

IB Groups, Rings, and Modules // Example Sheet 2

All rings in this course are commutative and have a multiplicative identity.

1. Let $\omega = \frac{1}{2}(1 + \sqrt{-3}) \in \mathbb{C}$, let $R = \{a + b\omega : a, b \in \mathbb{Z}\}$, and let $F = \{a + b\omega : a, b \in \mathbb{Q}\}$. Show that R is a subring of \mathbb{C} , and that F is a subfield of \mathbb{C} . What are the units of R ?
2. An element r of a ring R is called *nilpotent* if $r^n = 0$ for some n .
 - (i) What are the nilpotent elements of $\mathbb{Z}/6\mathbb{Z}$? Of $\mathbb{Z}/8\mathbb{Z}$? Of $\mathbb{Z}/24\mathbb{Z}$? Of $\mathbb{Z}/180\mathbb{Z}$?
 - (ii) Show that if r is nilpotent then r is not a unit, but $1 + r$ and $1 - r$ are units.
 - (iii) Show that set of the nilpotent elements form an ideal N of R . What are the nilpotent elements in the quotient ring R/N ?
3. Let r be an element of a ring R . Show that the polynomial $1 + rX \in R[X]$ is a unit if and only if r is nilpotent. Is it possible for the polynomial $1 + X$ to be a product of two non-units?
4. Let $I_1 \subset I_2 \subset I_3 \subset \dots$ be ideals in a ring R . Show that the union $I = \bigcup_{n=1}^{\infty} I_n$ is also an ideal. If each I_n is proper, explain why I must be proper.
5. Show that if I and J are ideals in the ring R , then so is $I \cap J$, and the quotient $R/(I \cap J)$ is isomorphic to a subring of the product $R/I \times R/J$. Show further that if there exist $x \in I$ and $y \in J$ with $x + y = 1$ then $R/(I \cap J) \cong R/I \times R/J$. What does this result say when $R = \mathbb{Z}$?
6. Let R be an integral domain. Show that a polynomial in $R[X]$ of degree d can have at most d roots. Deduce that the natural ring homomorphism from $R[X]$ to the ring of all functions $R \rightarrow R$ is injective if and only if R is infinite. Give an example of a monic quadratic polynomial in $(\mathbb{Z}/8\mathbb{Z})[X]$ that has more than two roots.
7. Write down a prime ideal in $\mathbb{Z} \times \mathbb{Z}$ that is not maximal. Explain why in a finite ring all prime ideals are maximal.
8. Explain why, for p a prime number, there is a unique ring of order p . How many rings are there of order 4?
9. Let R be an integral domain and F be its field of fractions. Suppose that $\phi : R \rightarrow K$ is an injective ring homomorphism from R to a field K . Show that ϕ extends to an injective homomorphism $\Phi : F \rightarrow K$ from F to K . What happens if we do not assume that ϕ is injective?
10. An element r of a ring R is called *idempotent* if $r^2 = r$.
 - (i) What are the idempotent elements of $\mathbb{Z}/6\mathbb{Z}$? Of $\mathbb{Z}/8\mathbb{Z}$? Of $\mathbb{Z}/24\mathbb{Z}$? How many idempotents are there in $\mathbb{Z}/180\mathbb{Z}$?
 - (ii) Show that if r is idempotent then so is $r' = 1 - r$, and that $rr' = 0$. Show also that the ideal (r) is naturally a ring, and that R is isomorphic as a ring to $(r) \times (r')$.
11. Let F be a field, and let $R = F[X, Y]$ be the polynomial ring in two variables.
 - (i) Let I be the principal ideal $(X - Y)$ of R . Show that $R/I \cong F[X]$.
 - (ii) Describe R/I when $I = (X^2 + Y)$.
 - (iii) What can you say about $R/(X^2 - Y^2)$? Is it an integral domain? Does it have nilpotent or idempotent elements?
 - (iv) Construct an isomorphism from the ring $\mathbb{C}[X, Y]/(X^2 + Y^2 - 1)$ to the ring $\mathbb{C}[T, T^{-1}]$. [Hint: Think about trigonometric functions.]

Optional Questions

12. Give an example of an abelian group which is not the additive group of some ring; is every abelian group the additive group of some ideal in some ring?
13. Suppose a ring R has the property that for each $x \in R$ there is a $n \geq 2$ such that $x^n = x$. Show that every prime ideal of R is maximal.
14. This question illustrates a construction of the real numbers, so you should avoid mentioning them in your answer.

A sequence $\{a_n\}$ of rational numbers is a *Cauchy sequence* if $|a_n - a_m| \rightarrow 0$ as $m, n \rightarrow \infty$, and $\{a_n\}$ is a *null sequence* if $a_n \rightarrow 0$ as $n \rightarrow \infty$. Quoting any standard results from Analysis, show that the set of Cauchy sequences with componentwise addition and multiplication form a ring C , and that the null sequences form a maximal ideal N .

Deduce that C/N is a field, which contains a subfield which may be identified with \mathbb{Q} . Explain briefly why the equation $x^2 = 2$ has a solution in this field.

15. Let ϖ be a set of prime numbers. Write \mathbb{Z}_ϖ for the collection of all rationals m/n (in lowest terms) such that the only prime factors of the denominator n are in ϖ .
 - (i) Show that \mathbb{Z}_ϖ is a subring of the field \mathbb{Q} of rational numbers.
 - (ii) Show that any subring R of \mathbb{Q} is of the form \mathbb{Z}_ϖ for some set ϖ of primes.
 - (iii) Given (ii), what are the maximal subrings of \mathbb{Q} ?

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