

# Abstract Algebra (3rd Edition)

Chapter 5.5, Problem 10E Bookmark Show all steps:  on

### Step-by-step solution

#### Step 1 of 28

**Fundamental theorem of finitely generated abelian groups:** Let  $G$  be a finitely generated abelian group. Then  $G \cong Z^r \times Z_{n_1} \times Z_{n_2} \times \dots \times Z_{n_k}$  for some integers  $r, n_1, n_2, \dots, n_k$  satisfying the following condition:

(i)  $r \geq 0$  and for all  $i, n_i \geq 2$   
 (ii)  $n_i \mid n_j$  for  $1 \leq i < j \leq k$

The expression defined above is unique if  $G \cong Z^r \times Z_{n_1} \times Z_{n_2} \times \dots \times Z_{n_k}$  where,  $r, m_1, m_2, \dots, m_k$  satisfy (i) and (ii) then  $r = r, m_i = n_i$  for all  $i$ .

**Sylow theorem:** If  $G$  is a finite group of order  $p^m$ , where  $p$  is a prime and does not divide  $m$ , then  $G$  has a subgroup of order  $p^r$ .

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**Lagrange's theorem:** If  $G$  is a finite group and  $H$  is a subgroup of  $G$ , then the order of  $H$  divides the order of  $G$  and the number of left cosets of  $H$  in  $G$  equals  $\frac{|G|}{|H|}$ .

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#### Step 3 of 28

This exercise aims to classify the groups of order 147.

(a) Prove that there are two abelian groups of order 147.  
 It can be seen that  $147 = 3 \cdot 7^2$ . By Fundamental theorem of finitely generated abelian groups, the abelian groups of order 147 are  $Z_{147}$  and  $Z_{21} \times Z_7$ . Thus, there are two abelian groups of order 147.

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(b) Prove that every group of order 147 has a normal Sylow 7-subgroup.

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Using Sylow's Theorem, the number  $n_7$  of Sylow 7-subgroups divides 3 and is congruent to 1 mod 7; hence  $n_7 = 1$ . Therefore, the Sylow 7-subgroup of a group of order 147 is unique, thus normal.

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(c) Prove that there is a unique non-abelian group of order 147 whose Sylow 7-subgroup is cyclic.

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Suppose  $G$  be a non-abelian group of order 147. Suppose  $H \leq G$  be the unique Sylow 7-subgroup of  $G$ , and let  $H \cong Z_7$ . Now suppose  $K = \langle x \rangle \cong Z_3$  be any Sylow 3-subgroup of  $G$ . By Lagrange theorem,  $H \cap K = 1$ , so that  $HK = G$ . By the recognition theorem for semi-direct products, we have  $G \cong Z_7 \rtimes_\varphi Z_3$  for some group homomorphism  $\varphi: Z_3 \rightarrow \text{Aut}(Z_7)$ . Recall that  $\text{Aut}(H) \cong Z_6$ , and that  $42 = 2 \cdot 3 \cdot 7$ . With the help of Cauchy's Theorem, it can be said that  $\text{Aut}(H)$  contains an element  $\alpha$  of order 3. However, the Sylow 3-subgroups of  $\text{Aut}(H)$  are those of order 3, and by Sylow's Theorem, every order 3 subgroup is conjugate to  $\langle \alpha \rangle$ .

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Suppose  $Z_i = \langle x^i \rangle$  and define  $\varphi: K \rightarrow \text{Aut}(H)$  by  $\varphi(x) = \alpha$ . Since  $\varphi$  is nontrivial,  $Z_7 \rtimes_\varphi Z_3$  is a non-abelian group of order 147. Suppose that  $\psi: K \rightarrow \text{Aut}(H)$  is some other nontrivial group homomorphism such that  $H \rtimes_\psi K$  is non-abelian. Since  $K \cong Z_3$  is simple,  $\ker \psi$  is trivial, so that  $\psi$  is injective. Hence,  $\text{im } \psi$  is an order 3 subgroup of  $\text{Aut}(H)$ , which is conjugate to  $\langle \alpha \rangle$ . Since  $K$  is cyclic, so  $H \rtimes_\psi K \cong H \rtimes_\alpha K$ . Hence, there exists a unique non-abelian group of order 147 whose Sylow 7-subgroup is cyclic  $\overline{[Z_7 \rtimes_\alpha Z_3]}$ .

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(d) Suppose  $t_1, t_2 \in GL_2(\mathbb{F}_7)$ . Prove that  $P = \langle t_1, t_2 \rangle$  is a Sylow 3-subgroup of  $GL_2(\mathbb{F}_7)$  and that  $P \cong Z_3 \times Z_3$ .

Deduce that every subgroup of  $GL_2(\mathbb{F}_7)$  of order 3 is conjugate in  $GL_2(\mathbb{F}_7)$  to some subgroup of  $P$ .

$$t_1 = \begin{bmatrix} 2 & 0 \\ 0 & 1 \end{bmatrix}, t_2 = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}$$

Note that  $|GL_2(\mathbb{F}_7)| = 2^2 \cdot 3^2 \cdot 7$ . Do the following calculations,  $t_1^3 = 1, t_2^3 = 1$  and

$$t_1^2 = \begin{bmatrix} 4 & 0 \\ 0 & 1 \end{bmatrix}, t_2^2 = \begin{bmatrix} 1 & 0 \\ 0 & 4 \end{bmatrix}$$

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However, following is seen:

$$t_1 t_2 = t_1 t_2 = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}$$

Let,  $Z_i^2 = \langle t_i^2 \rangle \times \langle b \rangle$ , there exists a unique group homomorphism  $\theta: Z_i^2 \rightarrow \langle t_i, t_2 \rangle$  such that  $\theta(a) = t_i$  and  $\theta(b) = t_2$ . It can be seen that every element of  $\langle t_i, t_2 \rangle$  has the form  $t_i^j t_2^k$  for some  $0 \leq i, j < 3$ , so that  $|\langle t_i, t_2 \rangle| \leq 9$ .

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However, note the following:  $\theta(1) = 1, \theta(b) = t_2, \theta(b^2) = t_2^2$  and  $\theta(a) = t_1, \theta(a^2) = t_1^2$  also.

$$\theta(ab) = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}, \theta(ab^2) = \begin{bmatrix} 2 & 0 \\ 0 & 4 \end{bmatrix}, \theta(a^2b) = \begin{bmatrix} 4 & 0 \\ 0 & 2 \end{bmatrix}, \theta(a^2b^2) = \begin{bmatrix} 4 & 0 \\ 0 & 4 \end{bmatrix}$$

Hence,  $\ker \theta = 1$ , so that  $\theta$  is injective, and then  $|\theta| = 9$ . Specifically,  $\overline{[P \leq GL_2(\mathbb{F}_7)]}$  is a Sylow 3-subgroup. Note that if  $A \leq GL_2(\mathbb{F}_7)$  is a subgroup of order 3, then  $A$  is contained in some Sylow 3-subgroup  $Q$  and thus is conjugate to a subgroup of  $\langle \alpha \rangle$ .

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(e) Suppose the group  $P$  has 4 subgroups of order 3 as follows:  $P_1 = \langle t_1 \rangle, P_2 = \langle t_2 \rangle, P_3 = \langle t_1 t_2 \rangle$ , and  $P_4 = \langle t_1^2 t_2 \rangle$ . For each  $i = 1, 2, 3, 4$ , let  $G_i = \langle Z_7 \times Z_3 \rangle \rtimes_\varphi Z_3$  where  $\varphi: Z_3 \rightarrow GL_2(\mathbb{F}_7)$  is given by  $\varphi(x) = \alpha_i$ . Here,  $\alpha_i = P_i$ . For each  $i$  describe  $G_i$  in terms of generators and relations and deduce that  $G_i \cong G_j$ .

Note the following:

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$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} 2 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}$$

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Since  $Z_3 = \langle x \rangle$  is cyclic so  $\overline{[G_i \cong G_j]}$ . Each group is generated by the following:

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$$\mu = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \eta = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \omega = x$$

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$$\text{And } \mu\eta = \eta\mu.$$

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For  $G_i$  we have the following:

$$\omega\mu = (1, x) \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} \varphi_1(x) \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, x \end{bmatrix} = \begin{bmatrix} t_1 \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, x \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ 1 \end{bmatrix}, x = \begin{bmatrix} 2 \\ 0 \\ 1 \end{bmatrix} (1, x) = \mu^2 \omega$$

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And

$$\omega\eta = (1, x) \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} \varphi_2(x) \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}, x \end{bmatrix} = \begin{bmatrix} t_2 \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}, x \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}, x = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix} (1, x) = \eta \omega$$

Therefore,  $G_i$  has the following presentation:

$$\overline{[\mu, \eta, \omega | \mu^3 = \eta^3 = \omega^3, \mu\eta = \eta\mu, \omega\eta = \eta\omega, \omega\mu = \mu^2\omega]}$$

For  $G_j$  we have the following:

$$\omega\mu = \begin{bmatrix} \varphi_3(x) \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, x \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ 1 \end{bmatrix}, x = \mu^2 \omega$$

And

$$\omega\eta = \begin{bmatrix} \varphi_4(x) \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}, x \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 2 \end{bmatrix}, x = \eta^2 \omega$$

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Therefore,  $G_i$  has the following presentation:

$$\overline{[\mu, \eta, \omega | \mu^3 = \eta^3 = \omega^3, \mu\eta = \eta\mu, \omega\eta = \eta^2\omega, \omega\mu = \mu^2\omega]}$$

For  $G_j$  in a similar fashion we have  $\omega\mu = \mu^2\omega$  and  $\omega\eta = \eta^2\omega$ . Thus  $G_j$  has the following presentation:

$$\overline{[\mu, \eta, \omega | \mu^3 = \eta^3 = \omega^3, \mu\eta = \eta\mu, \omega\eta = \eta^2\omega, \omega\mu = \mu^2\omega]}$$

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(f) Prove that  $G_i$  is not isomorphic to either of  $G_j$  and  $G_k$ .

Let us begin with some lemmas:

**Lemma 1:** Suppose  $G$  be a group and let  $a, b \in G$  such that  $ab = b^k a$ . Then for all integers  $m, n \geq 1$ ,  $a^m b^n = b^{nk} a^m$ .

**Proof:** Let us proceed by induction on  $m$ .

**Base case:** suppose  $m = 1$ . We proceed by induction on  $n$ . For the base case, suppose  $n = 1$ . Then:

$$a^1 b^1 = ab = b^k a = b^k a^1$$

For the inductive step, let the conclusion holds for some  $n \geq 1$ . Now,

$$a^1 b^{n+1} = ab^{n+1} = b^{nk} a b^n = b^{nk} a^2 b^n = b^{nk} b^k a^2 b^n = b^{(n+1)k} a^2 b^n = b^{(n+1)k} a^2 b^n$$

Hence, the conclusion holds also for  $n+1$ . By induction  $a^m b^n = b^{nk} a^m$  for all  $n$ .

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For the inductive step, let the conclusion holds for some  $m \geq 1$ . We proceed by induction on  $n$ .

**For the base case,** suppose  $n = 1$ . So,

$$a^{m+1} b^1 = a a^m b = a b^{k^m} a^m = b^{k^{m+1}} a^{m+1} = b^{k^{m+1}} a^{m+1}$$

For the inductive step, let the conclusion holds for some  $n \geq 1$ . So,

$$a^{m+1} b^{n+1} = a a^m b^{n+1} = a b^{k^m a^n} b = b^{k^m a^n} a b = b^{k^m a^n} b^{k^m} a = b^{k^m(a^n+1)} a = b^{k^{m+1}(a^n+1)} a^{m+1}$$

By induction we can say that  $a^{m+1} b^n = b^{k^{m+1} a^n}$  for all  $n$ , so that the conclusion holds also for  $m+1$ . Hence, by induction,  $a^m b^n = b^{k^m a^n}$  holds for all integers  $m, n \geq 1$ .

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**Lemma 2:** Let  $m, n$  are positive integers such that  $m+a \cdot 2^k = a+m \cdot 2^k \pmod{7}$  for all positive integers  $a$  and  $b$ . Then,  $m = 0 \pmod{7}$  and  $n = 0 \pmod{3}$ .

**Proof:** Suppose  $b = 3$  and  $0 < a < 7$ . Then,  $m+a \cdot 2^k = a+m \pmod{7}$ , so that  $a \cdot 2^k = a \pmod{7}$ . Now  $a$  is invertible mod 7, so that  $2^k = 1 \pmod{7}$ . Since  $|2| = 3$  in  $Z(7)$ , we have  $n = 0 \pmod{3}$ . Now we have  $m+a = a+m \cdot 2^k \pmod{7}$ , so that  $m = m \cdot 2^k \pmod{7}$ . If  $m \not\equiv 0 \pmod{7}$ , then  $1 = 2^k \pmod{7}$  for all integers  $b$ , which is not correct. Hence,  $m = 0 \pmod{7}$ .

Now, we will calculate the centers of  $G_i, G_j$  and  $G_k$ .

Note from the presentation of  $G_i$  that every element in this group can be written in the form  $\mu^i \eta^j \omega^k$  for some  $0 < i, j \leq 7$  and  $0 < k \leq 3$ . There are 147 such forms, and because it is known that  $|G_i| = 147$ , then in fact each element can be written in this form uniquely.

Consider that  $x = \mu^i \eta^j \omega^k \in Z(G_i)$ . Then for every element  $\mu^l \eta^m \omega^n$  and by using Lemma 1 we have the following:

$$\mu^l \eta^m \omega^n \mu^i \eta^j \omega^k = \mu^{l+i} \eta^{m+j} \omega^{n+k} = \mu^i \eta^j \omega^k \mu^l \eta^m \omega^n = \mu^{i+l} \eta^{j+m} \omega^{k+n}$$

Hence, we have that, for some fixed positive integers  $a$  and  $c$ ,  $a+i2^k = i+a2^k \pmod{7}$  for all positive integers  $i$  and  $k$ . By Lemma 2, we have  $a = 0 \pmod{7}$  and  $c = 0 \pmod{3}$ . Hence  $x \in \langle \eta \rangle$ . Also,  $\langle \eta \rangle \leq Z(G_i)$ , so  $Z(G_i) = \langle \eta \rangle$ .

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Again, it can be seen that every element of  $G_j$  can be written in the form  $\mu^i \eta^j \omega^k$  for some  $0 < i, j \leq 7$  and  $0 < k \leq 3$ , and it is known that  $|G_j| = 147$ , every element can be written uniquely in this form. Consider that  $x = \mu^i \eta^j \omega^k \in Z(G_j)$ . Then for every element  $\mu^l \eta^m \omega^n$ , following is equivalent given as follows:

$$\mu^l \eta^m \omega^n \mu^i \eta^j \omega^k = \mu^{l+i} \eta^{m+j} \omega^{n+k} = \mu^i \eta^j \omega^k \mu^l \eta^m \omega^n = \mu^{i+l} \eta^{j+m} \omega^{k+n}$$

Comparing exponents and using Lemma 2, we have  $a = b = 0 \pmod{7}$  and  $c = 0 \pmod{3}$ . Hence  $x = 1$  and we have  $Z(G_j) = 1$ .

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Again, we can see that every element of  $G_k$  can be written in the form  $\mu^i \eta^j \omega^k$  for some  $0 < i, j \leq 7$  and  $0 < k \leq 3$ , and it is known that  $|G_k| = 147$ , every element can be written uniquely in this form. Consider that  $x = \mu^i \eta^j \omega^k \in Z(G_k)$ . Then for every element  $\mu^l \eta^m \omega^n$ , following is equivalent given as follows:

$$\mu^l \eta^m \omega^n \mu^i \eta^j \omega^k = \mu^{l+i} \eta^{m+j} \omega^{n+k} = \mu^i \eta^j \omega^k \mu^l \eta^m \omega^n = \mu^{i+l} \eta^{j+m} \omega^{k+n}$$

Comparing the exponents of  $\mu$  and by Lemma 2 we have  $a = 0 \pmod{7}$  and  $c = 0 \pmod{3}$ . Comparing the exponents of  $\eta$ , we have  $b+j = j+b4 \pmod{7}$ , so that  $b = b4 \pmod{7}$ . If  $b \not\equiv 0 \pmod{7}$ , then  $1 = 4 \pmod{7}$  for all  $0 < k \leq 3$ , which is not correct. Hence,  $b = 0 \pmod{7}$ . Thus,  $x = 1$  and we have  $Z(G_k) = 1$ .

Specifically, it is seen that  $\overline{[G_i \cong G_j]}$  and  $\overline{[G_j \cong G_k]}$  since  $Z(G_i)$  and  $Z(G_j)$  are trivial while  $Z(G_k)$  is not.

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(g) Prove that  $G_i$  is not isomorphic to  $G_j$ .

It is known that the Sylow 7-subgroups of  $G_i$  and  $G_j$  are unique, so that every subgroup of order 7 in each is contained in  $H = Z_i^2$ . Recall that there are 8 such subgroups given as follows:  $\langle \mu \rangle, \langle \mu\eta \rangle, \langle \mu\eta^2 \rangle, \langle \mu\eta^3 \rangle, \langle \mu\eta^4 \rangle, \langle \mu\eta^5 \rangle, \langle \mu\eta^6 \rangle$  and  $\langle \eta \rangle$ . Note the following:

$$\omega\eta\omega^{-1} = \eta^2 \in \langle \eta \rangle$$

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$= \langle \mu\eta \rangle$   
 $\in \langle \mu\eta^3 \rangle$

Hence, every subgroup of  $G$ , order 7 is normal there.

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On the other hand, in  $G_4$ , we have

$$\begin{aligned} \omega\mu\eta\omega^3 &= \mu^2\omega\eta\omega^3 \\ &= \mu^2\eta^3 \\ &= (\mu\eta^3)^2 \\ &\in \langle \mu\eta^3 \rangle \end{aligned}$$

By Lagrange  $\langle \mu\eta \rangle \cap \langle \mu\eta^3 \rangle = 1, \omega\mu\eta\omega^3 \in \langle \mu\eta \rangle$ . Hence,  $\langle \mu\eta \rangle$  is an order 7 subgroup which is not normal in  $G_4$ . Thus  $\overline{G_4} \cong G_4$ .

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(h) Classify the groups of order 147 by showing that the six non-isomorphic groups described above are all the groups of order 147.

Suppose  $G$  be a group of order  $147 = 3 \cdot 7^2$ . If  $G$  is abelian, then  $G$  is isomorphic to one of  $Z_{147}$  and  $Z_{49} \times Z_3$ . If  $G$  is non-abelian, then by part (b),  $G$  has a normal Sylow 7-subgroup  $H$ . Suppose  $K \cong Z_3$  be any Sylow 3-subgroup of  $H$ . By Lagrange,  $H \cap K = 1$ , so that  $G = HK$ . With the help of the recognition theorem for semi-direct products,  $G \cong H \rtimes_\varphi K$ , where  $K = \langle z \rangle$ ,  $|H| = 49$ , and  $\varphi: K \rightarrow \text{Aut}(H)$ .

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Hence, classifying the non-abelian groups of order 147 is equivalent to determining the non-isomorphic groups constructed in this manner. By part (c), there is an essentially unique non-abelian group of the form  $Z_7 \rtimes_\varphi Z_7$ . Consider that  $H = Z_7^2$ . Since  $G$  is non-abelian,  $\varphi$  is nontrivial. As  $K$  is simple, we have  $\ker \varphi = 1$ ; thus  $\text{im} \varphi$  is a subgroup of order 3 in  $\text{Aut}(H) \cong GL_2(\mathbb{F}_7)$ . By part (d),  $\text{im} \varphi$  is conjugate to one of the four subgroups of the Sylow 3-subgroup  $P \leq GL_2(\mathbb{F}_7)$  identified above. Since  $K$  is cyclic,  $H \rtimes_\varphi K$  is isomorphic to one of the groups  $G_i$  identified above. It is showed in parts (e), (f), and (g) that three of these are distinct. Thus the groups of order 147 up to isomorphism are as follows.

In all case, let  $Z_3 = \langle x \rangle, Z_{49} = \langle y \rangle$  and  $Z_7^2 = \langle a \rangle \times \langle b \rangle$ .

- $\overline{Z_{147}}$
- $\overline{Z_{49} \times Z_3}$
- $\overline{Z_7 \rtimes_\varphi Z_7}$  where  $\varphi(x)(y) = y^{-4}$
- $\overline{Z_7^2 \rtimes_\varphi Z_3}$  where  $\varphi_1(x)(a) = a^{-2}$  and  $\varphi_1(x)(b) = b$
- $\overline{Z_7^2 \rtimes_\varphi Z_3}$  where  $\varphi_2(x)(a) = a^2$  and  $\varphi_2(x)(b) = b^2$
- $\overline{Z_7^2 \rtimes_\varphi Z_3}$  where  $\varphi_3(x)(a) = a^2$  and  $\varphi_3(x)(b) = b^4$

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