Part IB

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Groups Rings and Modules

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Year
2017
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Paper 3, Section I

1E Groups, Rings and Modules

Let $R$ be a commutative ring and let $M$ be an $R$-module. Show that $M$ is a finitely generated $R$-module if and only if there exists a surjective $R$-module homomorphism $R^n \to M$ for some $n$.

Find an example of a $\mathbb{Z}$-module $M$ such that there is no surjective $\mathbb{Z}$-module homomorphism $\mathbb{Z} \to M$ but there is a surjective $\mathbb{Z}$-module homomorphism $\mathbb{Z}^2 \to M$ which is not an isomorphism. Justify your answer.

Paper 2, Section I

2E Groups, Rings and Modules

(a) Define what is meant by a unique factorisation domain and by a principal ideal domain. State Gauss’s lemma and Eisenstein’s criterion, without proof.

(b) Find an example, with justification, of a ring $R$ and a subring $S$ such that

(i) $R$ is a principal ideal domain, and

(ii) $S$ is a unique factorisation domain but not a principal ideal domain.

Paper 4, Section I

2E Groups, Rings and Modules

Let $G$ be a non-trivial finite $p$-group and let $Z(G)$ be its centre. Show that $|Z(G)| > 1$. Show that if $|G| = p^3$ and if $G$ is not abelian, then $|Z(G)| = p$.

Paper 1, Section II

10E Groups, Rings and Modules

(a) State Sylow’s theorem.

(b) Let $G$ be a finite simple non-abelian group. Let $p$ be a prime number. Show that if $p$ divides $|G|$, then $|G|$ divides $n_p!/2$ where $n_p$ is the number of Sylow $p$-subgroups of $G$.

(c) Let $G$ be a group of order 48. Show that $G$ is not simple. Find an example of $G$ which has no normal Sylow 2-subgroup.
Paper 2, Section II
11E Groups, Rings and Modules
Let $R$ be a commutative ring.

(a) Let $N$ be the set of nilpotent elements of $R$, that is,

$$N = \{ r \in R \mid r^n = 0 \text{ for some } n \in \mathbb{N} \}.$$ 

Show that $N$ is an ideal of $R$.

(b) Assume $R$ is Noetherian and assume $S \subseteq R$ is a non-empty subset such that if $s, t \in S$, then $st \in S$. Let $I$ be an ideal of $R$ disjoint from $S$. Show that there is a prime ideal $P$ of $R$ containing $I$ and disjoint from $S$.

(c) Again assume $R$ is Noetherian and let $N$ be as in part (a). Let $\mathcal{P}$ be the set of all prime ideals of $R$. Show that

$$N = \bigcap_{P \in \mathcal{P}} P.$$ 

Paper 4, Section II
11E Groups, Rings and Modules

(a) State (without proof) the classification theorem for finitely generated modules over a Euclidean domain. Give the statement and the proof of the rational canonical form theorem.

(b) Let $R$ be a principal ideal domain and let $M$ be an $R$-submodule of $R^n$. Show that $M$ is a free $R$-module.

Paper 3, Section II
11E Groups, Rings and Modules

(a) Define what is meant by a Euclidean domain. Show that every Euclidean domain is a principal ideal domain.

(b) Let $p \in \mathbb{Z}$ be a prime number and let $f \in \mathbb{Z}[x]$ be a monic polynomial of positive degree. Show that the quotient ring $\mathbb{Z}[x]/(p, f)$ is finite.

(c) Let $\alpha \in \mathbb{Z}[\sqrt{-1}]$ and let $P$ be a non-zero prime ideal of $\mathbb{Z}[\alpha]$. Show that the quotient $\mathbb{Z}[\alpha]/P$ is a finite ring.
Paper 3, Section I
1E Groups, Rings and Modules
Let $G$ be a group of order $n$. Define what is meant by a permutation representation of $G$. Using such representations, show $G$ is isomorphic to a subgroup of the symmetric group $S_n$. Assuming $G$ is non-abelian simple, show $G$ is isomorphic to a subgroup of $A_n$. Give an example of a permutation representation of $S_3$ whose kernel is $A_3$.

Paper 4, Section I
2E Groups, Rings and Modules
Give the statement and the proof of Eisenstein’s criterion. Use this criterion to show $x^{p-1} + x^{p-2} + \cdots + 1$ is irreducible in $\mathbb{Q}[x]$ where $p$ is a prime.

Paper 2, Section I
2E Groups, Rings and Modules
Let $R$ be an integral domain.

Define what is meant by the field of fractions $F$ of $R$. [You do not need to prove the existence of $F$.]

Suppose that $\phi : R \to K$ is an injective ring homomorphism from $R$ to a field $K$. Show that $\phi$ extends to an injective ring homomorphism $\Phi : F \to K$.

Give an example of $R$ and a ring homomorphism $\psi : R \to S$ from $R$ to a ring $S$ such that $\psi$ does not extend to a ring homomorphism $F \to S$.

Paper 1, Section II
10E Groups, Rings and Modules
(a) Let $I$ be an ideal of a commutative ring $R$ and assume $I \subseteq \bigcup_{i=1}^{n} P_i$ where the $P_i$ are prime ideals. Show that $I \subseteq P_i$ for some $i$.

(b) Show that $(x^2 + 1)$ is a maximal ideal of $\mathbb{R}[x]$. Show that the quotient ring $\mathbb{R}[x]/(x^2 + 1)$ is isomorphic to $\mathbb{C}$.

(c) For $a, b \in \mathbb{R}$, let $I_{a,b}$ be the ideal $(x - a, y - b)$ in $\mathbb{R}[x, y]$. Show that $I_{a,b}$ is a maximal ideal. Find a maximal ideal $J$ of $\mathbb{R}[x, y]$ such that $J \neq I_{a,b}$ for any $a, b \in \mathbb{R}$. Justify your answers.
Paper 3, Section II
11E Groups, Rings and Modules
(a) Define what is meant by an algebraic integer $\alpha$. Show that the ideal

$$I = \{h \in \mathbb{Z}[x] \mid h(\alpha) = 0\}$$

in $\mathbb{Z}[x]$ is generated by a monic irreducible polynomial $f$. Show that $\mathbb{Z}[\alpha]$, considered as a $\mathbb{Z}$-module, is freely generated by $n$ elements where $n = \deg f$.

(b) Assume $\alpha \in \mathbb{C}$ satisfies $\alpha^5 + 2\alpha + 2 = 0$. Is it true that the ideal $(5)$ in $\mathbb{Z}[\alpha]$ is a prime ideal? Is there a ring homomorphism $\mathbb{Z}[\alpha] \to \mathbb{Z}[\sqrt{-1}]$? Justify your answers.

(c) Show that the only unit elements of $\mathbb{Z}[\sqrt{-5}]$ are 1 and $-1$. Show that $\mathbb{Z}[\sqrt{-5}]$ is not a UFD.

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Paper 4, Section II
11E Groups, Rings and Modules
Let $R$ be a Noetherian ring and let $M$ be a finitely generated $R$-module.

(a) Show that every submodule of $M$ is finitely generated.

(b) Show that each maximal element of the set

$$\mathcal{A} = \{\text{Ann}(m) \mid 0 \neq m \in M\}$$

is a prime ideal. [Here, maximal means maximal with respect to inclusion, and $\text{Ann}(m) = \{r \in R \mid rm = 0\}$]

(c) Show that there is a chain of submodules

$$0 = M_0 \subseteq M_1 \subseteq \cdots \subseteq M_l = M,$$

such that for each $0 < i \leq l$ the quotient $M_i/M_{i-1}$ is isomorphic to $R/P_i$ for some prime ideal $P_i$.

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Paper 2, Section II
11E Groups, Rings and Modules
(a) State Sylow’s theorems and give the proof of the second theorem which concerns conjugate subgroups.

(b) Show that there is no simple group of order 351.

(c) Let $k$ be the finite field $\mathbb{Z}/(31)$ and let $GL_2(k)$ be the multiplicative group of invertible $2 \times 2$ matrices over $k$. Show that every Sylow 3-subgroup of $GL_2(k)$ is abelian.
Paper 3, Section I

1F Groups, Rings and Modules

State two equivalent conditions for a commutative ring to be Noetherian, and prove they are equivalent. Give an example of a ring which is not Noetherian, and explain why it is not Noetherian.

Paper 4, Section I

2F Groups, Rings and Modules

Let \( R \) be a commutative ring. Define what it means for an ideal \( I \subseteq R \) to be prime. Show that \( I \subseteq R \) is prime if and only if \( R/I \) is an integral domain.

Give an example of an integral domain \( R \) and an ideal \( I \subset R \), \( I \neq R \), such that \( R/I \) is not an integral domain.

Paper 2, Section I

2F Groups, Rings and Modules

Give four non-isomorphic groups of order 12, and explain why they are not isomorphic.

Paper 1, Section II

10F Groups, Rings and Modules

(i) Give the definition of a \( p \)-Sylow subgroup of a group.

(ii) Let \( G \) be a group of order \( 2835 = 3^4 \cdot 5 \cdot 7 \). Show that there are at most two possibilities for the number of 3-Sylow subgroups, and give the possible numbers of 3-Sylow subgroups.

(iii) Continuing with a group \( G \) of order 2835, show that \( G \) is not simple.
Paper 4, Section II
11F Groups, Rings and Modules
Find $a \in \mathbb{Z}_7$ such that $\mathbb{Z}_7[x]/(x^3 + a)$ is a field $F$. Show that for your choice of $a$, every element of $\mathbb{Z}_7$ has a cube root in the field $F$.

Show that if $F$ is a finite field, then the multiplicative group $F^\times = F \setminus \{0\}$ is cyclic.

Show that $F = \mathbb{Z}_2[x]/(x^3 + x + 1)$ is a field. How many elements does $F$ have? Find a generator for $F^\times$.

Paper 3, Section II
11F Groups, Rings and Modules
Can a group of order 55 have 20 elements of order 11? If so, give an example. If not, give a proof, including the proof of any statements you need.

Let $G$ be a group of order $pq$, with $p$ and $q$ primes, $p > q$. Suppose furthermore that $q$ does not divide $p - 1$. Show that $G$ is cyclic.

Paper 2, Section II
11F Groups, Rings and Modules
(a) Consider the homomorphism $f : \mathbb{Z}^3 \to \mathbb{Z}^4$ given by

$$f(a, b, c) = (a + 2b + 8c, 2a - 2b + 4c, -2b + 12c, 2a - 4b + 4c).$$

Describe the image of this homomorphism as an abstract abelian group. Describe the quotient of $\mathbb{Z}^3$ by the image of this homomorphism as an abstract abelian group.

(b) Give the definition of a Euclidean domain.

Fix a prime $p$ and consider the subring $R$ of the rational numbers $\mathbb{Q}$ defined by

$$R = \{\frac{q}{r} \mid \gcd(p, r) = 1\},$$

where ‘gcd’ stands for the greatest common divisor. Show that $R$ is a Euclidean domain.
Paper 3, Section I
1E Groups, Rings and Modules
State and prove Hilbert’s Basis Theorem.

Paper 4, Section I
2E Groups, Rings and Modules
Let $G$ be the abelian group generated by elements $a, b$ and $c$ subject to the relations: $3a + 6b + 3c = 0, 9b + 9c = 0$ and $-3a + 3b + 6c = 0$. Express $G$ as a product of cyclic groups. Hence determine the number of elements of $G$ of order 3.

Paper 2, Section I
2E Groups, Rings and Modules
List the conjugacy classes of $A_6$ and determine their sizes. Hence prove that $A_6$ is simple.

Paper 1, Section II
10E Groups, Rings and Modules
Let $G$ be a finite group and $p$ a prime divisor of the order of $G$. Give the definition of a Sylow $p$-subgroup of $G$, and state Sylow’s theorems.

Let $p$ and $q$ be distinct primes. Prove that a group of order $p^2q$ is not simple.

Let $G$ be a finite group, $H$ a normal subgroup of $G$ and $P$ a Sylow $p$-subgroup of $H$. Let $N_G(P)$ denote the normaliser of $P$ in $G$. Prove that if $g \in G$ then there exist $k \in N_G(P)$ and $h \in H$ such that $g = kh$. 

Part IB, 2014 List of Questions [TURN OVER
Paper 4, Section II

11E Groups, Rings and Modules

(a) Consider the four following types of rings: Principal Ideal Domains, Integral Domains, Fields, and Unique Factorisation Domains. Arrange them in the form \( A \implies B \implies C \implies D \) (where \( A \implies B \) means if a ring is of type \( A \) then it is of type \( B \)).

Prove that these implications hold. [You may assume that irreducibles in a Principal Ideal Domain are prime.] Provide examples, with brief justification, to show that these implications cannot be reversed.

(b) Let \( R \) be a ring with ideals \( I \) and \( J \) satisfying \( I \subseteq J \). Define \( K \) to be the set \( \{ r \in R : rJ \subseteq I \} \). Prove that \( K \) is an ideal of \( R \). If \( J \) and \( K \) are principal, prove that \( I \) is principal.

Paper 3, Section II

11E Groups, Rings and Modules

Let \( R \) be a ring, \( M \) an \( R \)-module and \( S = \{m_1, \ldots, m_k\} \) a subset of \( M \). Define what it means to say \( S \) spans \( M \). Define what it means to say \( S \) is an independent set.

We say \( S \) is a basis for \( M \) if \( S \) spans \( M \) and \( S \) is an independent set. Prove that the following two statements are equivalent.

1. \( S \) is a basis for \( M \).
2. Every element of \( M \) is uniquely expressible in the form \( r_1m_1 + \cdots + r_km_k \) for some \( r_1, \ldots, r_k \in R \).

We say \( S \) generates \( M \) freely if \( S \) spans \( M \) and any map \( \Phi : S \to N \), where \( N \) is an \( R \)-module, can be extended to an \( R \)-module homomorphism \( \Theta : M \to N \). Prove that \( S \) generates \( M \) freely if and only if \( S \) is a basis for \( M \).

Let \( M \) be an \( R \)-module. Are the following statements true or false? Give reasons.

(i) If \( S \) spans \( M \) then \( S \) necessarily contains an independent spanning set for \( M \).
(ii) If \( S \) is an independent subset of \( M \) then \( S \) can always be extended to a basis for \( M \).
Prove that every finite integral domain is a field.

Let $F$ be a field and $f$ an irreducible polynomial in the polynomial ring $F[X]$. Prove that $F[X]/(f)$ is a field, where $(f)$ denotes the ideal generated by $f$.

Hence construct a field of 4 elements, and write down its multiplication table.

Construct a field of order 9.
Paper 3, Section I
1G Groups, Rings and Modules
Define the notion of a free module over a ring. When $R$ is a PID, show that every ideal of $R$ is free as an $R$-module.

Paper 4, Section I
2G Groups, Rings and Modules
Let $p$ be a prime number, and $G$ be a non-trivial finite group whose order is a power of $p$. Show that the size of every conjugacy class in $G$ is a power of $p$. Deduce that the centre $Z$ of $G$ has order at least $p$.

Paper 2, Section I
2G Groups, Rings and Modules
Show that every Euclidean domain is a PID. Define the notion of a Noetherian ring, and show that $\mathbb{Z}[i]$ is Noetherian by using the fact that it is a Euclidean domain.

Paper 1, Section II
10G Groups, Rings and Modules
(i) Consider the group $G = GL_2(\mathbb{R})$ of all 2 by 2 matrices with entries in $\mathbb{R}$ and non-zero determinant. Let $T$ be its subgroup consisting of all diagonal matrices, and $N$ be the normaliser of $T$ in $G$. Show that $N$ is generated by $T$ and $\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, and determine the quotient group $N/T$.

(ii) Now let $p$ be a prime number, and $F$ be the field of integers modulo $p$. Consider the group $G = GL_2(F)$ as above but with entries in $F$, and define $T$ and $N$ similarly. Find the order of the group $N$. 
Paper 4, Section II
11G Groups, Rings and Modules

Let $R$ be an integral domain, and $M$ be a finitely generated $R$-module.

(i) Let $S$ be a finite subset of $M$ which generates $M$ as an $R$-module. Let $T$ be a maximal linearly independent subset of $S$, and let $N$ be the $R$-submodule of $M$ generated by $T$. Show that there exists a non-zero $r \in R$ such that $rx \in N$ for every $x \in M$.

(ii) Now assume $M$ is torsion-free, i.e. $rx = 0$ for $r \in R$ and $x \in M$ implies $r = 0$ or $x = 0$. By considering the map $M \to N$ mapping $x$ to $rx$ for $r$ as in (i), show that every torsion-free finitely generated $R$-module is isomorphic to an $R$-submodule of a finitely generated free $R$-module.

Paper 3, Section II
11G Groups, Rings and Modules

Let $R = \mathbb{C}[X,Y]$ be the polynomial ring in two variables over the complex numbers, and consider the principal ideal $I = (X^3 - Y^2)$ of $R$.

(i) Using the fact that $R$ is a UFD, show that $I$ is a prime ideal of $R$. [Hint: Elements in $\mathbb{C}[X,Y]$ are polynomials in $Y$ with coefficients in $\mathbb{C}[X]$]

(ii) Show that $I$ is not a maximal ideal of $R$, and that it is contained in infinitely many distinct proper ideals in $R$.

Paper 2, Section II
11G Groups, Rings and Modules

(i) State the structure theorem for finitely generated modules over Euclidean domains.

(ii) Let $\mathbb{C}[X]$ be the polynomial ring over the complex numbers. Let $M$ be a $\mathbb{C}[X]$-module which is 4-dimensional as a $\mathbb{C}$-vector space and such that $(X - 2)^4 \cdot x = 0$ for all $x \in M$. Find all possible forms we obtain when we write $M \cong \bigoplus_{i=1}^{m} \mathbb{C}[X]/(P_i^{n_i})$ for irreducible $P_i \in \mathbb{C}[X]$ and $n_i \geq 1$.

(iii) Consider the quotient ring $M = \mathbb{C}[X]/(X^3 + X)$ as a $\mathbb{C}[X]$-module. Show that $M$ is isomorphic to a $\mathbb{C}[X]$-module to the direct sum of three copies of $\mathbb{C}$. Give the isomorphism and its inverse explicitly.
Paper 3, Section I
1G Groups, Rings and Modules
What is a Euclidean domain?

Giving careful statements of any general results you use, show that in the ring \( \mathbb{Z}[\sqrt{-3}] \), 2 is irreducible but not prime.

Paper 2, Section I
2G Groups, Rings and Modules
What does it mean to say that the finite group \( G \) acts on the set \( \Omega \)?

By considering an action of the symmetry group of a regular tetrahedron on a set of pairs of edges, show there is a surjective homomorphism \( S_4 \rightarrow S_3 \).

[You may assume that the symmetric group \( S_n \) is generated by transpositions.]

Paper 4, Section I
2G Groups, Rings and Modules
An idempotent element of a ring \( R \) is an element \( e \) satisfying \( e^2 = e \). A nilpotent element is an element \( e \) satisfying \( e^N = 0 \) for some \( N \geq 0 \).

Let \( r \in R \) be non-zero. In the ring \( R[X] \), can the polynomial \( 1 + rX \) be (i) an idempotent, (ii) a nilpotent? Can \( 1 + rX \) satisfy the equation \( (1 + rX)^3 = (1 + rX) \)? Justify your answers.

Paper 1, Section II
10G Groups, Rings and Modules
Let \( G \) be a finite group. What is a Sylow \( p \)-subgroup of \( G \)?

Assuming that a Sylow \( p \)-subgroup \( H \) exists, and that the number of conjugates of \( H \) is congruent to 1 mod \( p \), prove that all Sylow \( p \)-subgroups are conjugate. If \( n_p \) denotes the number of Sylow \( p \)-subgroups, deduce that

\[
  n_p \equiv 1 \pmod{p} \quad \text{and} \quad n_p \mid |G|.
\]

If furthermore \( G \) is simple prove that either \( G = H \) or

\[
  |G| \mid n_p!.
\]

Deduce that a group of order 1,000,000 cannot be simple.
Paper 2, Section II

11G Groups, Rings and Modules

State Gauss’s Lemma. State Eisenstein’s irreducibility criterion.

(i) By considering a suitable substitution, show that the polynomial $1 + X^3 + X^6$ is irreducible over $\mathbb{Q}$.

(ii) By working in $\mathbb{Z}_2[X]$, show that the polynomial $1 - X^2 + X^5$ is irreducible over $\mathbb{Q}$.

Paper 3, Section II

11G Groups, Rings and Modules

For each of the following assertions, provide either a proof or a counterexample as appropriate:

(i) The ring $\mathbb{Z}_2[X]/\langle X^2 + X + 1 \rangle$ is a field.

(ii) The ring $\mathbb{Z}_3[X]/\langle X^2 + X + 1 \rangle$ is a field.

(iii) If $F$ is a finite field, the ring $F[X]$ contains irreducible polynomials of arbitrarily large degree.

(iv) If $R$ is the ring $C[0, 1]$ of continuous real-valued functions on the interval $[0, 1]$, and the non-zero elements $f, g \in R$ satisfy $f \mid g$ and $g \mid f$, then there is some unit $u \in R$ with $f = u \cdot g$. 
Let $R$ be a commutative ring with unit 1. Prove that an $R$-module is finitely generated if and only if it is a quotient of a free module $R^n$, for some $n > 0$.

Let $M$ be a finitely generated $R$-module. Suppose now $I$ is an ideal of $R$, and $\phi$ is an $R$-homomorphism from $M$ to $M$ with the property that

$$\phi(M) \subset I \cdot M = \{m \in M \mid m = rm' \text{ with } r \in I, m' \in M\}.$$ 

Prove that $\phi$ satisfies an equation

$$\phi^n + a_{n-1}\phi^{n-1} + \cdots + a_1\phi + a_0 = 0$$

where each $a_j \in I$. [You may assume that if $T$ is a matrix over $R$, then $\text{adj}(T) T = \det T (\text{id})$, with id the identity matrix.]

Deduce that if $M$ satisfies $I \cdot M = M$, then there is some $a \in R$ satisfying

$$a - 1 \in I \text{ and } aM = 0.$$ 

Give an example of a finitely generated $\mathbb{Z}$-module $M$ and a proper ideal $I$ of $\mathbb{Z}$ satisfying the hypothesis $I \cdot M = M$, and for your example, give an explicit such element $a$. 


Paper 2, Section I

2F Groups, Rings and Modules
Show that the quaternion group \( Q_8 = \{ \pm 1, \pm i, \pm j, \pm k \} \), with \( ij = k = -ji \), \( i^2 = j^2 = k^2 = -1 \), is not isomorphic to the symmetry group \( D_8 \) of the square.

Paper 3, Section I

1F Groups, Rings and Modules
Suppose that \( A \) is an integral domain containing a field \( K \) and that \( A \) is finite-dimensional as a \( K \)-vector space. Prove that \( A \) is a field.

Paper 4, Section I

2F Groups, Rings and Modules
A ring \( R \) satisfies the descending chain condition (DCC) on ideals if, for every sequence \( I_1 \supseteq I_2 \supseteq I_3 \supseteq \ldots \) of ideals in \( R \), there exists \( n \) with \( I_n = I_{n+1} = I_{n+2} = \ldots \). Show that \( \mathbb{Z} \) does not satisfy the DCC on ideals.

Paper 1, Section II

10F Groups, Rings and Modules
(i) Suppose that \( G \) is a finite group of order \( p^n r \), where \( p \) is prime and does not divide \( r \). Prove the first Sylow theorem, that \( G \) has at least one subgroup of order \( p^n \), and state the remaining Sylow theorems without proof.

(ii) Suppose that \( p, q \) are distinct primes. Show that there is no simple group of order \( pq \).

Paper 2, Section II

11F Groups, Rings and Modules
Define the notion of a Euclidean domain and show that \( \mathbb{Z}[i] \) is Euclidean.

Is \( 4 + i \) prime in \( \mathbb{Z}[i] \)?
Suppose that \( A \) is a matrix over \( \mathbb{Z} \). What does it mean to say that \( A \) can be brought to Smith normal form?

Show that the structure theorem for finitely generated modules over \( \mathbb{Z} \) (which you should state) follows from the existence of Smith normal forms for matrices over \( \mathbb{Z} \).

Bring the matrix \( \begin{pmatrix} -4 & -6 \\ 2 & 2 \end{pmatrix} \) to Smith normal form.

Suppose that \( M \) is the \( \mathbb{Z} \)-module with generators \( e_1, e_2 \), subject to the relations

\[-4e_1 + 2e_2 = -6e_1 + 2e_2 = 0.\]

Describe \( M \) in terms of the structure theorem.

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State and prove the Hilbert Basis Theorem.

Is every ring Noetherian? Justify your answer.
Paper 2, Section I
2H Groups Rings and Modules
Give the definition of conjugacy classes in a group $G$. How many conjugacy classes are there in the symmetric group $S_4$ on four letters? Briefly justify your answer.

Paper 3, Section I
1H Groups Rings and Modules
Let $A$ be the ring of integers $\mathbb{Z}$ or the polynomial ring $\mathbb{C}[X]$. In each case, give an example of an ideal $I$ of $A$ such that the quotient ring $R = A/I$ has a non-trivial idempotent (an element $x \in R$ with $x \neq 0, 1$ and $x^2 = x$) and a non-trivial nilpotent element (an element $x \in R$ with $x \neq 0$ and $x^n = 0$ for some positive integer $n$). Exhibit these elements and justify your answer.

Paper 4, Section I
2H Groups Rings and Modules
Let $M$ be a free $\mathbb{Z}$-module generated by $e_1$ and $e_2$. Let $a, b$ be two non-zero integers, and $N$ be the submodule of $M$ generated by $ae_1 + be_2$. Prove that the quotient module $M/N$ is free if and only if $a, b$ are coprime.

Paper 1, Section II
10H Groups Rings and Modules
Prove that the kernel of a group homomorphism $f : G \rightarrow H$ is a normal subgroup of the group $G$.

Show that the dihedral group $D_8$ of order 8 has a non-normal subgroup of order 2. Conclude that, for a group $G$, a normal subgroup of a normal subgroup of $G$ is not necessarily a normal subgroup of $G$. 
Paper 2, Section II

11H Groups Rings and Modules

For ideals $I, J$ of a ring $R$, their product $IJ$ is defined as the ideal of $R$ generated by the elements of the form $xy$ where $x \in I$ and $y \in J$.

(1) Prove that, if a prime ideal $P$ of $R$ contains $IJ$, then $P$ contains either $I$ or $J$.

(2) Give an example of $R, I$ and $J$ such that the two ideals $IJ$ and $I \cap J$ are different from each other.

(3) Prove that there is a natural bijection between the prime ideals of $R/IJ$ and the prime ideals of $R/(I \cap J)$.

Paper 3, Section II

11H Groups Rings and Modules

Let $R$ be an integral domain and $R^\times$ its group of units. An element of $S = R \setminus (R^\times \cup \{0\})$ is irreducible if it is not a product of two elements in $S$. When $R$ is Noetherian, show that every element of $S$ is a product of finitely many irreducible elements of $S$.

Paper 4, Section II

11H Groups Rings and Modules

Let $V = \mathbb{Z}/3\mathbb{Z}^2$, a 2-dimensional vector space over the field $\mathbb{Z}/3\mathbb{Z}$, and let $e_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \ e_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \in V$.

(1) List all 1-dimensional subspaces of $V$ in terms of $e_1, e_2$. (For example, there is a subspace $\langle e_1 \rangle$ generated by $e_1$.)

(2) Consider the action of the matrix group

$$ G = \text{GL}_2(\mathbb{Z}/3\mathbb{Z}) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid a, b, c, d \in \mathbb{Z}/3\mathbb{Z}, \ ad - bc \neq 0 \right\} $$

on the finite set $X$ of all 1-dimensional subspaces of $V$. Describe the stabiliser group $K$ of $\langle e_1 \rangle \in X$. What is the order of $K$? What is the order of $G$?

(3) Let $H \subset G$ be the subgroup of all elements of $G$ which act trivially on $X$. Describe $H$, and prove that $G/H$ is isomorphic to $S_4$, the symmetric group on four letters.
Paper 2, Section I
2F Groups, Rings and Modules
State Sylow’s theorems. Use them to show that a group of order 56 must have either a normal subgroup of order 7 or a normal subgroup of order 8.

Paper 3, Section I
1F Groups, Rings and Modules
Let $F$ be a field. Show that the polynomial ring $F[X]$ is a principal ideal domain. Give, with justification, an example of an ideal in $F[X, Y]$ which is not principal.

Paper 4, Section I
2F Groups, Rings and Modules
Let $M$ be a module over an integral domain $R$. An element $m \in M$ is said to be torsion if there exists a nonzero $r \in R$ with $rm = 0$; $M$ is said to be torsion-free if its only torsion element is 0. Show that there exists a unique submodule $N$ of $M$ such that (a) all elements of $N$ are torsion and (b) the quotient module $M/N$ is torsion-free.

Paper 1, Section II
10F Groups, Rings and Modules
Prove that a principal ideal domain is a unique factorization domain.
Give, with justification, an example of an element of $\mathbb{Z}[\sqrt{-3}]$ which does not have a unique factorization as a product of irreducibles. Show how $\mathbb{Z}[\sqrt{-3}]$ may be embedded as a subring of index 2 in a ring $R$ (that is, such that the additive quotient group $R/\mathbb{Z}[\sqrt{-3}]$ has order 2) which is a principal ideal domain. [You should explain why $R$ is a principal ideal domain, but detailed proofs are not required.]
11F Groups, Rings and Modules

Define the centre of a group, and prove that a group of prime-power order has a nontrivial centre. Show also that if the quotient group $G/Z(G)$ is cyclic, where $Z(G)$ is the centre of $G$, then it is trivial. Deduce that a non-abelian group of order $p^3$, where $p$ is prime, has centre of order $p$.

Let $F$ be the field of $p$ elements, and let $G$ be the group of $3 \times 3$ matrices over $F$ of the form

$$
\begin{pmatrix}
1 & a & b \\
0 & 1 & c \\
0 & 0 & 1
\end{pmatrix}
$$

Identify the centre of $G$.

11F Groups, Rings and Modules

Let $S$ be a multiplicatively closed subset of a ring $R$, and let $I$ be an ideal of $R$ which is maximal among ideals disjoint from $S$. Show that $I$ is prime.

If $R$ is an integral domain, explain briefly how one may construct a field $F$ together with an injective ring homomorphism $R \to F$.

Deduce that if $R$ is an arbitrary ring, $I$ an ideal of $R$, and $S$ a multiplicatively closed subset disjoint from $I$, then there exists a ring homomorphism $f : R \to F$, where $F$ is a field, such that $f(x) = 0$ for all $x \in I$ and $f(y) \neq 0$ for all $y \in S$.

[You may assume that if $T$ is a multiplicatively closed subset of a ring, and $0 \notin T$, then there exists an ideal which is maximal among ideals disjoint from $T$.]

11F Groups, Rings and Modules

Let $R$ be a principal ideal domain. Prove that any submodule of a finitely-generated free module over $R$ is free.

An $R$-module $P$ is said to be projective if, whenever we have module homomorphisms $f : M \to N$ and $g : P \to N$ with $f$ surjective, there exists a homomorphism $h : P \to M$ with $f \circ h = g$. Show that any free module (over an arbitrary ring) is projective. Show also that a finitely-generated projective module over a principal ideal domain is free.
1/II/10G  Groups, Rings and Modules

(i) Show that $A_4$ is not simple.

(ii) Show that the group Rot($D$) of rotational symmetries of a regular dodecahedron is a simple group of order 60.

(iii) Show that Rot($D$) is isomorphic to $A_5$.

2/I/2G  Groups, Rings and Modules

What does it mean to say that a complex number $\alpha$ is algebraic over $\mathbb{Q}$? Define the minimal polynomial of $\alpha$.

Suppose that $\alpha$ satisfies a nonconstant polynomial $f \in \mathbb{Z}[X]$ which is irreducible over $\mathbb{Z}$. Show that there is an isomorphism $\mathbb{Z}[X]/(f) \cong \mathbb{Z}[\alpha]$.

[You may assume standard results about unique factorisation, including Gauss’s lemma.]

2/II/11G  Groups, Rings and Modules

Let $F$ be a field. Prove that every ideal of the ring $F[X_1,\ldots,X_n]$ is finitely generated.

Consider the set

$$ R = \left\{ p(X,Y) = \sum c_{ij}X^iY^j \in F[X,Y] \mid c_{0j} = c_{j0} = 0 \text{ whenever } j > 0 \right\}. $$

Show that $R$ is a subring of $F[X,Y]$ which is not Noetherian.

3/I/1G  Groups, Rings and Modules

Let $G$ be the abelian group generated by elements $a$, $b$, $c$, $d$ subject to the relations

\begin{align*}
4a - 2b + 2c + 12d &= 0, \\
-2b + 2c &= 0, \\
2b + 2c &= 0, \\
8a + 4c + 24d &= 0.
\end{align*}

Express $G$ as a product of cyclic groups, and find the number of elements of $G$ of order 2.
What is a Euclidean domain? Show that a Euclidean domain is a principal ideal domain.

Show that \( \mathbb{Z}[\sqrt{-7}] \) is not a Euclidean domain (for any choice of norm), but that the ring
\[
\mathbb{Z}\left[\frac{1 + \sqrt{-7}}{2}\right]
\]
is Euclidean for the norm function \( N(z) = z\bar{z} \).

Let \( n \geq 2 \) be an integer. Show that the polynomial \((X^n - 1)/(X - 1)\) is irreducible over \( \mathbb{Z} \) if and only if \( n \) is prime.

[You may use Eisenstein’s criterion without proof.]

Let \( R \) be a ring and \( M \) an \( R \)-module. What does it mean to say that \( M \) is a free \( R \)-module? Show that \( M \) is free if there exists a submodule \( N \subseteq M \) such that both \( N \) and \( M/N \) are free.

Let \( M \) and \( M' \) be \( R \)-modules, and \( N \subseteq M, N' \subseteq M' \) submodules. Suppose that \( N \cong N' \) and \( M/N \cong M'/N' \). Determine (by proof or counterexample) which of the following statements holds:

1. If \( N \) is free then \( M \cong M' \).
2. If \( M/N \) is free then \( M \cong M' \).
1/II/10G Groups, Rings and Modules

(i) State a structure theorem for finitely generated abelian groups.

(ii) If $K$ is a field and $f$ a polynomial of degree $n$ in one variable over $K$, what is the maximal number of zeroes of $f$? Justify your answer in terms of unique factorization in some polynomial ring, or otherwise.

(iii) Show that any finite subgroup of the multiplicative group of non-zero elements of a field is cyclic. Is this true if the subgroup is allowed to be infinite?

2/I/2G Groups, Rings and Modules

Define the term Euclidean domain.

Show that the ring of integers $\mathbb{Z}$ is a Euclidean domain.

2/II/11G Groups, Rings and Modules

(i) Give an example of a Noetherian ring and of a ring that is not Noetherian. Justify your answers.

(ii) State and prove Hilbert’s basis theorem.

3/I/1G Groups, Rings and Modules

What are the orders of the groups $GL_2(\mathbb{F}_p)$ and $SL_2(\mathbb{F}_p)$ where $\mathbb{F}_p$ is the field of $p$ elements?

3/II/11G Groups, Rings and Modules

(i) State the Sylow theorems for Sylow $p$-subgroups of a finite group.

(ii) Write down one Sylow 3-subgroup of the symmetric group $S_5$ on 5 letters. Calculate the number of Sylow 3-subgroups of $S_5$.

4/I/2G Groups, Rings and Modules

If $p$ is a prime, how many abelian groups of order $p^4$ are there, up to isomorphism?
A regular icosahedron has 20 faces, 12 vertices and 30 edges. The group $G$ of its rotations acts transitively on the set of faces, on the set of vertices and on the set of edges.

(i) List the conjugacy classes in $G$ and give the size of each.

(ii) Find the order of $G$ and list its normal subgroups.

[A normal subgroup of $G$ is a union of conjugacy classes in $G$.]
Groups, Rings and Modules

Find all subgroups of indices 2, 3, 4 and 5 in the alternating group $A_5$ on 5 letters. You may use any general result that you choose, provided that you state it clearly, but you must justify your answers.

[You may take for granted the fact that $A_4$ has no subgroup of index 2.]

Groups, Rings and Modules

(i) Give the definition of a Euclidean domain and, with justification, an example of a Euclidean domain that is not a field.

(ii) State the structure theorem for finitely generated modules over a Euclidean domain.

(iii) In terms of your answer to (ii), describe the structure of the $\mathbb{Z}$-module $M$ with generators $\{m_1, m_2, m_3\}$ and relations $2m_3 = 2m_2$, $4m_2 = 0$.

Groups, Rings and Modules

(i) Prove the first Sylow theorem, that a finite group of order $p^n r$ with $p$ prime and $p$ not dividing the integer $r$ has a subgroup of order $p^n$.

(ii) State the remaining Sylow theorems.

(iii) Show that if $p$ and $q$ are distinct primes then no group of order $pq$ is simple.

Groups, Rings and Modules

(i) Give an example of an integral domain that is not a unique factorization domain.

(ii) For which integers $n$ is $\mathbb{Z}/n\mathbb{Z}$ an integral domain?

Groups, Rings and Modules

Suppose that $R$ is a ring. Prove that $R[X]$ is Noetherian if and only if $R$ is Noetherian.
4/I/2E Groups, Rings and Modules

How many elements does the ring \( \mathbb{Z}[X]/(3, X^2 + X + 1) \) have?

Is this ring an integral domain?

Briefly justify your answers.

4/II/11E Groups, Rings and Modules

(a) Suppose that \( R \) is a commutative ring, \( M \) an \( R \)-module generated by \( m_1, \ldots, m_n \) and \( \phi \in \text{End}_R(M) \). Show that, if \( A = (a_{ij}) \) is an \( n \times n \) matrix with entries in \( R \) that represents \( \phi \) with respect to this generating set, then in the sub-ring \( R[\phi] \) of \( \text{End}_R(M) \) we have \( \det(a_{ij} - \phi \delta_{ij}) = 0 \).

[Hint: \( A \) is a matrix such that \( \phi(m_i) = \sum a_{ij} m_j \) with \( a_{ij} \in R \). Consider the matrix \( C = (a_{ij} - \phi \delta_{ij}) \) with entries in \( R[\phi] \) and use the fact that for any \( n \times n \) matrix \( N \) over any commutative ring, there is a matrix \( N' \) such that \( N'N = (\det N)1_n \).]

(b) Suppose that \( k \) is a field, \( V \) a finite-dimensional \( k \)-vector space and that \( \phi \in \text{End}_k(V) \). Show that if \( A \) is the matrix of \( \phi \) with respect to some basis of \( V \) then \( \phi \) satisfies the characteristic equation \( \det(A - \lambda 1) = 0 \) of \( A \).
1/II/10C Groups, Rings and Modules

Let $G$ be a group, and $H$ a subgroup of finite index. By considering an appropriate action of $G$ on the set of left cosets of $H$, prove that $H$ always contains a normal subgroup $K$ of $G$ such that the index of $K$ in $G$ is finite and divides $n!$, where $n$ is the index of $H$ in $G$.

Now assume that $G$ is a finite group of order $pq$, where $p$ and $q$ are prime numbers with $p < q$. Prove that the subgroup of $G$ generated by any element of order $q$ is necessarily normal.

2/I/2C Groups, Rings and Modules

Define an automorphism of a group $G$, and the natural group law on the set Aut($G$) of all automorphisms of $G$. For each fixed $h$ in $G$, put $\psi(h)(g) = hgh^{-1}$ for all $g$ in $G$. Prove that $\psi(h)$ is an automorphism of $G$, and that $\psi$ defines a homomorphism from $G$ into Aut($G$).

2/II/11C Groups, Rings and Modules

Let $A$ be the abelian group generated by two elements $x, y$, subject to the relation $6x + 9y = 0$. Give a rigorous explanation of this statement by defining $A$ as an appropriate quotient of a free abelian group of rank 2. Prove that $A$ itself is not a free abelian group, and determine the exact structure of $A$.

3/I/1C Groups, Rings and Modules

Define what is meant by two elements of a group $G$ being conjugate, and prove that this defines an equivalence relation on $G$. If $G$ is finite, sketch the proof that the cardinality of each conjugacy class divides the order of $G$. 
3/II/11C Groups, Rings and Modules

(i) Define a primitive polynomial in \( \mathbb{Z}[x] \), and prove that the product of two primitive polynomials is primitive. Deduce that \( \mathbb{Z}[x] \) is a unique factorization domain.

(ii) Prove that \( \mathbb{Q}[x]/(x^5 - 4x + 2) \) is a field. Show, on the other hand, that \( \mathbb{Z}[x]/(x^5 - 4x + 2) \) is an integral domain, but is not a field.

4/I/2C Groups, Rings and Modules

State Eisenstein’s irreducibility criterion. Let \( n \) be an integer > 1. Prove that \( 1 + x + \ldots + x^{n-1} \) is irreducible in \( \mathbb{Z}[x] \) if and only if \( n \) is a prime number.

4/II/11C Groups, Rings and Modules

Let \( R \) be the ring of Gaussian integers \( \mathbb{Z}[i] \), where \( i^2 = -1 \), which you may assume to be a unique factorization domain. Prove that every prime element of \( R \) divides precisely one positive prime number in \( \mathbb{Z} \). List, without proof, the prime elements of \( R \), up to associates.

Let \( p \) be a prime number in \( \mathbb{Z} \). Prove that \( R/pR \) has cardinality \( p^2 \). Prove that \( R/2R \) is not a field. If \( p \equiv 3 \mod 4 \), show that \( R/pR \) is a field. If \( p \equiv 1 \mod 4 \), decide whether \( R/pR \) is a field or not, justifying your answer.
1/I/2F Groups, Rings and Modules

Let $G$ be a finite group of order $n$. Let $H$ be a subgroup of $G$. Define the normalizer $N(H)$ of $H$, and prove that the number of distinct conjugates of $H$ is equal to the index of $N(H)$ in $G$. If $p$ is a prime dividing $n$, deduce that the number of Sylow $p$-subgroups of $G$ must divide $n$.

[You may assume the existence and conjugacy of Sylow subgroups.]

Prove that any group of order 72 must have either 1 or 4 Sylow 3-subgroups.

1/II/13F Groups, Rings and Modules

State the structure theorem for finitely generated abelian groups. Prove that a finitely generated abelian group $A$ is finite if and only if there exists a prime $p$ such that $A/pA = 0$.

Show that there exist abelian groups $A \neq 0$ such that $A/pA = 0$ for all primes $p$. Prove directly that your example of such an $A$ is not finitely generated.

2/I/2F Groups, Rings and Modules

Prove that the alternating group $A_5$ is simple.

2/II/13F Groups, Rings and Modules

Let $K$ be a subgroup of a group $G$. Prove that $K$ is normal if and only if there is a group $H$ and a homomorphism $\phi: G \to H$ such that

$K = \{g \in G : \phi(g) = 1\}.$

Let $G$ be the group of all $2 \times 2$ matrices \[
\begin{pmatrix}
a & b \\
c & d
\end{pmatrix}
\] with $a, b, c, d$ in $\mathbb{Z}$ and $ad - bc = 1$.

Let $p$ be a prime number, and take $K$ to be the subset of $G$ consisting of all \[
\begin{pmatrix}
a & b \\
c & d
\end{pmatrix}
\] with $a \equiv d \equiv 1 (\text{mod } p)$ and $c \equiv b \equiv 0 (\text{mod } p)$. Prove that $K$ is a normal subgroup of $G$. 

Part IB 2004
3/I/2F Groups, Rings and Modules

Let \( R \) be the subring of all \( z \) in \( \mathbb{C} \) of the form
\[
z = \frac{a + b\sqrt{-3}}{2}
\]
where \( a \) and \( b \) are in \( \mathbb{Z} \) and \( a \equiv b \pmod{2} \). Prove that \( N(z) = z\bar{z} \) is a non-negative element of \( \mathbb{Z} \), for all \( z \) in \( R \). Prove that the multiplicative group of units of \( R \) has order 6. Prove that \( 7R \) is the intersection of two prime ideals of \( R \).

[You may assume that \( R \) is a unique factorization domain.]

3/II/14F Groups, Rings and Modules

Let \( L \) be the group \( \mathbb{Z}^3 \) consisting of 3-dimensional row vectors with integer components. Let \( M \) be the subgroup of \( L \) generated by the three vectors
\[
u = (1, 2, 3), \quad v = (2, 3, 1), \quad w = (3, 1, 2)\,.
\]

(i) What is the index of \( M \) in \( L \)?

(ii) Prove that \( M \) is not a direct summand of \( L \).

(iii) Is the subgroup \( N \) generated by \( u \) and \( v \) a direct summand of \( L \)?

(iv) What is the structure of the quotient group \( L/M \)?

4/I/2F Groups, Rings and Modules

State Gauss’s lemma and Eisenstein’s irreducibility criterion. Prove that the following polynomials are irreducible in \( \mathbb{Q}[x] \):

(i) \( x^5 + 5x + 5 \);

(ii) \( x^3 - 4x + 1 \);

(iii) \( x^{p-1} + x^{p-2} + \ldots + x + 1 \), where \( p \) is any prime number.

4/II/12F Groups, Rings and Modules

Answer the following questions, fully justifying your answer in each case.

(i) Give an example of a ring in which some non-zero prime ideal is not maximal.

(ii) Prove that \( \mathbb{Z}[x] \) is not a principal ideal domain.

(iii) Does there exist a field \( K \) such that the polynomial \( f(x) = 1 + x + x^3 + x^4 \) is irreducible in \( K[x] \)?

(iv) Is the ring \( \mathbb{Q}[x]/(x^3 - 1) \) an integral domain?

(v) Determine all ring homomorphisms \( \phi : \mathbb{Q}[x]/(x^3 - 1) \to \mathbb{C} \).