Algebra: Chapter 0 Exercises
Chapter 2, Section 8

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Problem 8.1. If a group H may be realized as a subgroup of two groups G_1 and G_2, and

$$\frac{G_1}{H} \cong \frac{G_2}{H},$$

does it follow that $G_1 \cong G_2$? Give a proof or counterexample

Solution. No. As a counterexample, take $G_1 = D_6$, $G_2 = C_6$, and $H = C_3$. In this case, we have $D_6/C_3 \cong C_2 \cong C_6/C_3$, but $D_6 \not\cong C_3$. ■

Problem 8.2. Suppose G is a group, and $H \subseteq G$ is a subgroup of index 2. Prove that H is normal in G.

Solution. Consider the function $\varphi : G \to C_2$ defined by

$$\varphi(g) = \begin{cases} 0 & g \in H \\ 1 & g \notin H \end{cases}$$

To check that this is a homomorphism, suppose $g_1, g_2 \notin H$. In particular, $g_2^{-1} \notin H$, so

$$g_1 H = g_2^{-1} H,$$

since there are only two left cosets of H in G, so

$$g_1 g_2 \in H$$

and hence

$$\begin{aligned} \varphi(g_1 g_2) &= 0 \\ &= 1 + 1 \\ &= \varphi(g_1) + \varphi(g_2). \end{aligned}$$

Clearly $\ker\ \varphi = H$, so H is normal in G. ■

Problem 8.7. Let $\langle A|\mathscr{R}\rangle$ resp. $\langle A'|\mathscr{R}'\rangle$ be presentations for two groups G resp. G'; we may assume that A and A' are disjoint. Prove that the groups $G * G'$ presented by

$$\langle A \cup A' | \mathscr{R} \cup \mathscr{R}'\rangle$$

satisfies the universal property for the coproduct of G and G' in **Grp**.

Solution. Let G, G' and $A, A', \mathscr{R}, \mathscr{R}'$ be as described above, let R resp. R' resp. $\hat{R}$ be the normal closures of $\mathscr{R}$ resp. $\mathscr{R}'$ $\mathscr{R} \cup \mathscr{R}'$, and let H be any group. Consider the diagram below, in which we use the universal properties of free groups and quotient groups to construct two morphisms $\tau : G \to G * G'$ and $\tau' : G' \to G * G'$:

$$\begin{tikzcd}
& H & \\
\frac{F(A)}{R} \arrow[ur, "\varphi"] \arrow[r, dashed, "\tau"] & \frac{F(A\cup A')}{\hat{R}} \arrow[u, dashed, "\hat{\varphi}"'] & \frac{F(A)}{R'} \arrow[ul, "\varphi'"'] \arrow[l, dashed, "\tau'"'] \\
F(A) \arrow[u, "\pi"] \arrow[ur, "q"] \arrow[r, dashed, "p"] & F(A \cup A') \arrow[u, "\hat{\pi}"] & F(A') \arrow[u, "\pi'"'] \arrow[ul, "q'"'] \arrow[l, dashed, "p'"'] \\
A \arrow[u, "j"] \arrow[ur, "u"] \arrow[r, "\iota"] & A \cup A' \arrow[u, "\hat{j}"] & A' \arrow[u, "j'"'] \arrow[ul, "u'"'] \arrow[l, "\iota'"']
\end{tikzcd}$$

Here, ι and ι' are canonical inclusions (since A and A' are disjoint), $j, \hat{j}, j'$ are the canonical inclusions into the free groups, u resp. u' are defined by $\hat{j}\iota$ resp. $\hat{j}\iota'$, and p and p' are obtained by applying the universal property of free groups.
The morphisms $\pi, \hat{\pi}$, and π' are the canonical projections, q resp q' are defined by $\hat{\pi}p$ resp. $\hat{\pi}p'$, and τ and τ' are obtained by invoking the universal property of quotient groups.
Finally, φ, φ' are any morphisms, and we propose that there exists a unique morphism $\hat{\varphi}$ such that $\hat{\varphi}\tau = \varphi$ and $\hat{\varphi}\tau' = \varphi'$. For this, we simply must prove that if we define $\hat{\varphi}$ by those two relations, then $\hat{\varphi}$ is well defined.
Hence, suppose $\tau(w_1 R) = \tau(w_2 R)$. We then have

$$\tau(\pi(w_1)) = \tau(\pi(w_2)),$$

and hence

$$q(w_1 w_2^{-1}) = 0.$$

Note that

$$\begin{aligned}
\ker q &= \ker(\hat{\pi}p) \\
&= \ker(p) \cup p^{-1}(\ker \hat{\pi}) \\
&= p^{-1}(\ker \hat{\pi}) \\
&= p^{-1}(\hat{R}) \\
&= R.
\end{aligned}$$

This tells us that $w_1 w_2^{-1} \in R$, and so $w_1 R = w_2 R$; hence τ is injective. The same reasoning applies to τ'. Since $F(A \cup A')/\hat{R}$ is generated by the images of τ and τ', this $\hat{\varphi}$ is well-defined, and hence unique. ∎

Problem 8.12. Prove 'by hand' (that is, by using Proposition 6.2), that if H, K are subgroups of G, then HK is a subgroup of G if H is normal.

Solution. Let h_1, h_2 and k_1, k_2 be in H and K, respectively. We then have

$$\begin{aligned}(h_1k_1)(h_2k_2)^{-1} &= h_1k_1k_2^{-1}h_2^{-1} \\ &= k_1(k_1^{-1}h_1k_1)(k_2^{-1}h_2^{-1}k_2)k_2^{-1} \\ &= k_1h'h''k_1^{-1} \\ &\in H.\end{aligned}$$

Hence HK is a group by Proposition 6.2. ■

Problem 8.13. Let G be a finite commutative group, and assume $|G|$ is odd. Prove that every element of G is a square.

Solution. Let $g \in G$. Since $|G|$ is odd, $|g|$ is also odd (by Lagrange's Theorem), so $|g|+1$ is even. We then have

$$\begin{aligned}\left(g^{\frac{|g|+1}{2}}\right)^2 &= g^{|g|+1} \\ &= g\end{aligned}$$

Hence g is a square. ■

Problem 8.14. Generalize the result of Exercise 8.13: if G is a group of order n, and k is an integer relatively prime to n, then the function $G \to G$, $g \mapsto g^k$ is surjective.

Proof. Suppose $g \in g$. If $\gcd(k, n) = 1$, then by Lagrange's Theorem, we have $\gcd(|g|, k) = 1$ as well. Hence there exist integers a and b such that $a|g| + bk = 1$. Let a, b be integers that satisfy this property. We then have:

$$\begin{aligned}g &= g^{a|g|+bk} \\ &= g^{a|g|}g^{bk} \\ &= g^{bk} \\ &= (g^b)^k\end{aligned}$$

Hence every $g \in G$ is in the image of the map mentioned above. □

Problem 8.15. Let a, n be positive integers. Prove that n divides $\phi(a^n - 1)$, where ϕ is Euler's ϕ-function.

Solution. Let $m = a^n - 1$, and consider the group $G = (\mathbb{Z}/m\mathbb{Z})^*$. If $a = 1$ then the question is nonsense, and if $n = 1$ then clearly $1|\phi(a-1)$. Hence, assume that $m > 1$ and $n > 1$. We know that $a \in G$ because $a^n - 1 > a$ and $\gcd(a, a^n - 1) = 1$. We also know that

$$a^n \equiv 1 \mod m.$$

Since $x < n$ implies

$$1 < a \leq a^x < a^n - 1,$$

it then follows that $|a| = n$, and hence $n \mid |G| = \phi(a^n - 1)$. ■

Problem 8.16. Generalize Fermat's Little Theorem to congruences modulo arbitrary integers.

Solution.

Euler's Theorem. Let a, b be positive integers. Then

$$a^{\phi(n)} \equiv 1 \mod n.$$

Proof. We have $[a^{\phi(n)}]_n = [1]_n$ in $(\mathbb{Z}/n\mathbb{Z})^*$. □

■

Problem 8.17. Assume G is a finite abelian group, and let p be a prime divisor of $|G|$. Prove that there exists an element in G of order p.

Solution. Let $G_0 = G$. We will soon define each G_k to be a quotient G_{k-1}/H, where H is a subgroup of prime order. We will proceed by (strong) induction on this subscript k, proving that, for $0 \leq k < \Omega(|G|)$:

1. If $\Omega(n)$ is the number of prime divisors of n including multiplicity, then
$$\Omega(|G_k|) = \Omega(|G|) - k.$$
2. There exists an element of $|G_k|$ of prime order.
3. If $g \in G_k$, has prime order p, then there exists an element of G of order p.

Proof.
Base case (n=0): Let $G_0 = G$.

1. $\Omega(|G_0|) = \Omega(|G|) = \Omega(|G|) - 0$
2. Let $g_0 \in G_0$, and for some prime divisor q_0 of $|g_0|$, let $h_0 = g_0^{\frac{|g_0|}{q_0}}$. We then have $|h_0| = q_0$, hence (2) holds.
3. Trivial.

Induction ($n = k + 1$): Suppose (1), (2), and (3) hold for $n \leq k$. Let $H_k = \langle h_k \rangle$ (which is normal because G is abelian), and define $G_{k+1} = G_k/H_k$.

1. We have:
$$\begin{aligned} \Omega(|G_{k+1}|) &= \Omega\left(\left|\frac{G_k}{H}\right|\right) \\ &= \Omega\left(\frac{|G_k|}{|H|}\right) \\ &= \Omega\left(\frac{|G_k|}{q}\right) \\ &= \Omega(|G_k|) - 1 \\ &= \Omega(G) - k - 1 \end{aligned}$$
as desired.

2. Same as the base case - let q_{k+1} be a prime divisor of $|G_{k+1}|$, let $g_{k+1} \in G_{k+1}$, and define $h_{k+1} := g^{\frac{|g_{k+1}|}{q_{k+1}}}$. Then $|h_{k+1}| = q_{k+1}$.
3. Suppose $gH_k \in G_{k+1}$ has order p, where p is a prime divisor of $|G_{k+1}|$. It then follows that $(gH_k)^p = e$, and so $g^p = h_k^m$ for some integer m. Since $e = (h^k)^x = g^{px}$ for some $x = |h^k|$, we then have $|g^x| = p$ in G_k. By our inductive hypothesis, then, we have an element of G of order p, as desired.

The set $\{q_0, \ldots, q_n\}$ where $n = \Omega(G) - 1$ is the set of all prime divisors of $|G|$, since at each step of the process we have removed a prime divisor before choosing a new one.. At the end of this process, we have proven that G contains an element of order q_n for each n, and hence an element of order p for each prime divisor p of $|G|$. $\square$

$\blacksquare$

Solution. [Alternative (better) proof]
Let p be any prime divisor of $|G|$. We will proceed by strong induction on $|G|$.
Base Case ($|G| = p$): Since $|G|$ is of prime order, it is cyclic, and so any non-identity element will be a generator, i.e. of order p.
Induction ($|G| = n$): Suppose the statement holds for every group of order $p \leq k < n$. Take some $g \in G$, and consider the group $\langle g \rangle$. If we take some prime divisor q of $|g|$, then $h := g^{\frac{|g|}{q}}$ has order q. If $q = p$, then we're done. Otherwise, let $H =< h >$, and consider the group G/H.
We know that $\left|\frac{G}{H}\right| = \frac{|G|}{q} < |G|$. Moreover, p divides $|H|$, so by our inductive hypothesis, there exists a $gH \in G/H$ of order p. The same argument from part 3 of the inductive step of the other proof of this exercise applies here, giving us an element of G of order p, as desired. $\blacksquare$

Problem 8.18. Let G be an abelian group of order $2n$, where n is odd. Prove that G has exactly one element of order 2.

Solution. Let g, h be distinct elements of G. If g and h both have order 2, then the subgroup generated by g and h equals $\{e_G, g, h, gh\}$, which has order 4. But 4 is not a divisor of $|G| = 2n$ for n odd (otherwise n would be even), so g and h do not both have order 2.
This does not necessarily hold if G is not commutative. A counterexample is the dihedral group D_6, where $f \neq rfr^{-1}$ both have order 2. $\blacksquare$

Problem 8.19. Let G be a finite group, and let d be a proper divisor of $|G|$. Is it necessarily true that there exists an element of G of order d?

Solution. No. The group S_4 has no elements of order 8, or more generally, of order greater than 4. $\blacksquare$