

Title

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1 List of Topics

Chapters 1-9 of Dummit and Foote

- Left and right cosets
- Lagrange's theorem
- Isomorphism theorems
- Group generated by a subset
- Structure of cyclic groups
- Composite groups
 - HK is a subgroup iff $HK = KH$
- Normalizer
 - $HK \leq H$ if $H \leq N_G(K)$
- Symmetric groups
 - Conjugacy classes are determined by cycle types
- Group actions
 - Actions of G on X are equivalent to homomorphisms from G into $\text{Sym}(X)$
- Cayley's theorem
- Orbits of an action
- Orbit stabilizer theorem
- Orbits act on left cosets of subgroups
- Subgroups of index p , the smallest prime dividing $|G|$, are normal
- Action of G on itself by conjugation
- Class equation
- p -groups
 - Have non trivial center
- p^2 groups are abelian
- Automorphisms, the automorphism group
 - Inner automorphisms
 - $\text{Inn}(G) \cong Z/Z(G)$
 - $\text{Aut}(S_n) = \text{Inn}(S_n)$ unless $n = 6$
 - $\text{Aut}(G)$ for cyclic groups
 - $G \cong Z_p^n$, then $\text{Aut}(G) \cong GL_n(Z_p)$
- Proof of Sylow theorems
- A_n is simple for $n \geq 5$

- Recognition of internal direct product
- Recognition of semi-direct product
- Classifications:
 - pq
- Free group & presentations
- Commutator subgroup
- Solvable groups
 - S_n is solvable for $n \leq 4$
- Derived series
 - Solvable iff derived series reaches e
- Nilpotent groups
 - Nilpotent iff all sylow-p subgroups are normal
 - Nilpotent iff all maximal subgroups are normal
- Upper central series
 - Nilpotent iff series reaches G
- Lower central series
 - Nilpotent iff series reaches e
- Frattini's argument
- Rings
 - I maximal iff R/I is a field
 - Zorn's lemma
 - Chinese remainder theorem
 - Localization of a domain
 - Field of fractions
 - Factorization in domains
 - Euclidean algorithm
 - Gaussian integers
 - Primes and irreducibles
 - Domains
 - * Primes are irreducible
 - UFDs
 - * Have GCDs
 - * Sometimes PIDs
 - PIDs
 - * Noetherian
 - * Irreducibles are prime
 - * Are UFDs
 - * Have GCDs
 - Euclidean domains
 - * Are PIDs
 - Factorization in $Z[i]$
 - Polynomial rings
 - Gauss' lemma
 - Remainder and factor theorem
 - Polynomials
 - Reducibility
 - Rational root test
 - Eisenstein's criterion

2 Groups

2.1 Definitions

2.1.1 Subgroup Generated by a set A

- $\langle A \rangle = \{a_1^{\pm 1}, a_2^{\pm 1}, \dots, a_n^{\pm 1} : a_i \in A, n \in \mathbb{N}\}$
- Equivalently, the intersection of all H such that $A \subseteq H \leq G$

2.1.2 Free Group on a set X

- Equivalently, words over the alphabet X made into a group via concatenation

2.1.3 Centralizer of an element or a subgroup

- $C_G(a) = \{g \in G : ga = ag\}$

•

$$C_G(H) = \{g \in G : \forall h \in H, gh = hg\} = \bigcap_{h \in H} C_G(h)$$

– Note - requires the same g on both sides!

- Facts:

- $C_G(H) \leq G$
- $C_G(H) \trianglelefteq N_G(H)$
- $C_G(G) = Z(G)$
- $C_H(a) = H \cap C_G(a)$

2.1.4 Center of a group

- $Z(G) = \{g \in G : \forall x \in G, gx = xg\}$

- Facts

–

$$Z(G) = \bigcap_{a \in G} C_G(a)$$

2.1.5 Normalizer of a subgroup

•

$$N_G(H) = \{g \in G : gHg^{-1} = H\}$$

- Equivalently, $\bigcup \{K : H \trianglelefteq K \leq G\}$ (the largest $K \leq G$ for which $H \trianglelefteq K$)
- Equivalently, the stabilizer of H under G acting on its subgroups via conjugation
- Differs from centralizer; can have $gh = h'g$
- Facts:
 - $C_G(H) \subseteq N_G(H) \leq G$
 - $N_G(H)/C_G(H) \cong A \leq \text{Aut}(H)$

- Given $H \subseteq G$, let

$$S(H) = \bigcup_{g \in G} gHg^{-1}$$

, so $|S(H)|$ is the number of conjugates to H . Then

$$|S(H)| = [G : N_G(H)]$$

* i.e. the number of subgroups conjugate to H equals the index of the normalizer of H .

2.1.6 Normal Core of a subgroup

-

$$H_G = \bigcap_{g \in G} gHg^{-1}$$

- Equivalently, $H_G = \langle N : N \trianglelefteq G \text{ \& } N \leq H \rangle$
 - Largest normal subgroup that contains H
- Equivalently, $H_G = \ker \psi$ where $\psi : G \rightarrow \text{Sym}(G/H)$; $g \sim (xH) = (gx)H$
- Facts:
 - $H_G \trianglelefteq G$ and is an idempotent operation

2.1.7 Normal Closure of a subgroup

- $H^G = \{gHg^{-1} : g \in G\}$
- Equivalently,

$$H^G = \bigcap \{N : H \leq N \trianglelefteq G\}$$

- (The smallest normal subgroup of G containing H)

2.1.8 Group Action of a group on a set

- Given as a function

$$\phi : G \times X \rightarrow X(g, x) \mapsto g \sim x$$

which gives rise to a function

$$\phi_g : X \rightarrow Xx \mapsto g \sim x$$

(which is a bijection) where \sim denotes a group element acting on a set element, and $\forall x \in X$,

- $e \sim x = x$
- $(gh) \sim x = g \sim (h \sim x)$

- Equivalently, a function

$$\psi : G \rightarrow \text{Sym}(X)g \mapsto \phi_g$$

–

$$\ker \psi = \bigcap_{x \in X} G_x$$

(intersection of all stabilizers)

- Interesting actions:

- Left multiplication of G on G :

$$\phi : G \rightarrow G \rightarrow G \quad g \mapsto \phi_g : G \rightarrow G \quad h \mapsto gh$$

$$* \mathcal{O}_x = G \text{ (transitive)}$$

$$* G_x = e$$

- G acting via conjugation on itself:

$$\phi : G \rightarrow G \rightarrow G \quad g \mapsto \psi_g : G \rightarrow G \quad h \mapsto ghg^{-1}$$

$$* \text{ A common notation is } x^g = g^{-1}xg \text{ which obeys } (x^g)^h = x^{gh}$$

$$* \mathcal{O}_x = [x] \text{ (Conjugacy classes, so not generally transitive)}$$

$$* G_x = \{g \in G : gxg^{-1} = x\} = C_G(x)$$

- G acting on $S = \{H : H \leq G\}$ via conjugation:

*

$$\phi : G \rightarrow S \rightarrow S \quad g \mapsto \psi_g : S \rightarrow S \quad H \mapsto gHg^{-1}$$

$$* \mathcal{O}_H = [H] = \{gHg^{-1} : g \in G\}, \text{ conjugate subgroups of } H$$

$$* G_x = N_G(H) = \{g \in G : gHg^{-1} = H\}$$

2.1.9 Transitive group actions

- $\forall x, y \in X, \exists g \in G : g \sim x = y$
- Equivalent, actions with a single orbit

2.1.10 Orbit of a set element

$$\mathcal{O}_x = \{g \sim x : x \in X\} = \bigcup_{g \in G} \{g \sim x\}$$

- The set of all orbits is denoted X/G or $X_G = \{\mathcal{O}_x : x \in X\}$
- Partitions X according to the equivalence relation $x \cong y \iff \exists g \in G : g \sim x = y$
- G acts transitively on X when restricted to any single orbit

2.1.11 Stabilizer of a set element

- $G_x = \{g \in G : g \sim x = x\}$
- Facts:
 - $G_x \leq G$, not usually normal
 - $x, y \in \mathcal{O}_x \Rightarrow G_x$ is conjugate to G_y

2.1.12 Automorphisms of a group

- $\text{Aut}(G) = \{\phi : G \rightarrow G : \phi \text{ is an isomorphism}\}$

2.1.13 Inner Automorphisms of a group

- $\text{Inn}(G) = \{\phi_g \in \text{Aut}(G) : \phi_g(x) = gxg^{-1}\}$

- Also consider the map

$$\psi : G \rightarrow \text{Aut}(G) \quad g \mapsto (\lambda : x \mapsto gxg^{-1})$$

Then $\text{im}\psi = \text{Inn}(G)$, $\ker\psi = Z(G)$

- Facts:
 - $\text{Inn}(G) \trianglelefteq \text{Aut}(G)$
 - $\text{Inn}(G) \cong G/Z(G)$

2.1.14 Outer Automorphisms of a group

- $\text{Out}(G) = \text{Aut}(G)/\text{Inn}(G)$

2.1.15 Conjugacy Class of an element

-

$$[a] = \{gag^{-1} : g \in G\} = \bigcup_{g \in G} \{gag^{-1}\}$$

- Equivalently, $[a] = \mathcal{O}_a$ under G acting on itself via conjugation
- Facts:
 - Equivalence relation, partitions the group
 - $|[a]|$ divides $|G|$
 - $a \in Z(G) \Rightarrow [a] = \{a\}$

2.1.16 Characteristic subgroup

- $H \text{ char } G \iff \forall \phi \in \text{Aut}(G), \phi(H) = H$
 - i.e., H is fixed by all automorphisms of G .

2.1.17 Simple group

- G is simple $\iff H \trianglelefteq G \Rightarrow H = e$ or G
 - No non-trivial normal subgroups

2.1.18 Commutator of an element, or of subgroups

- $[g, h] = ghg^{-1}h^{-1}$
- $[G, H] = \langle [g, h] : g \in G, h \in H \rangle$ (Subgroup generated by commutators)

2.2 Structural Results

- Cyclic \Rightarrow abelian
- $G/Z(G)$ cyclic $\Rightarrow G$ is abelian
- Intersections of subgroups are also subgroups

2.2.1 Isomorphisms Theorems

-*First Isomorphism Theorem**

- Conditions:
 - $\phi : G \rightarrow G'$ is a homomorphism.
- Result:
 - $\ker \phi \trianglelefteq G$
 - $\text{im} \phi \leq G'$
 - $G/\ker \phi \cong \text{im} \phi$.
- Corollaries:
 - $\ker \phi = e \Rightarrow G \cong G'$

-*Second Isomorphism Theorem**

- Conditions:
 - $N \trianglelefteq G, H \leq G$
- Results:
 - $HN \leq G$
 - $N \cap H \trianglelefteq H$
 -

$$\frac{H}{H \cap N} \cong \frac{HN}{N}$$

- Corollaries:
 - (Weaker) Relaxing $N \trianglelefteq G$ to $H \subseteq N(N)$ yields
 - * $N \cap H \subseteq G$ (Not normal)
 - * $N \cap H \trianglelefteq H$

-*Third Isomorphism Theorem**

- Conditions:
 - $N \trianglelefteq G, N \leq A \leq G$
- Results:
 - $A/N \leq G/N$
 - * Every subgroup of G/N is of this form for *some* such A
 -

$$\frac{G/N}{A/N} \cong \frac{G}{A}$$

* Cancel the N !

- Corollaries:
 - $A \trianglelefteq G \Rightarrow A/N \trianglelefteq G/N$
 - * All normal subgroups of G/N are of this form for some A .

2.3 Misc Results

- G/N is abelian $\iff [G, G] \leq N$
- HK is not always a subgroup - see conditions in 2nd Isomorphism theorem'
- $H \trianglelefteq G, K \trianglelefteq G$ and $H \cap K = e \Rightarrow hk = kh \forall h \in H, \in K$
 - Normal subgroups with trivial intersection commute
- $H \text{ char } G \Rightarrow H \trianglelefteq G$

- Characteristic is a strictly stronger condition than normality
- $H \text{ char } K \text{ char } G \Rightarrow H \text{ char } G$
 - Characteristic is transitive
- $H \leq G, K \trianglelefteq G, H \text{ char } K \Rightarrow H \trianglelefteq G$
 - i.e., normality is **not** transitive, strengthening normality to char gives “weak transitivity”
- Recognizing (Internal) Direct Products: $H \leq G, K \leq G$
 - $H \cap K = e$
 - $\forall g \in G, \exists h \in H, k \in K : g = hk$
 - $H \trianglelefteq G, K \trianglelefteq G$
 - * **OR** Every element in H commutes with every element in K
- P Groups
 - $\bigcap P = O_P(G) \text{ char } G$. And $O_P(G) \trianglelefteq G$ as well.
 - $N \trianglelefteq G$ implies that $P_N \leq N$ are of the form $N \cap P_G$
 - $P \cap Q = e$

2.4 Numeric Results

2.4.1 Cauchy's Theorem

- For any p dividing $|G|$, there is a subgroup of order p .

2.4.2 Sylow Theorems: $|G| = p^k m$ where $p \nmid m$

- At least one Sylow- p subgroup always exists: $\exists P \leq G$ with $|P| = p^k$
- All such subgroups are conjugate: $\forall P, P', \exists g \in G : gPg^{-1} = P'$
- n_p satisfies:
 - n_p divides $m = [G : P]$
 - $n_p \equiv 1 \pmod{p}$
 - $n_p = [G : N_G(P)]$ (Not as useful)
- Every p -subgroup of G is a p -subgroup of P (i.e. P is maximal and contains all subgroups of order p^l with $l \leq k$)

2.4.3 Orbit-stabilizer Theorem

- Given a group action, $G/G_x \cong \mathcal{O}_x$
- Gives the numeric result $|\mathcal{O}_x| = |G/G_x| = [G : G_x] = \frac{|G|}{|G_x|}$
- Also useful in the form $|G| = |\mathcal{O}_x| |G_x|$
- Proof:
 - Use the map

$$\phi : G \rightarrow Xg \mapsto g \sim x$$

Where $\text{im}\phi = \mathcal{O}_x$ and $\ker\phi = G_x$.

2.4.4 Burnside's Lemma

•

$$|X_G| = \frac{1}{|G|} \sum_{g \in G} |X^g|$$

- $|X_G|$ is the number of orbits
- $X^g = \{x \in X : g \sim x = x\}$

2.4.5 The class equation

•

$$|G| = |Z(G)| + \sum_{a \in A} [G : C_G(a)]$$

- Where $A = \{a_1, a_2, \dots, a_n : a_1 \in [a_1], a_2 \in [a_2], \dots\}$ is a set containing one element from each conjugacy class
- $[G : C_G(a)]$ is the number of elements in $[a]$
- Each element in $Z(G)$ has a singleton conjugacy class

2.4.6 General facts

- $|G| = p \Rightarrow G$ is cyclic
- $|G| = p^e \Rightarrow Z(G) \neq e$
- $|G| = p^e$ (P-groups)
 - $Z(G) \neq \{e\}$ (Use class equation)
- $|G| = p$
 - Always cyclic
 - * Proof: Any nontrivial cyclic subgroup's order is > 1 and divides p , so equals p .
- $|G| = p^2$
 - Always abelian
 - * Proof: $|G/Z(G)| = 1, p$. If p , it's cyclic, and G is abelian. Otherwise it's 1, so $G = Z(G)$.
 - Two possibilities:
 - * Z_{p^2} (cyclic)
 - * $Z_p \times Z_p$
- $|G| = pq$
 - $p \nmid q-1$ ($q \not\equiv 1 \pmod p$):
 - * One possibility:
 - $G \cong Z_{pq}$ (cyclic)
 - * Facts:
 - $\exists P \trianglelefteq G$ (A Sylow- P subgroup)
 - p divides $q-1$ ($q \equiv 1 \pmod p$):
 - * Two possibilities:

- $G \cong Z_{pq}$ (cyclic)
 - $G \cong Z_q \rtimes Z_p$
- Never simple
- $|G| = p^2q$
 - $\exists P \trianglelefteq G$ (A Sylow- P subgroup)
- $|G| = p_1p_2p_3$ (distinct)
 - Not simple

2.5 Common Groups

2.5.1 S_3

$$S_3 = \langle (12), (23), (13) \rangle$$

- $Z(S_3) = e$
- $\text{Aut}(S_3) = \text{Inn}(S_3)$, since

$$Z(G) = e = \ker \psi \Rightarrow \text{Out}(S_3) = \text{Inn}(S_3) \Rightarrow \text{Aut}(S_3) \cong S_3$$

2.5.2 S_n

$$S_n, n \geq 4$$

- $Z(S_n) = e$
 - Let $\sigma(a) = b$, choose $\tau = (bc)$ so $\tau\sigma(a) = \tau(b) = c \neq b = \sigma(a) = \sigma\tau(a)$
- Conjugacy classes are determined entirely by cycle structure
 - There are exactly $p(n)$ of them (partition function)
- Disjoint cycles commute
- $\sigma \circ (a_1 \cdots a_k) \circ \sigma^{-1} = (\sigma(a_1), \cdots \sigma(a_k))$
- Every element is a product of disjoint cycles
- Every element is a product of transpositions
 - A cycle of length k can be written as $k - 1$ transpositions
 - Parity of the cycle equals the parity of $k - 1$.
- The order of an element is the lcm of the size of the cycles.

2.5.3 A_n

- Simple for $n \geq 5$
- Index 2 in S_n , so $A_n \trianglelefteq S_n$

2.5.4 D_n

- $\langle a, b \mid a^n = b^2 = 1, bab^{-1} = a^{-1} \rangle \cong \langle r, s \rangle$
- D_n/N is always another dihedral group for any $N \trianglelefteq D_n$
- All subgroups:
 - $\langle r^d \rangle \cong Z_{n/d}$ where d divides n (index $2d$)
 - $\langle r^d, r^i s \rangle \cong D_{\frac{n}{d}}$ where d divides n and $0 \leq i \leq d - 1$ (index d)

* All dihedral

3 Rings

3.1 Facts about ideals:

- Intersections, products, and sums of ideals are ideals
- Not necessarily unions
- Every ring has proper maximal ideals
- Apply Z.L. to $\{I \trianglelefteq R : I \neq R\}$
- Every proper ideal is contained in a maximal ideal

3.2 Maximal ideals

$I \trianglelefteq R$ maximal if $\nexists J \trianglelefteq R : I \subset J \subset R$

- Every nonzero ring has a maximal ideal (Krull's Theorem)
- R commutative $\implies R/I$ a field
- Union of maximal ideals $= R - R^\times$
- $(X - a) \trianglelefteq R[X]$ is maximal for $a \in R$

3.3 Prime ideals

$I \trianglelefteq R$ prime when $pq \in I \implies p \in I \vee q \in I$

- I prime $\iff R/I$ an integral domain,
- (maximal \implies prime)
- $\text{rad}(I^n) = I$

3.4 Radicals

$I \trianglelefteq R$ radical when $\forall a \in R, a^n \in I \implies a \in I$

- The nilradical: $\text{nilrad}(I) = \bigcap P$ such that $P \trianglelefteq R$ is prime
- $\text{rad}(I) = \{x \in R : \exists n : x^n \in I\}$
- $\text{rad}(0) = \text{nilrad}(R)$
- $\text{rad}(IJ) = \text{rad}(I) \cap \text{rad}(J)$
- $\text{rad}(I) = \bigcap J$ such that $I \subset J, J$ prime (i.e. intersection of all prime ideals containing I)

3.5 Other ideals

- $I \trianglelefteq R$ primary when $pq \in I \implies p \in I \vee \exists n \in \mathbb{N} : b^n \in I$
- Prime \implies primary
- $I \trianglelefteq R$ principal when $\exists a \in R : I = \langle a \rangle$
- $I \trianglelefteq R$ irreducible when $\nexists \{J \trianglelefteq R : I \subset J\} : I = \bigcap J$

- $I \subset R \iff 1, u \notin I \ (u \in R^\times)$
- $\{I : I \trianglelefteq R\}$ is a poset
- Zorn's lemma can be applied to $\{I \trianglelefteq R : 1 \notin I\}$
- Every proper ideal is contained in a maximal ideal.
- Facts about units
- R^\times is closed under multiplication, but *not* under addition.
- $R - R^\times$ an additive group $\iff R$ is a local ring
- Integral Domain
- Principal Ideal Domain
- (Prime \implies maximal) \implies UFD
- Unique Factorization Domain
- Field
- When (0) is the only proper ideal
- R/M a field $\iff M$ maximal
- Localization
- Zorn's Lemma: For every poset P , every chain in P has an upper bound $\implies P$ has a maximal element.
- Noetherian: Every ideal is finitely generated
- iff the ascending chain condition for ideals holds

3.6 Orders less than 16:

(Normal: Diamond, grouped by conjugacy class)

- 1 (The trivial group)
 - $Z_1 = \{e\}$
- 2 (One group)
 - $Z_2 \cong Z_3^\times \cong Z_4^\times \cong Z_6^\times$
 $= \{e, a\}$
 * Cyclic
 * One element of order 2
- 3 (One group)
 - $Z_3 \cong A_3$
 $\cong \{(), (123), (132)\}$
 * Cyclic
 * One element of order 3

- 4 (*Two groups, both abelian*)

- $Z_4 \cong Z_5^\times \cong Z_8^\times \cong Z_{10}^\times \cong Z_{12}^\times$

- * Cyclic

- * One element of order 4

- $Z_2 \times Z_2 \cong V_4 \cong D_2 \cong Z_8^\times$, which are all isomorphic to $\langle a, b \mid a^2 = b^2 = (ab)^2 = e \rangle \cong \langle (12)(34), (13)(24), (14)(23) \rangle$

- * Not cyclic, but abelian

- * All elements have order 2

- * $V_4 \trianglelefteq A_4 \leq S_4$



–

- 5 (*One group*)

- Z_5

- * Cyclic, one element of order 5

- 6 (*Two groups*)

- $Z_6 \cong Z_7^\times \cong Z_9^\times \cong Z_{14}^\times$

- * Cyclic, one element of order 6

- $S_3 \cong D_6$

- $\cong \langle a, b, c \mid a^2 = b^2 = c^3 = abc = e \rangle$

- * Non-abelian (smallest one)

– ! [img] (data:image/png;base64,iVBORwOKGgoAAAANSUhEUgAAArwAAAHOCAYAAADfWf7fAAAQAE1EQVR4Xuzd

- 7 (*One group*)

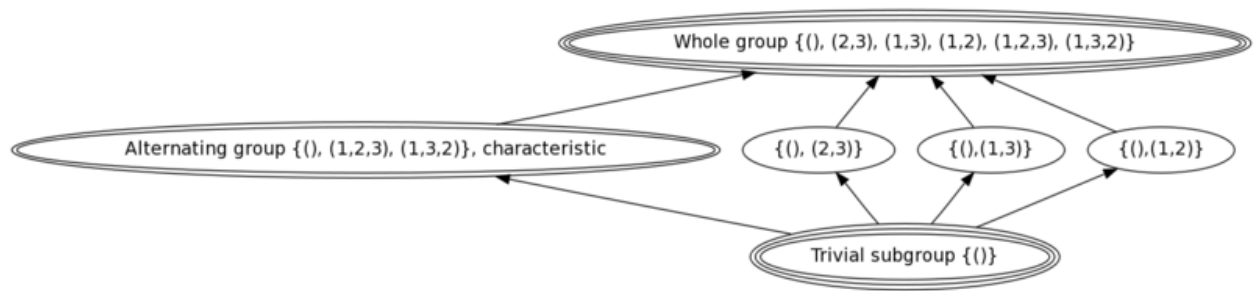
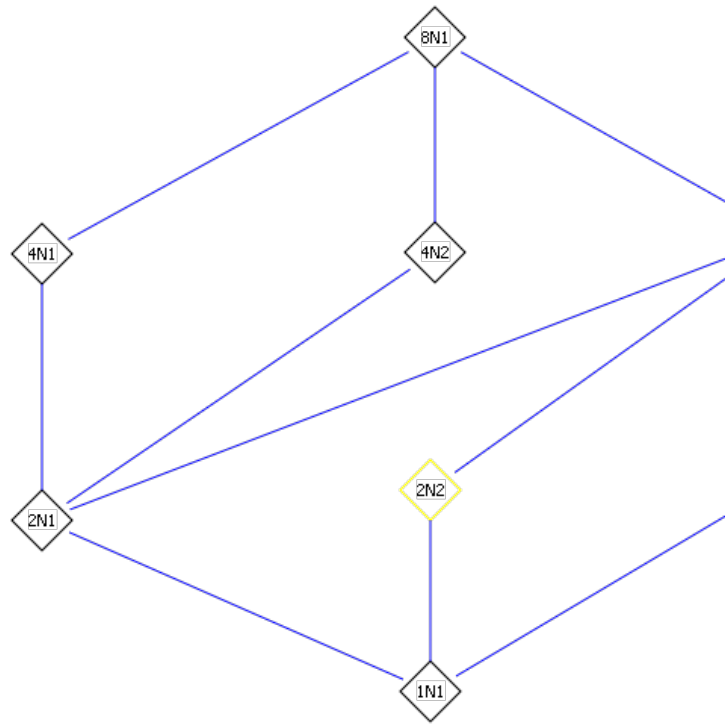


Figure 1: File:S3latticeofsubgroups.png

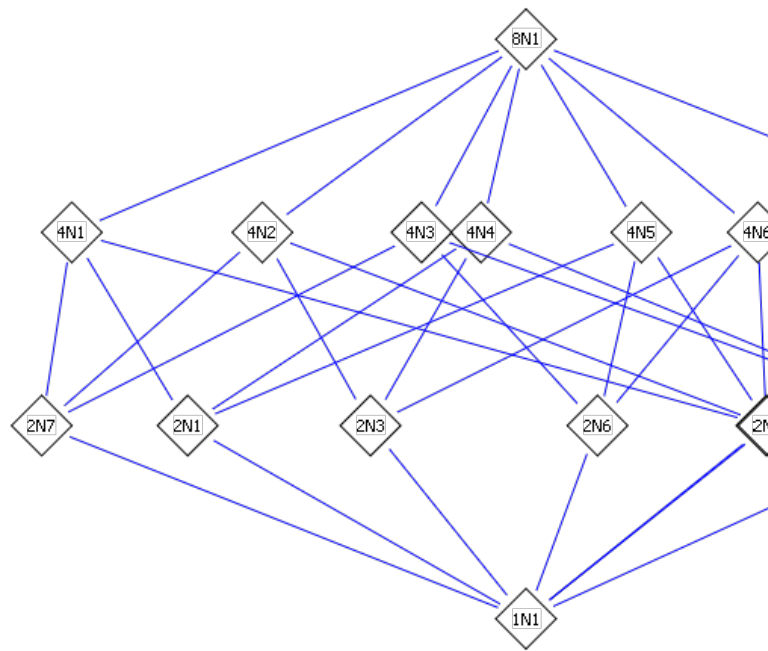
- Z_7
 - * Cyclic, one element of order 7
- 8 (Five groups)



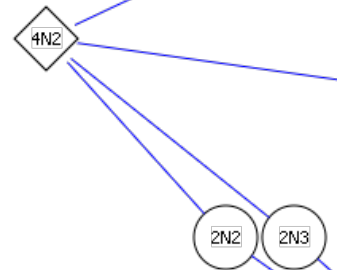
- $Z_8 \cong Z_{15}^\times \cong Z_{16}^\times$ (cyclic)
- $Z_2 \times Z_4$



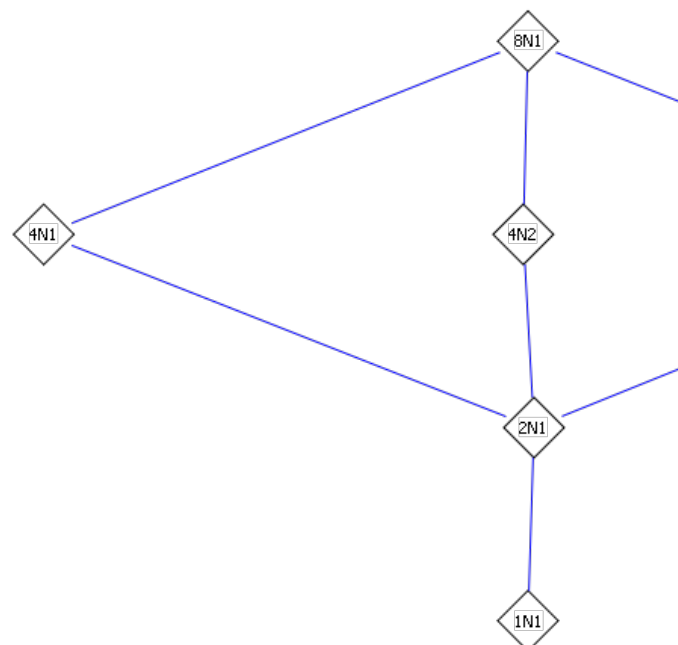
- * Abelian, one element of order 4
- $Z_2 \times Z_2 \times Z_2$



- * Abelian, every element has order 2
- $D_8 \cong \langle r, s \mid r^4 = s^2 = e, srs^{-1} = r^{-1} \rangle$



- $\cong \{(), (1234), (13)(24), (1432), (13)(24), (14)(23), (12)(34)\} \leq S_4$
- $Q_8 \cong \langle i, j, k \mid i^2 = j^2 = k^2 = ijk \rangle$
- $\cong \langle a, b, c \mid a^4 = b^4 = e, a^2 = b^2, ba = a^3b \rangle$
- * Every element has order 4



- * All subgroups are normal, but not abelian
- 9 (*Two groups*)

- Z_9
 - $Z_3 \times Z_3$
- 10 (*Two groups*)
 - $Z_{10} \cong Z_{11}^\times$
 - D_{10}
- 11 (One group)
 - Z_{11}
- 12 (**Five groups**)
 - $Z_{12} \cong Z_{13}^\times$
- 13 (One group)
 - Z_{13}
- 14 (*Two groups*)
 - Z_{14}
- 15 (One group)
 - Z_{15}
- 16 (***Fourteen groups!***)