Homework 6

Due: Mar 16th (Wednesday Class)

- Please make sure your handwriting is clear enough to read. Thanks.
- No late work will be accepted.

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(1) Finish the proof of ($\star\star$) in Lecture Slides §3.5, #14/18. That is to say,

If $G_1 \cong H_1$ and $G_2 \cong H_2$, then $G_1 \times G_2 \cong H_1 \times H_2$.

Proof: Let $\theta_1 : G_1 \to H_1, \theta_2 : G_2 \to H_2$. Define $\phi : G_1 \times G_2 \to H_1 \times H_2$ by

$$\phi\big((x_1, x_2)\big) = \big(\theta_1(x_1), \theta_2(x_2)\big), \quad \text{for all } (x_1, x_2) \in G_1 \times G_2.$$

To show ϕ is a group isomorphism.

If $G_1 \cong H_1$ and $G_2 \cong H_2$, then $G_1 \times G_2 \cong H_1 \times H_2$.

Let $\theta_1 : G_1 \to H_1$ and $\theta_2 : G_2 \to H_2$. Define $\phi : G_1 \times G_2 \to H_1 \times H_2$ by

$$\phi((x_1, x_2)) = (\theta_1(x_1), \theta_2(x_2)), \text{ for all } (x_1, x_2) \in G_1 \times G_2.$$

Claim: ϕ is a group isomorphism.

(i) well-defined: Trivial since $\theta_1(x_1) \in H_1$ and $\theta_2(x_2) \in H_2$.

(ii) ϕ respects the two operations: For any $(x_1, x_2), (y_1, y_2) \in G_1 \times G_2$

$$\begin{aligned}\phi((x_1, x_2)(y_1, y_2)) =& \phi((x_1 y_1, x_2 y_2)) \\ =& (\theta_1(x_1 y_1), \theta_2(x_2 y_2)) \\ =& (\theta_1(x_1)\theta_1(y_1), \theta_2(x_2)\theta_2(y_2)) \\ =& (\theta_1(x_1), \theta_2(x_2))(\theta_1(y_1), \theta_2(y_2)) \\ =& \phi((x_1, x_2))\phi((y_1, y_2))\end{aligned}$$

(iii) one-to-one: If $\phi((x_1, x_2)) = (\theta_1(x_1), \theta_2(x_2)) = (e_{H_1}, e_{H_2})$, then

$$\theta_1(x_1) = e_{H_1} \Rightarrow x_1 = e_{G_1}$$
$$\theta_2(x_2) = e_{H_2} \Rightarrow x_2 = e_{G_2}$$

and so $(x_1, x_2) = (e_{G_1}, e_{G_2}) = e_{G_1 \times G_2}$.

(iv) onto: Trivial since θ_1 and θ_2 are two groups isomorphisms. In particular, for any element $(h_1, h_2) \in H_1 \times H_2$, we can always find $x_1 \in G_1$ and $x_2 \in G_2$ such that $\theta_1(x_1) = h_1$ and $\theta_2(x_2) = h_2$, and so $\phi((x_1, x_2)) = (h_1, h_2)$.

(2) Let G be a group and let $a \in G$ be an element of order 30. List the powers of a that have order 2, order 3 or order 5.

Since $o(a) = 30 = |\langle a \rangle|$, then we have $\langle a \rangle \cong \mathbf{Z}_{30}$. In particular, you can think about the cyclic subgroup $\langle a \rangle$ generated by $a \in G$ is the "multiplicative version" of the additive group $\mathbf{Z}_{30}$. Thus, we have

$$\langle a^j \rangle = \langle a^d \rangle, \text{ where } d = (j, 30) \text{ and so } o(a^j) = |\langle a^j \rangle| = |\langle a^d \rangle| = \frac{30}{d}.$$

(i) $o(a^j) = 2 = \dfrac{30}{d} \Rightarrow d = (j, 30) = 15 \Rightarrow j = 15.$

(ii) $o(a^j) = 3 = \dfrac{30}{d} \Rightarrow d = (j, 30) = 10 \Rightarrow j = 10, 20.$

(iii) $o(a^j) = 5 = \dfrac{30}{d} \Rightarrow d = (j, 30) = 6 \Rightarrow j = 6, 12, 18, 24.$

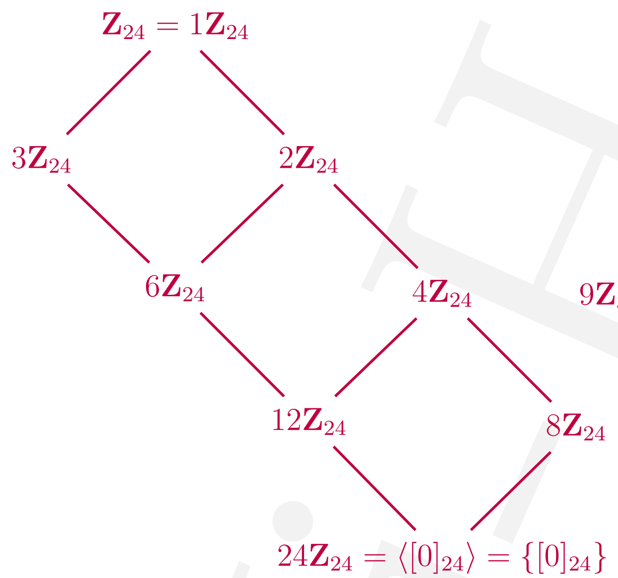
(3) Give the subgroup diagrams of the following groups.

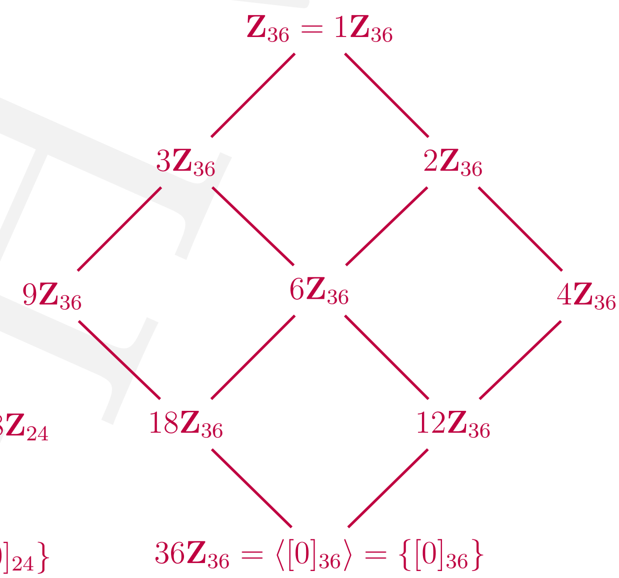
(a) $\mathbf{Z}_{24}$

(b) $\mathbf{Z}_{36}$

$24 = 2^3 3^1$: Any divisor $d = 2^i 3^j$, where $i = 0, 1, 2, 3$ and $j = 0, 1$.

$36 = 2^2 3^2$: Any divisor $d = 2^i 3^j$, where $i = 0, 1, 2$ and $j = 0, 1, 2$.





(4) Which of $\mathbf{Z}_{18}^{\times}, \mathbf{Z}_{20}^{\times}$ are cyclic? (*Hint: Do not use The Primitive Root Theorem. Check Lecture Slides §3.5, #17/18*)

(a) Check $\mathbf{Z}_{18}^{\times} : \varphi(18) = 18(1 - \frac{1}{2})(1 - \frac{1}{3}) = 6$

$$\mathbf{Z}_{18}^{\times} = \{[1], [5], [7], [11], [13], [17]\} = \{\pm[1], \pm[5], \pm[7]\}$$

(i) $[5]^2 = [25] = [7], [5]^3 = [35] = [-1]$, so $o([5]) = 6$ (Lagrange's Thm).

This implies that $\mathbf{Z}_{18}^{\times} = \langle [5] \rangle$, and so $\mathbf{Z}_{18}^{\times}$ is cyclic.

(b) Check $\mathbf{Z}_{20}^{\times} : \varphi(20) = 20(1 - \frac{1}{2})(1 - \frac{1}{5}) = 8$

$$\mathbf{Z}_{20}^{\times} = \{[1], [3], [7], [9], [11], [13], [17], [19]\} = \{\pm[1], \pm[3], \pm[7], \pm[9]\}$$

(i) $[3]^2 = [9], [3]^3 = [27] = [7], [3]^4 = [21] = [1]$, so $o([3]) = 4$.

(ii) There is no need to try $[7], [9]$ since $[7], [9] \in \langle [3] \rangle$.

(iii) $[11] = [-9], [11]^2 = [-9]^2 = 1$, so $o([11]) = 2$.

(iv) $[13] = [-7], [13]^2 = [-7]^2 = [9], [13]^4 = [9]^2 = [1]$, so $o([13]) = 4$. Why $o([13]) \neq 3$? Think about Lagrange's Theorem!

(v) $[17] = [-3], [17]^4 = [-3]^4 = 1$, so $o([17]) \leq 4$ since $o([17]) | 4$.

(vi) $[19] = [-1], [19]^2 = [-1]^2 = 1$, so $o([19]) = 2$.

This implies that there is no element of order 8, and so $\mathbf{Z}_{20}^{\times}$ is not cyclic.

(5) Prove that $\mathbf{Z}_{10}^{\times}$ is not isomorphic to $\mathbf{Z}_{12}^{\times}$. (*Hint: Do not use The Primitive Root Theorem. Check Lecture Slides §3.5, #18/18*)

(a) Check $\mathbf{Z}_{10}^{\times} : \varphi(10) = 10(1-\frac{1}{2})(1-\frac{1}{5}) = 4$

$$\mathbf{Z}_{10}^{\times} = \{[1],[3],[7],[9]\} = \{\pm[1], \pm[3]\}$$

(i) $[3]^2 = [9]$, so $o([3]) = 4$ (Lagrange's Thm).

This implies that $\mathbf{Z}_{10}^{\times} = \langle [3] \rangle$, and so $\mathbf{Z}_{10}^{\times}$ is cyclic.

(b) Check $\mathbf{Z}_{12}^{\times} : \varphi(12) = 12(1-\frac{1}{2})(1-\frac{1}{3}) = 4$

$$\mathbf{Z}_{12}^{\times} = \{[1],[5],[7],[11]\} = \{\pm[1], \pm[5]\}$$

$$[5]^2 = [7]^2 = [11]^2 = [1]$$

This implies that there is no element of order 4, and so $\mathbf{Z}_{12}^{\times}$ is not cyclic.

Thus we have $\mathbf{Z}_{10}^{\times} \ncong \mathbf{Z}_{12}^{\times}$.

(6) You need to show work to support your conclusions. (*Hint: Check Lecture Slides §3.5, #14/18*)

(a) Is $\mathbf{Z}_3 \times \mathbf{Z}_{30}$ isomorphic to $\mathbf{Z}_6 \times \mathbf{Z}_{15}$? Yes!

We have $\mathbf{Z}_3 \times \mathbf{Z}_{30} \cong \mathbf{Z}_3 \times \mathbf{Z}_6 \times \mathbf{Z}_5$ (or you can write $\mathbf{Z}_3 \times \mathbf{Z}_{30} \cong \mathbf{Z}_3 \times \mathbf{Z}_2 \times \mathbf{Z}_3 \times \mathbf{Z}_5$) and $\mathbf{Z}_6 \times \mathbf{Z}_{15} \cong \mathbf{Z}_6 \times \mathbf{Z}_3 \times \mathbf{Z}_5$ (or you can write $\mathbf{Z}_6 \times \mathbf{Z}_{15} \cong \mathbf{Z}_2 \times \mathbf{Z}_3 \times \mathbf{Z}_3 \times \mathbf{Z}_5$).
Consider the function $\phi : \mathbf{Z}_3 \times \mathbf{Z}_6 \times \mathbf{Z}_5 \to \mathbf{Z}_6 \times \mathbf{Z}_3 \times \mathbf{Z}_5$ by

$$\phi(([x_1]_3, [x_2]_6, [x_3]_5)) = ([x_2]_6, [x_1]_3, [x_3]_5)$$

for any element $([x_1]_3, [x_2]_6, [x_3]_5) \in \mathbf{Z}_3 \times \mathbf{Z}_6 \times \mathbf{Z}_5$. It is obvious that ϕ is an isomorphism. Thus, we prove that $\mathbf{Z}_3 \times \mathbf{Z}_{30} \cong \mathbf{Z}_6 \times \mathbf{Z}_{15}$.
Or you can consider $\phi : \mathbf{Z}_3 \times \mathbf{Z}_2 \times \mathbf{Z}_3 \times \mathbf{Z}_5 \to \mathbf{Z}_2 \times \mathbf{Z}_3 \times \mathbf{Z}_3 \times \mathbf{Z}_5$ by ...

(b) Is $\mathbf{Z}_9 \times \mathbf{Z}_{14}$ isomorphic to $\mathbf{Z}_6 \times \mathbf{Z}_{21}$? No!

We have $\mathbf{Z}_9 \times \mathbf{Z}_{14} \cong \mathbf{Z}_9 \times \mathbf{Z}_2 \times \mathbf{Z}_7$ and $\mathbf{Z}_6 \times \mathbf{Z}_{21} \cong \mathbf{Z}_6 \times \mathbf{Z}_3 \times \mathbf{Z}_7 \cong \mathbf{Z}_2 \times \mathbf{Z}_3 \times \mathbf{Z}_3 \times \mathbf{Z}_7$.
It shows that the first has an element of order 9, while the second has none. Thus we have $\mathbf{Z}_9 \times \mathbf{Z}_{14} \ncong \mathbf{Z}_6 \times \mathbf{Z}_{21}$.

(7) Let G be the set of all 3×3 matrices of the form $\begin{bmatrix} 1 & 0 & 0 \\ a & 1 & 0 \\ b & c & 1 \end{bmatrix}$. Show that if $a, b, c \in \mathbf{Z}_3$, then G is a group with exponent 3.

For any $a, b, c \in \mathbf{Z}_3$, we have

$$\begin{bmatrix} 1 & 0 & 0 \\ a & 1 & 0 \\ b & c & 1 \end{bmatrix}^2 = \begin{bmatrix} 1 & 0 & 0 \\ a & 1 & 0 \\ b & c & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ a & 1 & 0 \\ b & c & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 2a & 1 & 0 \\ 2b+ac & 2c & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 \\ a & 1 & 0 \\ b & c & 1 \end{bmatrix}^3 = \begin{bmatrix} 1 & 0 & 0 \\ a & 1 & 0 \\ b & c & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 2a & 1 & 0 \\ 2b+ac & 2c & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 3a & 1 & 0 \\ 3b+3ac & 3c & 1 \end{bmatrix} = I_3$$

(8) Prove that any cyclic group with more than two elements has at least two different generators.

If G is an infinite cyclic group, then $G \cong \mathbf{Z}$. And we know that 1 and -1 are the only two generators for $\mathbf{Z}$. That is, $\mathbf{Z} = \langle 1 \rangle = \langle -1 \rangle$.
If G is a finite cyclic group with $|G| = n > 2$, then $G \cong \mathbf{Z}_n$. Also we know that at least $[1]_n$ and $[-1]_n$ are generators for $\mathbf{Z}_n$ since they are units in $\mathbf{Z}_n$, i.e., $[1]_n, [-1]_n \in \mathbf{Z}_n^\times$. And $[1]_n \neq [-1]_n$ if $n > 2$. This completes the proof.

Or proof by contradiction: Let $G = \langle a \rangle$ for some element $a \neq e$. Suppose that a is the only generator of the group G. However, we also know that $G = \langle a^{-1} \rangle$. Since a is the only generator of G by assumption, we have

$$a = a^{-1} \Rightarrow a^2 = e \Rightarrow o(a) = |\langle a \rangle| = |G| = 2 \text{ since } a \neq e\text{, a contradiction.}$$

Thus, G has at least two different generators.

(9)* Let G be any group with no proper, nontrivial subgroups, and assume that G has more than one element. Prove that G must be isomorphic to $\mathbf{Z}_p$ for some prime p.

Question (9) is a bonus question. It is optional for the students who are in Math 546. However, it is required for the students who are in Math 701I.*

Assume that the only subgroups of G are the trivial subgroup $\{e\}$ and itself.

Since $|G| > 1$, there exists a non-identity element $a \in G$. Then we have $G = \langle a \rangle$ since $\langle a \rangle$ is a subgroup of G but not $\{e\}$, and so G is cyclic.

Moreover, G is a finite cyclic group. Otherwise, $\langle a^k \rangle$ is a proper, nontrivial subgroup of $G = \langle a \rangle$ for any positive integer k, a contradiction.

Let $|G| = n > 1$. And so we have $G \cong \mathbf{Z}_n$ since G is cyclic. In particular, for each divisor d of n, there exists a (unique) subgroup H of order d since G is a finite cyclic group. By assumption, d has only two possibilities, that is, $d = 1$ or $d = n$. This implies that n has to be a prime number p. Therefore, $G \cong \mathbf{Z}_p$.