thus G is isomorphic to quotient $(F_S/K)/\ker \tilde{f}$. $\square$

To show that a group presentation is isomorphic to a given finite group, it is enough to show (a) G is generated by S, (b) the equations $t_i = 1$ hold in G and (c) $|F_S/K| \le |G|$. For (c) one usually shows that every element of F_S/K can be written in one of $|G|$ forms.

8. Group actions

An **action** of a group G on a set X is a binary operation $\cdot : G \times X \to X$ such that

A1. For all $x \in X$, $\quad 1 \cdot x = x$,

A2. For all $g, h \in G,\ x \in X$, $\quad (gh) \cdot x = g \cdot (h \cdot x)$.

Lemma 8.1 *An action on G on X defines a homomorphism $\phi\colon G \to S_X$. Conversely any such homomorphism corresponds to an action of G on X.*

Proof. Let $\phi(g)$ be the map $X \to X$ defined by $\phi(g)(x) = g \cdot x$. A2 implies $\phi(gh) = \phi(g) \circ \phi(h)$ and A1 implies that $\phi(1) = 1_X$ is the identity map on X. Hence $\phi(g)\phi(g^{-1}) = \phi(g^{-1})\phi(g) = \phi(1) = 1_X$ and so $\phi(g^{-1})$ is a two sided inverse for $\phi(g)$. Therefore $\phi(g) \in S_X$ is a permutation and ϕ is a homomorphism $G \to S_X$ since $\phi(gh) = \phi(g)\phi(h)$. Conversely, if $\phi\colon G \to S_X$ is a homomorphism, define $g \cdot x = \phi(g)x$. Conditions A1 and A2 follow since $1 \cdot x = \phi(1)x = 1_X(x) = x$ and $(gh) \cdot x = \phi(gh)x = \phi(g)(\phi(h)(x)) = g \cdot (h \cdot x)$. □

An action is called **faithful** or **effective** if for all $g \neq 1$ there exists and x with $g \cdot x \neq x$. Equivalently, ϕ is injective.

Examples

1. S_n acts naturally on $\{1, \dots, n\}$. In this case ϕ is the identity.
2. Matrix groups $GL_n(\mathbb{R})$, $SL_n(\mathbb{R})$, etc., act on the set of vectors $\mathbb{R}^n$ by matrix multiplication.
3. G acts on $X = G$ by left multiplication $g \cdot x = gx$. [Recall the proof of Cayley's Theorem from Section 4.]
4. G acts on $X = \{\text{subsets of } G\}$ by left multiplication $g \cdot S = gS$. If $H \leq G$ then G acts on the set of left cosets $X = G/H$ by $g \cdot xH = gxH$.
5. G acts on $X = G$ by conjugation $g \cdot x = gxg^{-1}$ [Note: it is important here to use gxg^{-1}, not $g^{-1}xg$.]
6. G acts on $X = \{\text{subsets of } G\}$ by conjugation $g \cdot S = gSg^{-1}$. If $H \leq G$ then G acts on $X = \{\text{conjugates } xHx^{-1} \text{ of } H\}$ by $g \cdot xHx^{-1} = (gx)H(gx)^{-1}$.

The **orbit** of $x \in X$ under the action of G is the set of elements x is mapped to, i.e., $\mathrm{Orb}_G(x) = \{g \cdot x : g \in G\}$. The **Stabilizer** of $x \in X$ is the subset of G that fixes x, $\mathrm{Stab}_G(x) = \{g \in G : g \cdot x = x\}$.

Note: Both $\mathrm{Stab}_G(x)$ and $\mathrm{Orb}_G(x)$ depend very much on $x \in X$ (for a good example, consider the action of D_3, as a subgroup of $GL_2(\mathbb{R})$, acting on the plane $\mathbb{R}^2$.)

Lemma 8.2 *The orbits of any action of G on X form a partition of X.*

Proof. Define a relation $x \sim y$ iff $\exists g\colon g \cdot x = y$. It can be checked that this is an equivalence relation and the orbits are precisely the equivalence classes. $\square$

An action is **transitive** iff $\mathrm{Orb}_G(x) = X$ for some (and hence all) $x \in X$.

Theorem (Orbit-Stabilizer Theorem) *For any action of G on X, $\mathrm{Stab}_G(x)$ is a subgroup of G and $[G\colon \mathrm{Stab}_G(x)] = |\,\mathrm{Orb}_G(x)|$.*

Proof. Proof that $H = \mathrm{Stab}_G(x) \leq G$ is standard. For the second part consider the map $\phi\colon G \to \mathrm{Orb}_G(x)$ given by $\phi(g) = g \cdot x$. By definition of $\mathrm{Orb}_G(x)$, ϕ is surjective. Also $\phi(g) = \phi(h)$ holds iff $g \cdot x = h \cdot x$ which holds iff $h^{-1}g \cdot x = x$ or $h^{-1}g \in H$. Thus $\phi(g) = \phi(h)$ iff $gH = hH$. Thus there is a bijection between the left cosets of H and $\mathrm{Orb}_G(x)$. $\square$

Examples

1. If G acts on G by conjugation $g \cdot x = gxg^{-1}$ then $\mathrm{Orb}_G(x)$ is the **conjugacy class** C_x of x and $\mathrm{Stab}_G(x)$ is the **centralizer** of x, $C_G(x)$. In particular $|C_x| = [G{:}G_G(x)]$, so the size of any conjugacy class divides $|G|$.
2. If G acts on the conjugates of $H \leq G$ by conjugation, then the stabilizer of H is $N_G(H)$ and the action is transitive. Hence the number of conjugates of H in G is $[G{:}N_G(H)]$. In particular it is a factor of $[G{:}H]$.

Lemma 8.3 *If p is a prime and $p \mid |G|$ then G contains an element of order p.*

Proof. Let $X = \{(g_1, \dots, g_p) : g_1 g_2 \dots g_p = 1\} \subseteq G^p$ and let $\mathbb{Z}/p\mathbb{Z}$ act on X by cyclically permuting the coordinates: $i \cdot (g_1, \dots, g_p) = (g_{1+i}, \dots, g_i)$. It is easy to see that the result still lies in X and gives an action of $\mathbb{Z}/p\mathbb{Z}$ on X. The orbits are all of size p or 1, with 1 occurring when $g_1 = g_2 = \dots = g$ with $g^p = 1$. But $|X| = |G|^{p-1}$ since for any choice of $g_1, \dots, g_{p-1}$ there is a unique g_p with $(g_1, \dots, g_p) \in X$. Thus $p \mid |X|$, so the number of elements g with $g^p = 1$ is also divisible by p. Since $1^p = 1$, there is at least p such elements, and hence some elements of order p. $\square$

Note that this does not hold in general if p is not prime. Eg., D_3 has no element of order 6, A_5 has no element of order 30.

Lemma 8.4 *If G is a group of order p^n, p prime, $n > 0$, then $Z(G) \neq 1$.*

Proof. Write G as a union of conjugacy classes C_x. Each $|C_x|$ divides $|G|$ so is a power of p. Also $|C_x| = 1$ iff $zxz^{-1} = x$ for all $z \in G$, which is just the statement that $x \in Z(G)$. Thus $|G| = |Z(G)| + \sum_{|C_x|>1} |C_x|$ and so $0 \equiv |G| \equiv |Z(G)| + \sum 0 \bmod p$. So $p \mid |Z(G)|$ and thus $Z(G) \neq 1$. $\square$

Throughout this section, assume G is a finite group.

Theorem (Sylow 1) *If p is prime and $p^k \mid |G|$ then G contains a subgroup of order p^k.*

Proof. Induction on $|G|$. If $k = 0$ then the result is clear, hence we may assume $p \mid |G|$ and the result holds for smaller groups. Use the action of G on G by conjugation to write $|G| = \sum |\operatorname{Orb}_G(x)| = |Z(G)| + \sum_{|C_x|>1} |C_x|$. Since $|G| \equiv 0 \bmod p$, either $p \mid |Z(G)|$ or $p \nmid |C_x|$ for some $x \notin Z(G)$. In the second case $|C_x| = [G{:}C_G(x)] = |G|/|C_G(x)|$, so $p^k \mid |C_G(x)|$. But $C_G(x) < G$ since $x \notin Z(G)$, so by induction there is a subgroup $H \leq C_G(x)$ with order p^k. In the first case $p \mid |Z(G)|$. Now $Z(G)$ has an element of order p, thus there exists a normal subgroup $C \trianglelefteq G$ with $|C| = p$ (normal since $C \leq Z(G)$). Now by induction G/C contains a subgroup H/C of order p^{k-1}, which corresponds by the 2nd isomorphism theorem to a subgroup $H \leq G$ of order p^k. $\square$

A p-**group** is a group in which every element has order a power of p. For a finite group this is equivalent to $|G| = p^k$ for some k. A p-**Sylow** subgroup of a finite group G is a p-subgroup $P \leq G$ with $p \nmid [G{:}P]$. Equivalently, $|P| = p^k$ with p^k being the largest power of p dividing $|G|$.

Lemma 9.1 *If H is a p-subgroup of G and P is a p-Sylow subgroup of G with $H \leq N_G(P)$, then $H \leq P$.*

Proof. By assumption $H \leq N_G(P)$ and by definition of $N_G(P)$, $P \trianglelefteq N_G(P)$. Therefore by the 3rd Isomorphism Theorem, $HP/P \cong H/(H \cap P)$. But $|P|$ is the maximal power of p dividing $|G|$ and $|HP| \mid |G|$, so $p \nmid |HP|/|P| = |HP/P|$. On the other hand $|H/(H \cap P)|$ is a power of p since H (and hence $H/(H \cap P)$) is a p-group. Therefore $H/(H \cap P) = 1$ and so $H \leq P$. $\square$

Theorem (Sylow 2) *If P is a p-Sylow subgroup of G and H is any p-subgroup of G then H is a subgroup of some conjugate of P. In particular, any two p-Sylow subgroups are conjugate.*

Proof. Let $X = \{xPx^{-1} : x \in G\}$ be the set of conjugates of P and let G act on X by conjugation. The action of G is transitive, so $|X| = |\operatorname{Orb}_G(P)| = [G{:}\operatorname{Stab}_G(P)] = [G{:}N_G(P)] = |G|/|N_G(P)|$. But $P \leq N_G(P)$, so $|X|$ divides $|G|/|P|$. Thus $|X| \not\equiv 0 \bmod p$. Now restrict the action to one of H on X. At least one of the orbits $\operatorname{Orb}_H(P')$, $P' \in X$, must have size not divisible by p. But $|\operatorname{Orb}_H(P')| = [H{:}\operatorname{Stab}_H(P')]$ divides $|H|$ which is a power of p. Thus $\operatorname{Orb}_H(P') = \{P'\}$ and so $H \leq N_G(P')$. By Lemma 9.1, $H \leq P'$, where $P' \in X$ is a conjugate of P. $\square$

Theorem (Sylow 3) *The number n_p of p-Sylow subgroups of G is equivalent to 1 mod p and divides $|G|/|P|$.*

Proof. Use the action of P on $X = \{xPx^{-1} : x \in G\}$ by conjugation. $\operatorname{Orb}_P(P) = \{P\}$ has size 1. But for $P' \neq P$, $P \not\leq P'$. Thus by Lemma 9.1, $P \not\leq N_G(P')$, so

$\mathrm{Orb}_P(P') \neq \{P'\}$. But $|\,\mathrm{Orb}_P(P')|$ is a factor of $|P|$, so is divisible by p. Hence $n_p = |X| = |\,\mathrm{Orb}_P(P)| + \sum_{P' \neq P} |\,\mathrm{Orb}_P(P')| \equiv 1 \bmod p$. For the last part, $|X| = |\,\mathrm{Orb}_G(P)| = [G\colon \mathrm{Stab}_G(P)]$ divides $|G|$. But $|X|$ is relatively prime to p, so $|X|$ divides $|G|/p^k$. $\square$

Example Suppose $|G| = 28$, then $n_7 \equiv 1 \bmod 7$ and $n_7 \mid 28/7 = 4$. Hence $n_7 = 1$. But then all conjugates of a 7-Sylow subgroup P are equal to P and thus $P \trianglelefteq G$. Hence G has a normal subgroup of order 7.

Example Suppose $|G| = 56$, then $n_7 \equiv 1 \bmod 7$ and $n_7 \mid 8$. Hence $n_7 \in \{1, 8\}$. If $n_7 = 8$ then there are 8 7-Sylow subgroups $P_1, \dots, P_8$ each of which is cyclic of order 7. But $P_i \cap P_j < P_i$, so $P_i \cap P_j = \{1\}$ for $i \neq j$. Thus the sets $P_i \setminus \{1\}$ are disjoint and there are a total of (at least) $8 \times 6 = 48$ elements of G of order 7. But this gives only 8 remaining elements. Since 2-Sylow subgroups have order 8, there can only be one 2-Sylow subgroup. Hence G either has a normal subgroup of order 7 (when $n_7 = 1$) or it has a normal subgroup of order 8 (when $n_7 = 8$). In particular G is not simple.

Lemma 9.2 *If $|G| = 60$ and G is simple, then $G \cong A_5$.*

Proof. Assume first that G has a subgroup H of index $2 \leq m \leq 5$. Then G acts of the left cosets $X = \{xH : x \in G\}$ by left multiplication. This gives a homomorphism $\phi\colon G \to S_m$. Let $K = \ker \phi$. Then $K \trianglelefteq G$, so either $K = 1$ or $K = G$. But the action of G is not trivial (it it transitive on X), so $K \neq G$. Hence $K = 1$ and G is isomorphic to a subgroup of S_m, $m \leq 5$. Since $|G| = 60$, $m = 5$ and $G \leq S_5$. But then $G \cap A_n \trianglelefteq G$ and $[G{:}G \cap A_5] = [GA_5{:}A_5] \leq 2$, so $|G \cap A_5| \geq 60/2 > 1$ and so $G \cap A_5 = G$. Hence $G \leq A_5$, so $G = A_5$. Hence we may now assume G has no proper subgroup of index ≤ 5.

Count the number of p-Sylow subgroups for $p = 2, 3, 5$.

$$\begin{aligned} n_2 \equiv 1 \bmod 2,\ n_2 \mid 15 &\implies n_2 \in \{1, 3, 5, 15\} \\ n_3 \equiv 1 \bmod 3,\ n_3 \mid 20 &\implies n_3 \in \{1, 4, 10\} \\ n_5 \equiv 1 \bmod 5,\ n_5 \mid 12 &\implies n_5 \in \{1, 6\} \end{aligned}$$

If $n_p = 1$ then the p-Sylow subgroup P is normal in G. If $2 \leq n_p \leq 5$ then $N_G(P)$ has index $n_p \leq 5$ in G. Hence we may assume $n_2 = 15$, $n_3 = 10$, $n_5 = 6$.

Using $n_5 = 6$ we have 6 subgroups $P_1, \dots, P_6$, each of order 5 and $P_i \cap P_j = \{1\}$. Thus there are $6 \times 4 = 24$ non-identity elements in $\cup P_i$, each of order 5.
Using $n_3 = 10$, a similar argument gives $10 \times 2 = 20$ elements of order 3.
Using $n_2 = 15$ we must be a bit more careful since $P_i \cap P_j$ does not have to be trivial. Let P_i and P_j be two distinct 2-Sylow subgroups (of order 4) and $F = \langle P_i, P_j \rangle$. Then $4 < |F| \mid |G| = 60$, so $|F| \in \{12, 20, 60\}$. Since we may assume G has no subgroup of index $2 \leq [G{:}F] \leq 5$, we have $F = G$. Now if $|P_i \cap P_j| = 2$ then $P_i \cap P_j$ is normal in both P_i and P_j (index 2) and so in F, contradicting simplicity of $F = G$. Thus $P_i \cap P_j = 1$ and we get $15 \times 3 = 45$ elements of order 2 or 4.
The total number of elements of G accounted for so far is $1 + 24 + 20 + 45 > 60$, a contradiction. Thus $G \cong A_5$. $\square$

A **subnormal series** of a group G is a sequence of subgroups

$$1 = G_n \trianglelefteq \cdots \trianglelefteq G_2 \trianglelefteq G_1 \trianglelefteq G_0 = G,$$

with $G_n = 1$, $G_0 = G$ and $G_i \trianglelefteq G_{i-1}$ for all i. A **normal series** is a subnormal series in which each G_i is normal in G (not just in G_{i-1}). A **composition series** is a subnormal series in which each quotient G_{i-1}/G_i is simple, or equivalently (by the 2nd Isomorphism Theorem) it is a subnormal series in which $G_{i-1} \neq G_i$ and which cannot be 'refined' by inserting any additional groups: $G_i \triangleleft H \triangleleft G_{i-1}$.

Note: All finite groups must have a composition series (take G_i to be any maximal proper normal subgroup of G_{i-1} and note that eventually $G_n = 1$), however infinite groups do not necessarily have one. For example, $\mathbb{Z}$ has no composition series. Simple groups G have only one composition series: $1 \triangleleft G$.

Example $1 \triangleleft V \triangleleft A_4 \triangleleft S_4$ is a normal series but not a composition series. It can be refined to $1 \triangleleft \{1, (12)(34)\} \triangleleft V \triangleleft A_4 \triangleleft S_4$ which is a composition series, but is not normal.

Example $1 \triangleleft C_2 \triangleleft C_6$ and $1 \triangleleft C_3 \triangleleft C_6$ are two different composition series. The factor groups are C_2 and C_3 for both, but occur in a different order. For S_4 however, all composition series have factors C_2, C_2, C_3, C_2 in that order.

Theorem (Jordan-Hölder) *All composition series of a finite group G have the same composition factors (up to isomorphism) with the same multiplicities.*

Proof. We prove the result by induction on $|G|$, $|G| = 1$ being trivial. Suppose we have two composition series $1 \triangleleft \cdots \triangleleft G_1 \triangleleft G$ and $1 \triangleleft \cdots \triangleleft H_1 \triangleleft G$. If $H_1 = G_1$ then we are done by induction (applied to G_1). Hence we may assume $H_1 \neq G_1$. Let $1 \triangleleft \cdots \triangleleft K_1 \triangleleft G_1 \cap H_1$ be any composition series of $G_1 \cap H_1$. Now consider the following four series.

$$\begin{array}{lr}
1 \triangleleft \ldots \triangleleft G_3 \triangleleft \quad G_2 \quad \triangleleft G_1 \triangleleft G & (1) \\
1 \triangleleft \ldots \triangleleft K_1 \triangleleft G_1 \cap H_1 \triangleleft G_1 \triangleleft G & (2) \\
1 \triangleleft \ldots \triangleleft K_1 \triangleleft G_1 \cap H_1 \triangleleft H_1 \triangleleft G & (3) \\
1 \triangleleft \ldots \triangleleft H_3 \triangleleft \quad H_2 \quad \triangleleft H_1 \triangleleft G & (4)
\end{array}$$

Since $H_1 \neq G_1$ we may assume $H_1 \not\subseteq G_1$. Now $H_1, G_1 \trianglelefteq G$, so $G_1 \triangleleft H_1G_1 \trianglelefteq G$. Since (1) is a composition series, $H_1G_1 = G$. Thus by the 3rd Isomorphism Theorem $G/G_1 \cong H_1/(G_1 \cap H_1)$ and $G/H_1 \cong G_1/(G_1 \cap H_1)$. Thus both (2) and (3) have all their factors simple, and so are composition series for G. Moreover their factors are the same up to isomorphism. Now (1) and (2) have the same factors by induction applied to G_1, and (3) and (4) have the same factors by induction applied to H_1. Thus (1) and (4) have the same factors. $\square$

Exercise: Show that all the composition factors of a finite p-group are isomorphic to C_p.

A group G is **solvable** if it has a subnormal series $1 \trianglelefteq G_n \trianglelefteq \cdots \trianglelefteq G_1 \trianglelefteq G_0 = G$ where each quotient G_{i-1}/G_i is an abelian group. We will call this a solvable series.

Any abelian group is solvable even if it is infinite. Another interesting example is S_4 which has the solvable series $1 \trianglelefteq V \trianglelefteq A_4 \trianglelefteq S_4$. However S_5 is not solvable. Indeed $1 \triangleleft A_5 \triangleleft S_5$ is a composition series with an A_5 factor. Thus by Jordan-Hölder, every composition series, including one obtained by refining a solvable series would contain an A_5 factor, which is impossible since A_5 is not abelian. Indeed, for a finite group G, G is solvable if and only if all its composition factors are cyclic of prime order. In particular, all finite p-groups are solvable.

Define the **commutator subgroup** $G' = \langle \{xyx^{-1}y^{-1} : x, y \in G\} \rangle$ of G to be the subgroup of G generated by all **commutators** $xyx^{-1}y^{-1}$. (Note: not all elements of G' are necessarily commutators themselves, only products of commutators.)

Exercise: Show that (a) $G' \trianglelefteq G$; (b) for any $K \trianglelefteq G$, G/K is abelian iff $K \geq G'$; (c) if $H \leq G$ then $H' \leq G'$.

The n'th derived subgroup of G is defined inductively by $G^{(0)} = G$ and $G^{(n+1)} = (G^{(n)})'$. As a result we obtain the **derived** series of G:

$$\cdots \trianglelefteq G^{(2)} \trianglelefteq G^{(1)} \trianglelefteq G^{(0)} = G.$$

Note that this series may not reach 1. For example $A_5' = A_5$, so for $G = S_5$ the series is $\cdots \trianglelefteq A_5 \trianglelefteq A_5 \trianglelefteq A_5 \trianglelefteq S_5$.

Lemma 11.1 *A group G is solvable if and only if $G^{(n)} = 1$ for some n.*

Proof. If $G^{(n)} = 1$ then $1 = G^{(n)} \trianglelefteq \cdots \trianglelefteq G^{(1)} \trianglelefteq G$ is a solvable series for G. Conversely, we shall show that if $1 = G_n \trianglelefteq \cdots \trianglelefteq G_1 \trianglelefteq G$ is a solvable series then $G^{(i)} \leq G_i$, so in particular $G^{(n)} \leq G_n = 1$. We prove this by induction on i. For $i = 0$, $G^{(0)} = G_0 = G$. For $i > 0$, $G^{(i)} = (G^{(i-1)})' \leq (G_{i-1})'$, but $G'_{i-1} \leq G_i$ since G_{i-1}/G_i is abelian. □

Note that $G^{(n)} \trianglelefteq G$, so the derived series of a solvable group is in fact a normal series.

Lemma 11.2 *Let $H \leq G$ and $K \trianglelefteq G$.*

1. *If G is solvable then H is solvable.*
2. *If G is solvable then G/K is solvable.*
3. *If K and G/K are both solvable then G is solvable.*

Proof. 1. $H^{(n)} \leq G^{(n)}$. 2. $(G/K)^{(n)} = G^{(n)}K/K$. 3. Take a solvable series $K/K \trianglelefteq \cdots \trianglelefteq G_2/K \trianglelefteq G_1/K \trianglelefteq G/K$ for G/K and $1 \trianglelefteq \cdots \trianglelefteq K_2 \trianglelefteq K_1 \trianglelefteq K$ and put them together to form $1 \trianglelefteq \cdots \trianglelefteq K_2 \trianglelefteq K_1 \trianglelefteq K \trianglelefteq \cdots \trianglelefteq G_2 \trianglelefteq G_1 \trianglelefteq G$. This is a solvable series since $G_i/G_{i-1} \cong (G_i/K)/(G_{i-1}/K)$ is abelian. □