

Groups of size p^2

Groups of size p

Groups of size p

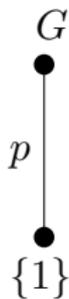
Let G be a finite group whose order is a prime number p .

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is

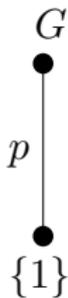
Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is



Groups of size p

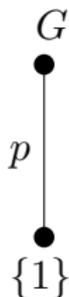
Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is



Theorem.

Groups of size p

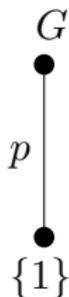
Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is



Theorem. Let G be a nontrivial group.

Groups of size p

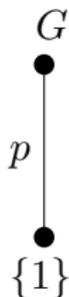
Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is



Theorem. Let G be a nontrivial group. The following are equivalent:

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is

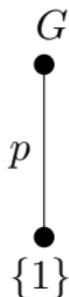


Theorem. Let G be a nontrivial group. The following are equivalent:

① $|G| = p$.

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is

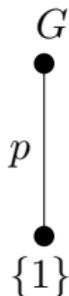


Theorem. Let G be a nontrivial group. The following are equivalent:

① $|G| = p$.

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is

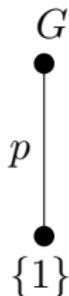


Theorem. Let G be a nontrivial group. The following are equivalent:

- 1 $|G| = p$.
- 2 G has no proper nontrivial subgroups.

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is

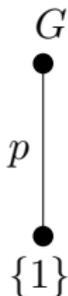


Theorem. Let G be a nontrivial group. The following are equivalent:

- 1 $|G| = p$.
- 2 G has no proper nontrivial subgroups.

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is

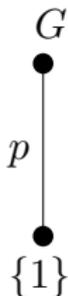


Theorem. Let G be a nontrivial group. The following are equivalent:

- 1 $|G| = p$.
- 2 G has no proper nontrivial subgroups.
- 3 $\text{Sub}(G)$ is a 2-element chain.

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is

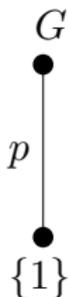


Theorem. Let G be a nontrivial group. The following are equivalent:

- 1 $|G| = p$.
- 2 G has no proper nontrivial subgroups.
- 3 $\text{Sub}(G)$ is a 2-element chain.

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is

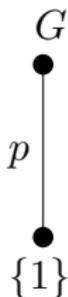


Theorem. Let G be a nontrivial group. The following are equivalent:

- 1 $|G| = p$.
- 2 G has no proper nontrivial subgroups.
- 3 $\text{Sub}(G)$ is a 2-element chain.
- 4 $G \cong C_p$.

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is

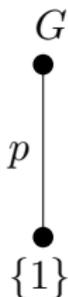


Theorem. Let G be a nontrivial group. The following are equivalent:

- 1 $|G| = p$.
- 2 G has no proper nontrivial subgroups.
- 3 $\text{Sub}(G)$ is a 2-element chain.
- 4 $G \cong C_p$.

Groups of size p

Let G be a finite group whose order is a prime number p . The subgroup lattice of G , labeled with indices, is



Theorem. Let G be a nontrivial group. The following are equivalent:

- 1 $|G| = p$.
- 2 G has no proper nontrivial subgroups.
- 3 $\text{Sub}(G)$ is a 2-element chain.
- 4 $G \cong C_p$.

Groups of size p^2 with one maximal subgroup

Groups of size p^2 with one maximal subgroup

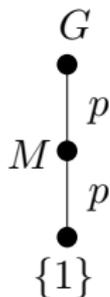
Let G be a finite group whose order p^2 with one maximal subgroup.

Groups of size p^2 with one maximal subgroup

Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is

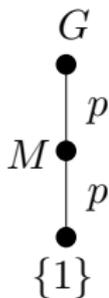
Groups of size p^2 with one maximal subgroup

Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is



Groups of size p^2 with one maximal subgroup

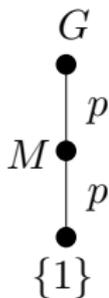
Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is



Theorem.

Groups of size p^2 with one maximal subgroup

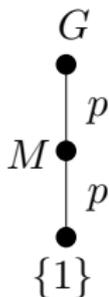
Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is



Theorem. Let G be a group of order p^2 .

Groups of size p^2 with one maximal subgroup

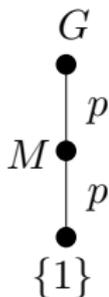
Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is



Theorem. Let G be a group of order p^2 . The following are equivalent:

Groups of size p^2 with one maximal subgroup

Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is

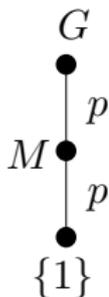


Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has one maximal subgroup.

Groups of size p^2 with one maximal subgroup

Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is

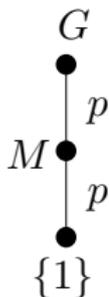


Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has one maximal subgroup.

Groups of size p^2 with one maximal subgroup

Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is

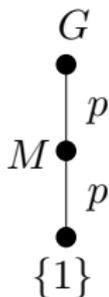


Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has one maximal subgroup.
- 2 $\text{Sub}(G)$ is a 3-element chain.

Groups of size p^2 with one maximal subgroup

Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is

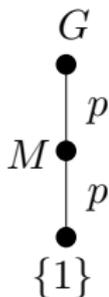


Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has one maximal subgroup.
- 2 $\text{Sub}(G)$ is a 3-element chain.

Groups of size p^2 with one maximal subgroup

Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is

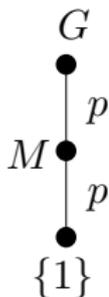


Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has one maximal subgroup.
- 2 $\text{Sub}(G)$ is a 3-element chain.
- 3 $G \cong C_{p^2}$.

Groups of size p^2 with one maximal subgroup

Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is

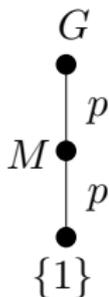


Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has one maximal subgroup.
- 2 $\text{Sub}(G)$ is a 3-element chain.
- 3 $G \cong C_{p^2}$.

Groups of size p^2 with one maximal subgroup

Let G be a finite group whose order p^2 with one maximal subgroup. The subgroup lattice of G , labeled with indices, is



Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has one maximal subgroup.
- 2 $\text{Sub}(G)$ is a 3-element chain.
- 3 $G \cong C_{p^2}$.

Groups of size p^2 with more than one maximal subgroup

Groups of size p^2 with more than one maximal subgroup

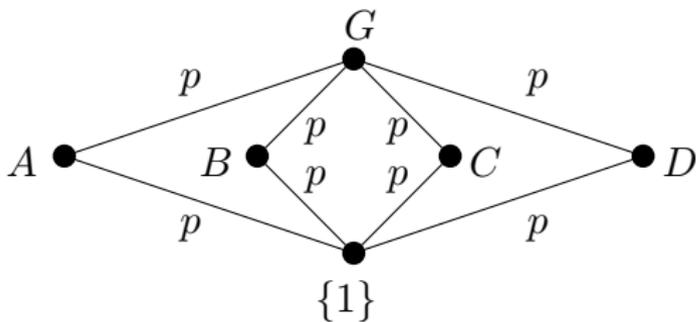
Let G be a finite group whose order p^2 with more than one maximal subgroup.

Groups of size p^2 with more than one maximal subgroup

Let G be a finite group whose order p^2 with more than one maximal subgroup. The subgroup lattice of G , labeled with indices, is

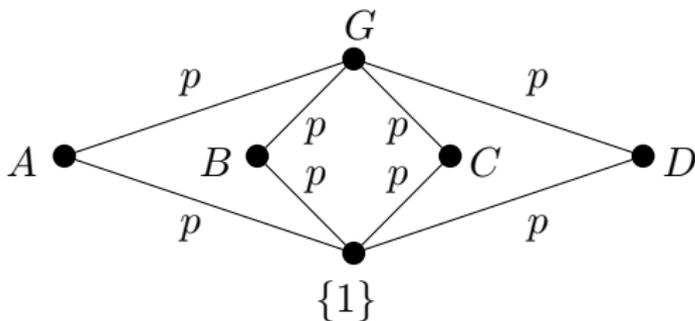
Groups of size p^2 with more than one maximal subgroup

Let G be a finite group whose order p^2 with more than one maximal subgroup. The subgroup lattice of G , labeled with indices, is



Groups of size p^2 with more than one maximal subgroup

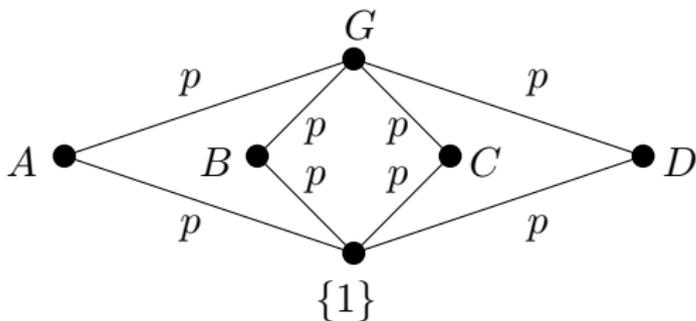
Let G be a finite group whose order p^2 with more than one maximal subgroup. The subgroup lattice of G , labeled with indices, is



Observations.

Groups of size p^2 with more than one maximal subgroup

Let G be a finite group whose order p^2 with more than one maximal subgroup. The subgroup lattice of G , labeled with indices, is

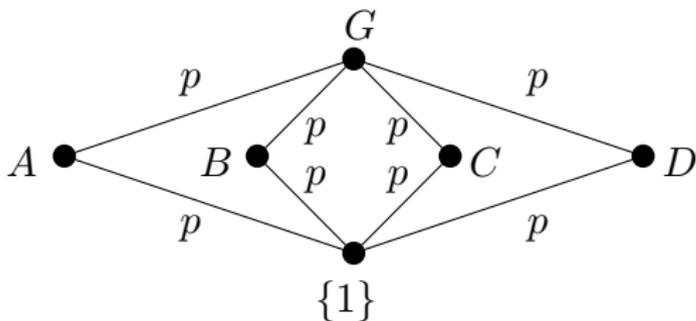


Observations.

- 1 In this case, G is not cyclic, so it satisfies $(\forall x)(x^p = 1)$.

Groups of size p^2 with more than one maximal subgroup

Let G be a finite group whose order p^2 with more than one maximal subgroup. The subgroup lattice of G , labeled with indices, is

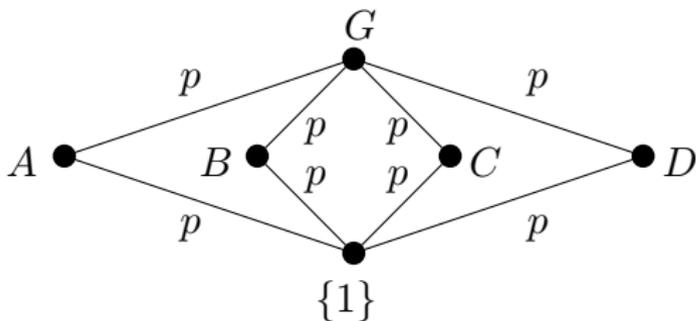


Observations.

- 1 In this case, G is not cyclic, so it satisfies $(\forall x)(x^p = 1)$.
- 2 If $\langle a \rangle \neq \langle b \rangle$, then $\langle a \rangle \cap \langle b \rangle = \{1\}$.

Groups of size p^2 with more than one maximal subgroup

Let G be a finite group whose order p^2 with more than one maximal subgroup. The subgroup lattice of G , labeled with indices, is

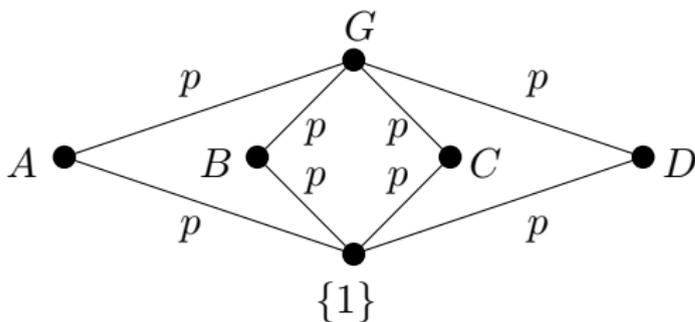


Observations.

- 1 In this case, G is not cyclic, so it satisfies $(\forall x)(x^p = 1)$.
- 2 If $\langle a \rangle \neq \langle b \rangle$, then $\langle a \rangle \cap \langle b \rangle = \{1\}$.
- 3 If $\langle a \rangle \neq \langle b \rangle$ are maximal, then $G = \langle a \rangle \cdot \langle b \rangle = \{a^i b^j \mid 0 \leq i, j < p\}$.

Groups of size p^2 with more than one maximal subgroup

Let G be a finite group whose order p^2 with more than one maximal subgroup. The subgroup lattice of G , labeled with indices, is



Observations.

- 1 In this case, G is not cyclic, so it satisfies $(\forall x)(x^p = 1)$.
- 2 If $\langle a \rangle \neq \langle b \rangle$, then $\langle a \rangle \cap \langle b \rangle = \{1\}$.
- 3 If $\langle a \rangle \neq \langle b \rangle$ are maximal, then $G = \langle a \rangle \cdot \langle b \rangle = \{a^i b^j \mid 0 \leq i, j < p\}$.
- 4 If $\langle a \rangle \neq \langle b \rangle$ are maximal, then for all $g \in G$, $g^{-1} a g \notin \langle b \rangle$.

Groups of size p^2 with more than one maximal subgroup

Groups of size p^2 with more than one maximal subgroup

Lemma.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$,

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G .

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G . The element a was chosen arbitrarily in $G - \{1\}$, so every maximal subgroup of G is normal.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G . The element a was chosen arbitrarily in $G - \{1\}$, so every maximal subgroup of G is normal.

Now choose $c, d \in G$ arbitrarily.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G . The element a was chosen arbitrarily in $G - \{1\}$, so every maximal subgroup of G is normal.

Now choose $c, d \in G$ arbitrarily. If they belong to one of the (cyclic) maximal subgroups of G , then they commute with each other.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G . The element a was chosen arbitrarily in $G - \{1\}$, so every maximal subgroup of G is normal.

Now choose $c, d \in G$ arbitrarily. If they belong to one of the (cyclic) maximal subgroups of G , then they commute with each other. Else, $\langle c \rangle \neq \langle d \rangle$.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G . The element a was chosen arbitrarily in $G - \{1\}$, so every maximal subgroup of G is normal.

Now choose $c, d \in G$ arbitrarily. If they belong to one of the (cyclic) maximal subgroups of G , then they commute with each other. Else, $\langle c \rangle \neq \langle d \rangle$. Now $(c^{-1}d^{-1}c)d = c^{-1}(d^{-1}cd) \in \langle d \rangle \cap \langle c \rangle = \{1\}$,

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G . The element a was chosen arbitrarily in $G - \{1\}$, so every maximal subgroup of G is normal.

Now choose $c, d \in G$ arbitrarily. If they belong to one of the (cyclic) maximal subgroups of G , then they commute with each other. Else, $\langle c \rangle \neq \langle d \rangle$. Now $(c^{-1}d^{-1}c)d = c^{-1}(d^{-1}cd) \in \langle d \rangle \cap \langle c \rangle = \{1\}$, so $c^{-1}d^{-1}cd = 1$.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G . The element a was chosen arbitrarily in $G - \{1\}$, so every maximal subgroup of G is normal.

Now choose $c, d \in G$ arbitrarily. If they belong to one of the (cyclic) maximal subgroups of G , then they commute with each other. Else, $\langle c \rangle \neq \langle d \rangle$. Now $(c^{-1}d^{-1}c)d = c^{-1}(d^{-1}cd) \in \langle d \rangle \cap \langle c \rangle = \{1\}$, so $c^{-1}d^{-1}cd = 1$. We may rewrite this as $cd = dc$.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G . The element a was chosen arbitrarily in $G - \{1\}$, so every maximal subgroup of G is normal.

Now choose $c, d \in G$ arbitrarily. If they belong to one of the (cyclic) maximal subgroups of G , then they commute with each other. Else, $\langle c \rangle \neq \langle d \rangle$. Now $(c^{-1}d^{-1}c)d = c^{-1}(d^{-1}cd) \in \langle d \rangle \cap \langle c \rangle = \{1\}$, so $c^{-1}d^{-1}cd = 1$. We may rewrite this as $cd = dc$. Thus, in all cases, $c, d \in G$ commute with each other.

Groups of size p^2 with more than one maximal subgroup

Lemma. If $|G| = p^2$, then G is abelian.

Proof. If G is cyclic, then it is abelian, so we are done in the case.

Else, G has more than one maximal subgroup, and each is of the form $\langle a \rangle$ for some $a \in G$. Choose one of them arbitrarily, $A = \langle a \rangle$. If A is not a normal subgroup of G , then there is some $g \in G$ such that $A \neq g^{-1}Ag$. Necessarily, $g^{-1}Ag = \langle b \rangle$ for some $b \in G$. But now $\langle a \rangle = A \neq g^{-1}Ag = \langle b \rangle$ and $g^{-1}ag \in g^{-1}Ag = \langle b \rangle$, contrary to an earlier observation. This contradiction shows that $A = \langle a \rangle$ is normal in G . The element a was chosen arbitrarily in $G - \{1\}$, so every maximal subgroup of G is normal.

Now choose $c, d \in G$ arbitrarily. If they belong to one of the (cyclic) maximal subgroups of G , then they commute with each other. Else, $\langle c \rangle \neq \langle d \rangle$. Now $(c^{-1}d^{-1}c)d = c^{-1}(d^{-1}cd) \in \langle d \rangle \cap \langle c \rangle = \{1\}$, so $c^{-1}d^{-1}cd = 1$. We may rewrite this as $cd = dc$. Thus, in all cases, $c, d \in G$ commute with each other. \square

Groups of size p^2 with more than one maximal subgroup

Groups of size p^2 with more than one maximal subgroup

Theorem.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 .

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)]

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

[(3) \Rightarrow (2)]

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

[(3) \Rightarrow (2)] Since every nontrivial proper subgroup of G is maximal and of the form $\langle a \rangle$ for some a ,

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

[(3) \Rightarrow (2)] Since every nontrivial proper subgroup of G is maximal and of the form $\langle a \rangle$ for some a , $\text{Sub}(G)$ is isomorphic to M_n for some n .

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

[(3) \Rightarrow (2)] Since every nontrivial proper subgroup of G is maximal and of the form $\langle a \rangle$ for some a , $\text{Sub}(G)$ is isomorphic to M_n for some n . Counting elements leads to $1 + n(p - 1) = p^2$,

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

[(3) \Rightarrow (2)] Since every nontrivial proper subgroup of G is maximal and of the form $\langle a \rangle$ for some a , $\text{Sub}(G)$ is isomorphic to M_n for some n . Counting elements leads to $1 + n(p - 1) = p^2$, or $n(p - 1) = p^2 - 1$,

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

[(3) \Rightarrow (2)] Since every nontrivial proper subgroup of G is maximal and of the form $\langle a \rangle$ for some a , $\text{Sub}(G)$ is isomorphic to M_n for some n . Counting elements leads to $1 + n(p - 1) = p^2$, or $n(p - 1) = p^2 - 1$, or $n = p + 1$.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

[(3) \Rightarrow (2)] Since every nontrivial proper subgroup of G is maximal and of the form $\langle a \rangle$ for some a , $\text{Sub}(G)$ is isomorphic to M_n for some n . Counting elements leads to $1 + n(p - 1) = p^2$, or $n(p - 1) = p^2 - 1$, or $n = p + 1$.

[(2) \Rightarrow (1)]

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

[(3) \Rightarrow (2)] Since every nontrivial proper subgroup of G is maximal and of the form $\langle a \rangle$ for some a , $\text{Sub}(G)$ is isomorphic to M_n for some n . Counting elements leads to $1 + n(p - 1) = p^2$, or $n(p - 1) = p^2 - 1$, or $n = p + 1$.

[(2) \Rightarrow (1)] By (2), the number of maximal subgroups of G is $p + 1$, which is greater than 1.

Groups of size p^2 with more than one maximal subgroup

Theorem. Let G be a group of order p^2 . The following are equivalent:

- 1 G has more than one maximal subgroup.
- 2 $\text{Sub}(G)$ is isomorphic to M_{p+1} .
- 3 $G \cong C_p \times C_p$.

Proof.

[(1) \Rightarrow (3)] By the Lemma, we know that $|G| = p^2$ implies that G is abelian. In the case where G has more than one maximal subgroup, we know that every $x \in G$ satisfies $x^p = 1$. Choose $a, b \in G$ that generate maximal subgroups $\langle a \rangle$ and $\langle b \rangle$. Verify that $h: C_p \times C_p \rightarrow G: (r^i, r^j) \mapsto a^i b^j$ is an isomorphism.

[(3) \Rightarrow (2)] Since every nontrivial proper subgroup of G is maximal and of the form $\langle a \rangle$ for some a , $\text{Sub}(G)$ is isomorphic to M_n for some n . Counting elements leads to $1 + n(p - 1) = p^2$, or $n(p - 1) = p^2 - 1$, or $n = p + 1$.

[(2) \Rightarrow (1)] By (2), the number of maximal subgroups of G is $p + 1$, which is greater than 1. \square

Final result

Final result

If p is prime, then any group of order p^2 is isomorphic to C_{p^2} or to $C_p \times C_p$.

Final result

If p is prime, then any group of order p^2 is isomorphic to C_{p^2} or to $C_p \times C_p$. These are not isomorphic to each other, since C_{p^2} has an element of order p^2 and $C_p \times C_p$ does not.

Final result

If p is prime, then any group of order p^2 is isomorphic to C_{p^2} or to $C_p \times C_p$. These are not isomorphic to each other, since C_{p^2} has an element of order p^2 and $C_p \times C_p$ does not. Another way to say this is that $C_p \times C_p$ satisfies the law $(\forall x)(x^p = 1)$ while C_{p^2} does not.