

Dummit & Foote Ch. 3.2: More on Cosets and Lagrange's Theorem

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Let G be a group.

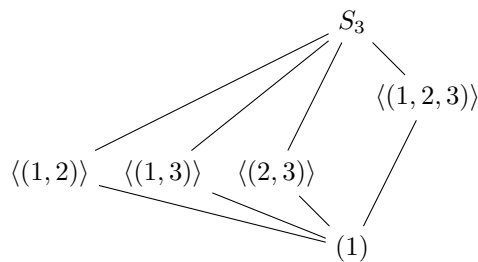
1. (10/1/23)

Which of the following are permissible orders of subgroups of a group of order 120: 1, 2, 5, 7, 9, 15, 60, 240? For each permissible order give the corresponding index.

Proof. From Lagrange's theorem, the order of a subgroup of a group of order 120 must divide 120. Then the permissible orders for subgroups are $1 = \frac{120}{120}$, $2 = \frac{120}{60}$, $5 = \frac{120}{24}$, $15 = \frac{120}{8}$, and $60 = \frac{120}{2}$. For each of these orders the index is given by the corresponding denominator. \square

2. (10/2/23)

Prove that the lattice of subgroups of S_3 below is correct (i.e., prove that it contains all subgroups of S_3 and that their pairwise joins and intersections are correctly drawn).



Proof. The symmetric group S_3 contains 6 elements. By Lagrange's theorem, its proper subgroups must have order 2 or 3. Each of the subgroups in the lattice above have order 2 or 3, so there are no smaller or larger subgroups not depicted above.

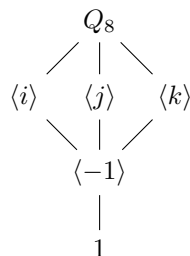
From Corollary 10, a subgroup of order 2 must be isomorphic to Z_2 , that is, cyclic and generated by a single element of order 2. The three subgroups generated by the three elements of order 2 (the 2-cycles of S_3) are depicted above. Similarly, a subgroup of order 3 must be isomorphic to Z_3 and generated by a single element of order 3. The subgroup generated by $(1, 2, 3)$ contains $(1, 3, 2)$, so there is only a single subgroup of order 3.

Next, again by Lagrange's Theorem, a subgroup of two different containing groups must have an order that divides the order of both of the containing groups. First consider a subgroup of order 2 and a subgroup of order 3. Only 1 divides 2 and 3, so the intersection must be the identity. Similarly, if a subgroup of order 2 and a subgroup of order 3 are contained in a larger group, then that group's order must have both 2 and 3 as divisors. The smallest integer for which this is possible is 6, which is the order of all of S_3 .

Finally, consider a pair of subgroups of order 2. Their intersection is either the identity or else they are the same subgroup. Their join must have even order, but 4 does not divide 6 and any larger even number exceeds the order of S_3 . Thus their join is all of S_3 . This concludes the proof that the lattice of subgroups of S_3 is correct. \square

3. (10/2/23)

Prove that the lattice of subgroups of Q_8 below is correct.



Proof. The group Q_8 has order $8 = 2^3$, so by Lagrange's theorem its proper subgroups must have order 2 or 4. We will start from the bottom and work toward the top: There is only one element of order 2 in Q_8 , -1 , and the cyclic subgroup generated by it is in the lattice.

For each of i, j , and k , $\langle -1 \rangle$ is contained in the subgroup generated by them (ex. $\langle i \rangle = \{\pm 1, \pm i\}$) and there are no intermediate subgroups, since there is no divisor of 4 that is strictly greater than 2. At this point, every element of Q_8 is represented, so there are no cyclic subgroups missing. We might ask if there is a subgroup of order 4 missing. If so, it cannot be cyclic, and from Ch. 1.1, Exercise 36, it must be isomorphic to V_4 . However, V_4 contains three elements of order 2, and Q_8 only has one, so there is no subgroup of Q_8 isomorphic to V_4 .

Finally, the join of any of the subgroups generated by i, j , or k must contain strictly more than 4 elements and its order must divide 8. Then any of their joins must have order 8, that is, be all of Q_8 . \square

4. (10/3/23)

Show that if $|G| = pq$ for some primes p and q (not necessarily distinct) then either G is abelian or $Z(G) = 1$.

Proof. We will show, equivalently, that if $|Z(G)| > 1$, then G is abelian.

Let $x \in Z(G)$. From Corollary 9, the order of x divides $|G| = pq$. If $|x| = pq$, then $G = \langle x \rangle$ and so is abelian. Suppose without loss of generality that $|x| = p$. Now since the center of a group is a subgroup, we must have $\langle x \rangle \leq Z(G)$. If there exists a $y \in Z(G), y \notin \langle x \rangle$, then the order of $Z(G)$ exceeds p and must divide pq , then it must be all of G and hence G is abelian. So suppose $Z(G) = \langle x \rangle$.

The center of a group is normal in that group, so $G/Z(G)$ is well-defined. Since $|Z(G)| = p$, it has q cosets in G ; that is, the quotient group $G/Z(G)$ has prime order q and is thus isomorphic to Z_q , hence cyclic. From Ch. 3.1, Exercise 36., G is thus abelian. \square

5. (10/4/23)

Let H be a subgroup of G and fix some element $g \in G$.

- (a) Prove that gHg^{-1} is a subgroup of G of the same order as H .

Proof. By definition elements of gHg^{-1} can be written in the form ghg^{-1} for some $h \in H$, so let $gh_1g^{-1}, gh_2g^{-1} \in gHg^{-1}$. Then we have:

$$(gh_1g^{-1})(gh_2g^{-1})^{-1} = gh_1g^{-1}gh_2^{-1}g = gh_1h_2^{-1}g \in gHg^{-1},$$

so gHg^{-1} fulfills the subgroup criterion and is thus a subgroup of G .

Next, let $\varphi_g : H \rightarrow gHg^{-1}$ be defined by $\varphi_g(h) = ghg^{-1}$ for all $h \in H$. This map is injective by the cancellation laws: $gh_1g^{-1} = gh_2g^{-1}$ implies that $h_1 = h_2$. It is also surjective: Let $x \in gHg^{-1}$. By definition $x = ghg^{-1}$ for some $h \in H$, so $\varphi_g(h) = x$. Therefore φ_g is a bijection, and so H and gHg^{-1} have the same order. \square

- (b) Deduce that if $n \in \mathbb{Z}^+$ and H is the unique subgroup of G of order n then $H \trianglelefteq G$.

Suppose that H is the unique subgroup of order n in G . Then for all $g \in G$, we must have $gHg^{-1} = H$ (it cannot be any other subgroup, because $|gHg^{-1}| = |H| = n$ and there is no other subgroup of order n in G). It follows that H is normal in G .

6. (10/4/23)

Let $H \leq G$ and let $g \in G$. Prove that if the right coset of Hg equals *some* left coset of H in G then it equals the left coset gH and g must be in $N_G(H)$.

Proof. Suppose $Hg = xH$ for some $x \in G$. Now $g \in Hg$, so we must also have $g \in xH$. Then $g = xh$ for some $h \in H$. It follows that $x = gh^{-1}$. So $Hg = xH = (gh^{-1})H = gH$, which in turns implies that $gHg^{-1} = H$. Therefore $g \in N_G(H)$. \square

7. (10/5/23)

Let $H \leq G$ and define a relation \sim on G by $a \sim b$ if and only if $b^{-1}a \in H$. Prove that \sim is an equivalence relation and describe the equivalence class of each $a \in G$. Use this to prove Proposition 4.

Proof. Let $a, b, c \in G$. We have $a \sim a$, because $a^{-1}a = 1 \in H$. If $a \sim b$, then we have $b^{-1}a \in H$. Now $b \sim a = a^{-1}b = (b^{-1}a)^{-1} \in H$, since H is closed under inverses, so $a \sim b$ implies that $b \sim a$ (and the logic holds in reverse). Finally, if $a \sim b$ and $b \sim c$, then $b^{-1}a, c^{-1}b \in H$. Then their product, $c^{-1}bb^{-1}a = c^{-1}a$, is an element of H , which implies $a \sim c$. The relation \sim is reflexive, symmetric, and transitive, therefore it is an equivalence relation.

Let $a \in G$ and let b lie in the left coset aH , so $b = ah$ for some $h \in H$. Then $b^{-1}a = (ah)^{-1}a = h^{-1}a^{-1}a = h^{-1} \in H$, so $a \sim b$. This implies that aH is a subset of the equivalence class of a . And, if we have $a \sim b$, then $b^{-1}a \in H$, so $b^{-1}a = h$ for some $h \in H$. It follows that $b = ah^{-1} \in aH$, so the equivalence class of a is a subset of aH . Since each is contained in the other, the equivalence class of a under \sim is the left coset aH .

Now Proposition 4 states that:

- The set of left cosets of H in G form a partition of G .
- For all $a, b \in G$, $aH = bH$ if and only if $b^{-1}a \in H$.
- In particular, $aH = bH$ if and only if a and b are representatives of the same coset.

Since the equivalence class of a under \sim is exactly the left coset aH and equivalence classes partition a set, the left cosets of H in G partition G . The proof for the remaining items follows directly from the proof above that $a \sim b \iff b^{-1}a \in H \iff b \in aH$. \square

8. (10/6/23)

Prove that if H and K are finite subgroups of G whose orders are relatively prime then $H \cap K = 1$.

Proof. Let $H, K \leq G$ be finite subgroups whose orders are relatively prime. Let $x \in H \cap K$, so $x \in H$ and $x \in K$. From Corollary 9, the order of x divides the orders of both H and K . Since $|H|$ and $|K|$ are relatively prime, the order of x must be 1, therefore $x = 1$. It follows that $H \cap K = 1$. \square

9. (10/12/23)

This exercise outlines a proof of Cauchy's Theorem due to James McKay (*Another proof of Cauchy's group theorem*, Amer. Math. Monthly, 66(1959), p. 119). Let G be a finite group and let p be a prime dividing $|G|$. Let \mathcal{S} denote the set of p -tuples of elements of G the product of whose coordinates is 1:

$$\mathcal{S} = \{(x_1, x_2, \dots, x_p) \mid x_1 x_2 \dots x_p = 1\}.$$

- (a) Show that \mathcal{S} has $|G|^{p-1}$ elements, hence has order divisible by p .

Proof. Construct an element of \mathcal{S} coordinate by coordinate. There are $|G|$ choices for the first element x_1 . There are again $|G|$ choices for the second element x_2 . We proceed similarly until the final element, which must satisfy the constraint that the product of all coordinates is 1. Therefore the final element must be equal to $(x_1 x_2 \dots x_{p-1})^{-1}$. We have freely chosen $p-1$ coordinates from among $|G|$ possibilities; therefore $|\mathcal{S}| = |G|^{p-1}$. \square

Define the relation \sim on \mathcal{S} by letting $\alpha \sim \beta$ if β is a cyclic permutation of α .

- (b) Show that a cyclic permutation of \mathcal{S} is again an element of \mathcal{S} .

Proof. Since $\alpha \sim \beta$ implies that β is a cyclic permutation of α , we have

$$\alpha = (x_1, x_2, \dots, x_p) \Rightarrow \beta = (x_{1+n}, x_{2+n}, \dots, x_{p+n}),$$

where the subscripts of elements of β are taken mod p (although wrapping from 1 to p , rather than 0 to $p-1$).

The product of the coordinates of α is:

$$\begin{aligned} 1 &= \prod \alpha = x_1 x_2 \dots x_p \\ &= (x_1 \dots x_n)(x_{n+1} \dots x_p) \\ &= (x_{n+1} \dots x_p)(x_1 \dots x_n) \text{ (if } ab = 1, \text{ then } ab = ba) \\ &= (x_{1+n} \dots x_{p-n+n})(x_{(p-n+1)+n} \dots x_{p+n}) \\ &= x_{1+n} \dots x_{p+n} = \prod \beta, \end{aligned}$$

and so the product of β 's coordinates is 1, making it an element of \mathcal{S} . \square

- (c) Prove that \sim is an equivalence relation on \mathcal{S} .

Proof. Let $\alpha, \beta, \gamma \in \mathcal{S}$. The relation \sim is:

- Reflexive: Let $\alpha = (x_1, x_2, \dots, x_p)$. Then $x_i = x_{i+0}$ for all coordinates x_i , so α is a cyclic permutation of itself, and therefore $\alpha \sim \alpha$.
- Symmetric: Let $\alpha \sim \beta$, α, β indexed by x, y respectively. Since β is a cyclic permutation of α , we have $y_i = x_{i+n}$ for all $i \in \{1, \dots, p\}$ for some $n \in \mathbb{Z}$. It follows that $x_i = y_{i+(p-n)}$ (subscripts mod p wrapping from 1 to p), so α is also a cyclic permutation of β , and therefore $\beta \sim \alpha$.
- Transitive: Let $\alpha \sim \beta$ and $\beta \sim \gamma$, with α, β as above and γ indexed by z . We have $y_i = x_{i+n}$ and $z_i = y_{i+k}$ for some $k, n \in \mathbb{Z}$. It follows that $z_i = x_{i+k+n}$, which implies that γ is a cyclic permutation of α , so $\alpha \sim \gamma$.

Therefore \sim is an equivalence relation on \mathcal{S} . \square

- (d) Prove that an equivalence class contains a single element if and only if it is of the form (x, x, \dots, x) with $x^p = 1$.

Proof. First, let $\alpha = (x, \dots, x)$ and let $\alpha \sim \beta$. Then β is a cyclic permutation of α . Since α consists of a single, repeated coordinate value, we must have $\beta = (x, \dots, x) = \alpha$. Therefore the equivalence class of α consists only of itself.

Next, let $\alpha \in \mathcal{S}$ and suppose that the equivalence class of α under \sim consists only of α . Suppose $\alpha = (x_1, x_2, \dots, x_p)$. Let β be a cyclic permutation of α shifted by 1: $\beta = (x_2, x_3, \dots, x_p, x_1)$. Now β is in the equivalence class of α , but we must have $\beta = \alpha$, so $x_{i+1} = x_i$ for all x_i . It follows that $x_2 = x_1, x_3 = x_2 = x_1$, and so every value is equal to x_1 . Then we have $\alpha = (x_1, \dots, x_1)$, which is of the form (x, \dots, x) , and by definition we must have $x^p = 1$. \square

- (e) Prove that every equivalence class has order 1 or p (this uses the fact that p is a *prime*). Deduce that $|G|^{p-1} = k + pd$, where k is the number of classes of size 1 and d is the number of classes of size p .

Proof. From (d), if $\alpha = (x, \dots, x)$ for some $x \in G$, its equivalence class has order 1.

Let $\alpha = (x_1, x_2, \dots, x_p)$. Then there are exactly p members in the equivalence class of α , and they are the cyclic permutations of α shifted by $0, 1, 2, \dots, p-1$, respectively. For example, the n -th member of the equivalence class is $(x_{1+n}, x_{2+n}, \dots, x_{p+n})$.

The equivalence classes of the elements of \mathcal{S} partition \mathcal{S} . Suppose there are k equivalence classes of order 1, and d equivalence classes of order p . From (a), the order of \mathcal{S} is $|G|^{p-1}$. Then we have $|G|^{p-1} = k + pd$. \square

- (f) Since $\{(1, 1, \dots, 1)\}$ is an equivalence class of size 1, conclude from (e) that there must be a nonidentity element x in G with $x^p = 1$, i.e., G contains an element of order p .

Proof. From (e), we have $|G|^{p-1} = k + pd$ for some $k, d \geq 0$. From (a), p divides the order of $\mathcal{S} = |G|^{p-1}$, so we can write $ps = k + pd$ for some $s > 0$. Then $k = ps - pd = p(s - d)$, and so p divides k . Because p is prime, this implies that $k > 1$, so there are at least two elements whose equivalence classes have size 1. We already know that one is the identity; therefore there must be some element $\alpha \in \mathcal{S}, \alpha \neq (1, \dots, 1)$ whose equivalence class under \sim has size 1. From (d), $\alpha = (x, \dots, x)$ for some $x \in G$, and we thus have $x^p = 1$, which implies that $|x| = p$. \square

12. (10/16/23)

Let $H \leq G$. Prove that the map $x \mapsto x^{-1}$ sends each left coset of H in G onto a right coset of H and gives a bijection between the set of left cosets and the set of right cosets of H in G (hence the number of left cosets of H in G equals the number of right cosets).

Proof. Let $\varphi : G \rightarrow G$ be defined by $\varphi(x) = x^{-1}$ for all $x \in G$. Consider:

$$\varphi(xH) = \{\varphi(xh) \mid h \in H\} = \{(xh)^{-1} \mid h \in H\} = \{h^{-1}x^{-1} \mid h \in H\} = Hx^{-1},$$

so φ maps left cosets of H onto right cosets of H .

Further, considering φ as a map from left cosets of H to right cosets of H , it is a bijection.

Toward injectivity, suppose that $\varphi(xH) = \varphi(yH)$ for some $x, y \in G$, and let $z \in xH$. Then $\varphi(z) = z^{-1} = hy^{-1}$, because $z \in xH$ and $\varphi(xH) = \varphi(yH)$. Inverting both sides, we obtain $z = (hy^{-1})^{-1} = yh^{-1} \in yH$, and so $xH \subseteq yH$. The same logic shows that $yH \subseteq xH$, so we must have $xH = yH$, and therefore φ is injective.

It is also surjective: Letting Hx be a right coset of H , by definition we have $\varphi(x^{-1}H) = Hx$. It is therefore a bijection, and so there are an equal number of left cosets and right cosets of H in G . \square

13. (10/16/23)

Fix any labelling of the vertices of a square and use this to identify D_8 as a subgroup of S_4 . Prove that the elements of D_8 and $\langle(1, 2, 3)\rangle$ do not commute in S_4 .

Proof. Label the vertices of a square starting at the upper-left corner and going clockwise 1, 2, 3, 4. We can assign to the generators r, s of D_8 the permutations $(1, 2, 3, 4), (2, 4) \in S_4$, respectively.

To show that the elements of D_8 and $\langle(1, 2, 3)\rangle$ do not commute, we note that:

$$(1, 2, 3) \cdot s = (1, 2, 3)(2, 4) = (1, 2, 4, 3), \text{ and} \\ s \cdot (1, 2, 3) = (2, 4)(1, 2, 3) = (1, 4, 2, 3),$$

so s does not commute with $(1, 2, 3) \in S_4$. Therefore D_8 and $\langle(1, 2, 3)\rangle$ are not commuting subgroups of S_4 . \square

14. (10/17/23)

Prove that S_4 does not have a normal subgroup of order 8 or a normal subgroup of order 3.

Proof. From Corollary 10, a subgroup of order 3 is isomorphic to Z_3 , hence cyclic. So, without loss of generality, consider $\langle(1, 2, 3)\rangle \leq S_4$. Consider the conjugate of $(1, 2, 3)$ by $(1, 2)(3, 4)$:

$$(1, 2)(3, 4) \cdot (1, 2, 3) \cdot (1, 2)(3, 4) = (1, 4, 2),$$

which is not an element of $\langle(1, 2, 3)\rangle$. Therefore there is an element of S_4 that does not normalize $\langle(1, 2, 3)\rangle$ and, by isomorphism, any subgroup of order 3, so S_4 does not contain any normal subgroups of order 3.

Next, let $X \leq S_4$ with $|X| = 8$ and suppose that $X \trianglelefteq S_4$. From Cauchy's Theorem, X contains an element of order 2, which may be either a single 2-cycle or a pair of disjoint 2-cycles. We will consider each case individually:

- Without loss of generality, suppose that $(1, 2) \in X$. Because X is normal in S_4 , the conjugate element $(1, 2, 3) \cdot (1, 2) \cdot (1, 3, 2) = (2, 3)$ must lie in X . Because X is closed, the product $(1, 2) \cdot (2, 3) = (1, 2, 3)$ must lie in X , a contradiction since (from Corollary 9) a subgroup of order 8 contains no elements of order 3. Thus X is not normal in S_4 .
- Similarly, suppose that $(1, 2)(3, 4) \in X$. Again, the conjugate $(1, 2, 3) \cdot (1, 2)(3, 4) \cdot (1, 3, 2) = (1, 4, 3, 2)$ must lie in X . So the product $(1, 2)(3, 4) \cdot (1, 4, 3, 2) = (1, 3)$ must lie in X . Then, since X contains a 2-cycle, it must contain an element of order 3, a contradiction. Thus X is again not normal in S_4 .

This concludes the proof that S_4 contains no normal subgroups of order 8 or order 3. \square

15. (10/19/23)

Let $G = S_n$ and for fixed $i \in \{1, 2, \dots, n\}$ let G_i be the stabilizer of i . Prove that $G \cong S_{n-1}$.

Proof. From Ch. 2.2, Exercise 8., we have defined a bijection $\varphi : G_i \rightarrow S_{n-1}$ defined on a permutation $\sigma \in G_i$ and an element $m \in \{1, 2, \dots, n\}$ it permutes:

$$\varphi(\sigma)(m) = \begin{cases} \sigma(m) & \text{if } \sigma(m) \leq i \\ \sigma(m) - 1 & \text{if } \sigma(m) > i \end{cases}.$$

For $\sigma_1, \sigma_2 \in G_i$ and $m \in \{1, \dots, n\}$, let $\sigma_2(m) = k$ and $\sigma_1(k) = p$. Let us consider the different cases for k and p .

1. $k \leq i, p \leq i$. Then:

$$\begin{aligned} (\sigma_1 \circ \sigma_2)(m) &= \sigma_1(\sigma_2(m)) = \sigma_1(k) = p \leq i, \text{ which implies that} \\ \varphi(\sigma_1 \circ \sigma_2)(m) &= (\sigma_1 \circ \sigma_2)(m) = p. \end{aligned}$$

Also:

$$\begin{aligned} \sigma_2(m) = k \leq i &\Rightarrow \varphi(\sigma_2(m)) = \sigma_2(m) = k, \text{ and} \\ \sigma_1(k) = p \leq i &\Rightarrow \varphi(\sigma_1(k)) = \sigma_1(k) = p, \text{ so} \\ (\varphi(\sigma_1) \circ \varphi(\sigma_2))(m) &= \varphi(\sigma_1)(\varphi(\sigma_2)(m)) \\ &= \varphi(\sigma_1)(\sigma_2(m)) \\ &= \varphi(\sigma_1)(k) = \sigma_1(k) = p, \end{aligned}$$

thus $\varphi(\sigma_1 \circ \sigma_2) = \varphi(\sigma_1) \circ \varphi(\sigma_2)$.

2. $k > i, p \leq i$. As above, we have $(\sigma_1 \circ \sigma_2)(m) = p \leq i$, which implies that $\varphi(\sigma_1 \circ \sigma_2)(m) = p$. Also:

$$\sigma_2(m) = k > i \Rightarrow \varphi(\sigma_2)(m) = \sigma_2(m) - 1 = k - 1.$$

Now note that, in the permutation $\varphi(\sigma_1)$, all values greater than or equal to i have been decremented by 1, so we have $\varphi(\sigma_1)(k - 1) = \sigma_1(k) = p$. It follows that:

$$\begin{aligned} (\varphi(\sigma_1) \circ \varphi(\sigma_2))(m) &= \varphi(\sigma_1)(\varphi(\sigma_2)(m)) \\ &= \varphi(\sigma_1)(k - 1) \\ &= \sigma_1(k) = p, \end{aligned}$$

thus $\varphi(\sigma_1 \circ \sigma_2) = \varphi(\sigma_1) \circ \varphi(\sigma_2)$.

3. $k \leq i, p > i$. Then $(\sigma_1 \circ \sigma_2)(m) = p > i$, which implies that $\varphi(\sigma_1 \circ \sigma_2)(m) = (\sigma_1 \circ \sigma_2)(m) = p - 1$. As in the first case, $\varphi(\sigma_2)(m) = \sigma_2(m) = k$. So:

$$\begin{aligned} (\varphi(\sigma_1) \circ \varphi(\sigma_2))(m) &= \varphi(\sigma_1)(\varphi(\sigma_2)(m)) \\ &= \varphi(\sigma_1)(k) \\ &= \sigma_1(k) - 1 = p - 1, \end{aligned}$$

thus $\varphi(\sigma_1 \circ \sigma_2) = \varphi(\sigma_1) \circ \varphi(\sigma_2)$.

4. $k > i, p > i$. As above, we have $\varphi(\sigma_1 \circ \sigma_2)(m) = p - 1$. As in the second case, we have $\varphi(\sigma_2)(m) = k - 1$; however, $\sigma_1(k) = p > i$, so $\varphi(\sigma_1(k - 1)) = \sigma_1(k) - 1 = p - 1$. Then:

$$\begin{aligned} (\varphi(\sigma_1) \circ \varphi(\sigma_2))(m) &= \varphi(\sigma_1)(\varphi(\sigma_2)(m)) \\ &= \varphi(\sigma_1)(k - 1) \\ &= \sigma_1(k - 1) - 1 = p - 1, \end{aligned}$$

thus $\varphi(\sigma_1 \circ \sigma_2) = \varphi(\sigma_1) \circ \varphi(\sigma_2)$.

This exhaustively shows that for all $\sigma_1, \sigma_2 \in G_i$, the equation $\varphi(\sigma_1 \circ \sigma_2) = \varphi(\sigma_1) \circ \varphi(\sigma_2)$ holds in S_{n-1} . Thus φ is an isomorphism, and so $G_i \cong S_{n-1}$. \square