

ALGEBRA QUALIFYING EXAM PROBLEMS RING THEORY

Nic Beike

June 28, 2022

Contents

1	Ring Theory	3
1.1	General Ring Theory	3
1.2	Prime, Maximal, and Primary Ideals	7
1.3	Commutative Rings	9
1.4	Domains	10
1.5	Polynomial Rings	12
1.6	Non-commutative Rings	12
1.7	Local Rings, Localization, Rings of Fractions	13
1.8	Chains and Chain Conditions	14

1 Ring Theory

1.1 General Ring Theory

1. Give an example of each of the following
 - (a) An irreducible polynomial of degree 3 in $\mathbb{Z}_3[x]$
 - (b) A polynomial in $\mathbb{Z}[x]$ that is not irreducible in $\mathbb{Z}[x]$ but is irreducible in $\mathbb{Q}[x]$
 - (c) A non-commutative ring of characteristic p , p a prime
 - (d) A ring with exactly 6 invertible elements
 - (e) An infinite non-commutative ring with only finitely many ideals.
 - (f) An infinite non-commutative ring with non-zero characteristic.
 - (g) An integral domain which is not a unique factorization domain.
 - (h) A unique factorization domain that is not a principal ideal domain
 - (i) A principal ideal domain that is not a Euclidean domain.
 - (j) A Euclidean domain other than the ring of integers of a field.
 - (k) A finite non-commutative ring.
 - (l) A commutative ring with a sequence $\{P_n\}_{n=1}^{\infty}$ of prime ideals such that P_n is properly contained in P_{n+1} for all n .
 - (m) A non-zero prime ideal of a commutative ring that is not a maximal ideal.
 - (n) An irreducible element of a commutative ring that is not a prime element.
 - (o) An irreducible element of an integral domain that is not a prime element.
 - (p) A commutative ring that has exactly one maximal ideal and is not a field.
 - (q) A non-commutative ring with exactly two maximal ideals.
2.
 - (a) How many units does the ring $\mathbb{Z}/60\mathbb{Z}$ have? Explain your answer.
 - (b) How many ideals does the ring $\mathbb{Z}/60\mathbb{Z}$ have? Explain your answer.

Proof. For (a), we can use the fact that a is a unit if $\gcd(a, n) = 1$. Thus $|U_{60}| = |\{1, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 57, 59\}| = 16$.

For (b) use the fact that $\mathbb{Z}/d\mathbb{Z}$ is an ideal of $\mathbb{Z}/n\mathbb{Z}$ when $d \mid n$. So let $D = \{d \in \mathbb{Z}/60\mathbb{Z} : d \mid 60\} = \{2^x \cdot 3^y \cdot 5^z : 0 \leq x \leq 2, 0 \leq y \leq 1, 0 \leq z \leq 1\}$. Thus the number of ideals is equal to $|D| = 3 \cdot 2 \cdot 2 = 12$ \square

3. How many ideals does the ring $\mathbb{Z}/90\mathbb{Z}$ have? Explain your answer.

Proof. Use the fact that $\mathbb{Z}/d\mathbb{Z}$ is an ideal of $\mathbb{Z}/n\mathbb{Z}$ when $d \mid n$. Let $D = \{d \in \mathbb{Z}/90\mathbb{Z} : d \mid 90\} = \{2^x \cdot 3^y \cdot 5^z : 0 \leq x \leq 1, 0 \leq y \leq 2, 0 \leq z \leq 1\}$. Then the number of ideals is equal to $|D| = 2 \cdot 3 \cdot 2 = 12$. \square

4. Denote the set of invertible elements of the ring \mathbb{Z}_n by U_n .

- (a) List all the elements of U_{18} .
 - (b) Is U_{18} a cyclic group under multiplication? Justify your answer.

Proof. Use the fact that a is a unit if $\gcd(a, 18) = 1$. So the invertible elements of \mathbb{Z}_{18} are $U_{18} = \{1, 5, 7, 11, 13, 17\}$. Note that $\langle 5 \rangle = \{5, 7, 17, 13, 11, 1\} = U_{18}$. Therefore U_{18} is cyclic. \square

5. Denote the set of invertible elements of the ring \mathbb{Z}_n by U_n .

- (a) List all the elements of U_{24} .
 - (b) Is U_{24} a cyclic group under multiplication? Justify your answer.

Proof. Use the fact that a is a unit if $\gcd(a, 24) = 1$. So the invertible elements of \mathbb{Z}_{18} are $U_{24} = \{1, 5, 7, 11, 13, 17, 19, 23\}$. Note that $x^2 = 1$ for all $x \in U_{24}$. Therefore U_{24} is not cyclic. \square

6. Find all positive integers n having the property that the group of units of $\mathbb{Z}/n\mathbb{Z}$ is an elementary abelian 2-group.
7. Let $U(R)$ denote the group of units of a ring R . Prove that if m divides n , then the natural ring homomorphism $\mathbb{Z}_n \rightarrow \mathbb{Z}_m$ maps $U(\mathbb{Z}_n)$ onto $U(\mathbb{Z}_m)$. Give an example that shows that $U(R)$ does not have to map onto $U(S)$ under a surjective ring homomorphism $R \rightarrow S$.
8. If p is a prime satisfying $p \equiv 1 \pmod{4}$, then p is a sum of two squares.
9. If (\div) denotes the Legendre symbol, prove Euler's Critereon: if p is a prime and a is any integer relatively prime to p , then $a^{(p-1)/2} \equiv \left(\frac{a}{p}\right) \pmod{p}$.
10. Let R_1 and R_2 be commutative rings with identities and let $R = R_1 \times R_2$. Show that every ideal I of R is of the form $I = I_1 \times I_2$ with I_i an ideal of R_i for $i = 1, 2$.

Proof. Let I be an ideal fo $R = R_1 \times R_2$. Define $I_1 = \{r \in R_1 : \exists s \in R_2 \text{ where } (r, s) \in I\}$ and $I_2 = \{s \in R_2 : \exists r \in R_1 \text{ where } (r, s) \in I\}$.

Note that if $r \in I_1$, then there exists $s \in R_2$ such that $(r, s) \in I$. Thus $(a, 1_{R_2})(r, s) = (ar, s) \in I$, and so $ar \in I_1$. Thus I_1 is an ideal of R_1 . By a similar argument, we can see that I_2 is an ideal of R_2 . Now it is clear that $I \subseteq I_1 \times I_2$.

To show the reverse inclusion, suppose that $r \in I_1$, and $s \in I_2$ such that $(r, s) \in I_1 \times I_2$. Since $r \in I_1$, then there is an $s' \in I_2$ such that $(r, s') \in I$. Also since $s \in I_2$, then there exists an $r' \in I_1$ such that $(r', s) \in I$. Now we see that $(1_R, s)(r, s') = (r, ss') \in I$, and $(1_R, s')(r', s) = (r', ss') \in I$. Thus $(r, ss') - (r', ss') + (r', s) = (r, s) \in I$. Therefore $I_1 \times I_2 \subseteq I$ so $I = I_1 \times I_2$, as desired. \square

11. Show that a non-zero ring R in which $x^2 = x$ for all $x \in R$ is of characteristic 2 and is commutative.

Proof. Let $x \in R$ and note that $x + x = (x + x)^2 = x^2 + x^2 + x^2 + x^2 = x + x + x + x$. Thus $x + x = 0$, so R has characteristic zero.

Now let $x, y \in R$. Then $x + y = (x + y)^2 = x^2 + xy + yx + y^2$. Rearranging terms gives $0 = xy + yx$. Now $xy = xy + xy + yx = (xy + xy) + yx = 0 + yx = yx$. Thus we conclude that R is commutative. \square

12. Let R be a finite commutative ring with more than one element and no zero-divisors. Show that R is a field.

Proof. Define $\phi : R \rightarrow R$ by $\phi(r) = xr$ for all $r \in R$ and a fixed nonzero element $x \in R$. Suppose that for two elements $r, s \in R$, $\phi(r) = \phi(s)$. Then we have $xr = xs$ or $xr - xs = 0$ or $x(r - s) = 0$. Since x is nonzero and R has no zero divisors, we see that $r - s = 0$, and so $r = s$. Thus the map ϕ is injective. Since we are mapping from $R \rightarrow R$, then ϕ must also be surjective and thus bijective.

First we show that R has an identity element. By the surjectivity of ϕ there must be an element $e \in R$ such that $x = \phi(e) = ex$. Now let $b \in R$. Then by the surjectivity of ϕ there is an element $y_b \in R$ such that $b = \phi(y_b) = y_b x$. Now we have $b = y_b x = y_b ex = (y_b x)e = be$. Thus $e = 1$ since it fixes every element in R .

Now again by the surjectivity of ϕ , we must have some $r \in R$ such that $\phi(r) = rx = 1$. Thus x is a unit and since the choice of x was arbitrary (except for the restriction of x being nonzero), we conclude that R must be a field. \square

13. Determine for which integers n the ring $\mathbb{Z}/n\mathbb{Z}$ is a direct sum of fields. Prove your answer.
14. Let R be a subring of a field F such that for each x in F either $x \in R$ or $x^{-1} \in R$. Prove that if I and J are ideals of R , then either $I \subseteq J$ or $J \subseteq I$.

Proof. Suppose $I \not\subseteq J$. It suffices to show that $J \subseteq I$. Since $I \not\subseteq J$, then there is a nonzero $a \in I \setminus J$. If $b \in J$, we want to show that $b \in I$.

If $b = 0$, then we are done since I is an ideal, and must contain zero. Now suppose $b \neq 0$. Then there is an inverse $b^{-1} \in F$ and so $ab^{-1} \in F$. Thus either $ab^{-1} \in R$ or $ba^{-1} \in R$. If $ab^{-1} \in R$, then $a = ab^{-1}b \in J$, a contradiction.

Thus it must be the case that $ba^{-1} \in R$, and so $b = ba^{-1}a \in I$. Therefore $b \in I$ and $J \subseteq I$, as desired. \square

15. The *Jacobson Radical* $J(R)$ of a ring R is defined to be the intersection of all maximal ideals of R . Let R be a commutative ring with 1 and let $x \in R$. Show that $x \in J(R)$ if and only if $1 - xy$ is a unit for all y in R .

Proof. Suppose that $x \in J(R)$. Then $x \in I_i$ where I_i is a maximal ideal. Then $xy \in I_i$ for all i , and so $xy \in J(R)$. Thus xy is quasiregular and so $1 - xy$ is a unit for all y in R .

Now suppose that $1 - xy$ is a unit for all $y \in R$ and $x \notin J(R)$. Then there exists a maximal ideal M such that $x \notin M$. Thus $\langle x \rangle + M = R$. So there exists a $y \in R$ and $m \in M$ such that $xy + m = 1$. Thus $m = 1 - xy \in M$ is a unit. So we must have $M = R$, but this is a contradiction to the maximality of M . \square

16. Let R be any ring with identity, and n any positive integer. If $M_n(R)$ denotes the ring of $n \times n$ matrices with entries in R , prove that $M_n(I)$ is an ideal of $M_n(R)$ whenever I is an ideal of R , and that every ideal of $M_n(R)$ has this form.
17. Let m, n be positive integers such that m divides n . Then the natural map $\phi : \mathbb{Z}_n \rightarrow \mathbb{Z}_m$ given by $a + (n) \mapsto a + (m)$ is a surjective ring homomorphism. If U_n, U_m are the units of \mathbb{Z}_n and \mathbb{Z}_m , respectively, show that $\phi : U_n \rightarrow U_m$ is a surjective group homomorphism.
18. Let R be a ring with the ideals A and B . Let $R/A \times R/B$ be the ring with coordinate-wise addition and multiplication. Show the following.
- (a) The map $R \rightarrow R/A \times R/B$ given by $r \mapsto (r + A, r + B)$ is a ring homomorphism.
 - (b) The homomorphism in part (a) is surjective if and only if $A + B = R$.
19. Let m and n be relatively prime integers.
- (a) Show that if c and d are any integers, then there is an integer x such that $x \equiv c \pmod{m}$ and $x \equiv d \pmod{n}$.
 - (b) Show that \mathbb{Z}_{mn} and $\mathbb{Z}_m \times \mathbb{Z}_n$ are isomorphic as rings.
20. Let R be a commutative ring with 1 and let I and J be ideals of R such that $I + J = R$. Show that $R/(I \cap J) \cong R/I \oplus R/J$.
21. Let R be a commutative ring with identity and let I_1, I_2, \dots, I_n be pairwise co-maximal ideals of R (i.e., $I_i + I_j = R$ if $i \neq j$). Show that $I_i + \bigcap_{j \neq i} I_j = R$ for all i .
22. Let R be a commutative ring, not necessarily with identity, and assume there is some fixed positive integer n such that $nr = 0$ for all $r \in R$. Prove that R embeds in a ring S with identity so that R is an ideal of S and $S/R \cong \mathbb{Z}/n\mathbb{Z}$.
23. Let R be a ring with identity 1 and $a, b \in R$ such that $ab = 1$. Denote $X = \{x \in R \mid ax = 1\}$. Show the following.
- (a) If $x \in X$, then $b + (1 - x) \in X$.
 - (b) If $\phi : X \rightarrow X$ is the mapping given by $\phi(x) = b + (1 - xa)$, then ϕ is one-to-one.
 - (c) If X has more than one element, then X is an infinite set.
24. Let R be a commutative ring with identity and define $U_2(R) = \left\{ \begin{bmatrix} a & b \\ 0 & c \end{bmatrix} \mid a, b, c \in R \right\}$. Prove that every R -automorphism of $U_2(R)$ is inner.

25. Let \mathbb{R} be the field of real numbers and let F be the set of all 2×2 matrices of the form $\begin{bmatrix} a & b \\ -3b & a \end{bmatrix}$, where $a, b \in \mathbb{R}$. Show that F is a field under the usual matrix operations.
26. Let R be the ring of all 2×2 matrices of the form $\begin{bmatrix} a & b \\ -b & a \end{bmatrix}$ where a and b are real numbers. Prove that R is isomorphic to \mathbb{C} , the field of complex numbers.
27. Let p be a prime and let R be the ring of all 2×2 matrices of the form $\begin{bmatrix} a & b \\ pb & a \end{bmatrix}$, where $a, b \in \mathbb{Z}$. Prove that R is isomorphic to $\mathbb{Z}[\sqrt{p}]$.
28. Let p be a prime and F_p the set of all 2×2 matrices of the form $\begin{bmatrix} a & b \\ -b & a \end{bmatrix}$, where $a, b \in \mathbb{Z}_p$.
- Show that F_p is a commutative ring with identity.
 - Show that F_7 is a field.
 - Show that F_{13} is not a field.
29. Let $I \subseteq J$ be right ideals of a ring R such that $J/I \cong R$ as right R -modules. Prove that there exists a right ideal K such that $I \cap K = (0)$ and $I + K = J$.
30. A ring R is called simple if $R^2 \neq 0$ and 0 and R are its only ideals. Show that the center of a simple ring is 0 or a field.
31. Give an example of a field F and a one-to-one ring homomorphism $\phi: F \rightarrow F$ which is not onto. Verify your example.
32. Let D be an integral domain and let $D[x_1, x_2, \dots, x_n]$ be the polynomial ring over D in the n indeterminates x_1, x_2, \dots, x_n . Let

$$V = \begin{bmatrix} x_1^{n-1} & \dots & x_1^2 & x_1 & 1 \\ x_2^{n-1} & \dots & x_2^2 & x_2 & 1 \\ \vdots & & \vdots & \vdots & \vdots \\ x_n^{n-1} & \dots & x_n^2 & x_n & 1 \end{bmatrix}.$$

Prove that the determinant of V is $\prod_{1 \leq i < j \leq n} (x_i - x_j)$.

33. Let $R = C[0, 1]$ be the set of all continuous real-valued functions on $[0, 1]$. Define addition and multiplication on R as follows. For $f, g \in R$ and $x \in [0, 1]$,
- $$(f + g)(x) = f(x) + g(x) \text{ and } (fg)(x) = f(x)g(x).$$
- Show that R with these operations is a commutative ring with identity.
 - Find the units of R .
 - If $f \in R$ and $f^2 = f$, then $f = 0_R$ or $f = 1_R$.
 - If n is a positive integer and $f \in R$ is such that $f^n = 0_R$, then $f = 0_R$.
34. Let S be the ring of all bounded, continuous functions $f: \mathbb{R} \rightarrow \mathbb{R}$, where \mathbb{R} is the set of real numbers. Let I be the set of functions f in S such that $f(t) \rightarrow 0$ as $|t| \rightarrow \infty$.
- Show that I is an ideal of S .
 - Suppose $x \in S$ is such that there is an $i \in I$ with $ix = x$. Show that $x(t) = 0$ for all sufficiently large $|t|$.
35. Let \mathbb{Q} be the field of rational numbers and $D = \{a + b\sqrt{2} \mid a, b \in \mathbb{Q}\}$.
- Show that D is a subring of the field of real numbers.
 - Show that D is a principal ideal domain.
 - Show that $\sqrt{3}$ is not an element of D .
36. Show that if p is a prime such that $p \equiv 1 \pmod{4}$, then $x^2 + 1$ is not irreducible in $\mathbb{Z}_p[x]$.
37. Show that if p is a prime such that $p \equiv 4 \pmod{4}$, then $x^2 + 1$ is irreducible in $\mathbb{Z}_p[x]$.
38. Show that if p is a prime such that $p \equiv 1 \pmod{6}$, then $x^3 + 1$ splits in $\mathbb{Z}_p[x]$.

1.2 Prime, Maximal, and Primary Ideals

39. Let R be a non-zero commutative ring with 1. Show that an ideal M of R is maximal if and only if R/M is a field.

Proof. By the correspondence theorem, M is a maximal ideal of R if and only if 0 is a maximal ideal of R/M . Also, it is known that a commutative ring is a field if and only if 0 is a maximal ideal. Thus the result follows. \square

40. Let R be a commutative ring with 1. Show that an ideal P of R is prime if and only if R/P is an integral domain.

Proof. First let P be a prime ideal of R . Then R/P is a prime ring. Let $a, b \in R/P$ such that $ab = 0$. Then we can say that $(a)(b) = 0$ where (a) and (b) are ideals generated by a and b respectively in R/P . But then we know that either $(a) = 0$ or $(b) = 0$ since R/P is a prime ring. Therefore, we must have $a = 0$ or $b = 0$ and so R/P is an integral domain.

Now suppose that R/P is an integral domain. Suppose A and B are ideals such that $AB = 0$. Then pick $a_1 \in A$. Then, since R/P is an integral domain, we have $a_1 b_i = 0$ for all $b_i \in B$ or $a_1 = 0$. Continuing in this way, we must have either $A = 0$ or $B = 0$. Thus R/P is prime so P is a prime ideal \square

41. (a) Let R be a commutative ring with 1. Show that if M is a maximal ideal of R then M is a prime ideal of R .
(b) Give an example of a non-zero prime ideal in a ring R that is not a maximal ideal.

Proof. For (a) since M is a maximal ideal then R/M is a field and thus an integral domain. Since R/M is an integral domain, then M is a prime ideal of R .

For (b) note that $\mathbb{Z}[x]/(x) \cong \mathbb{Z}$ so (x) is a prime ideal of $\mathbb{Z}[x]$ but (x) is not maximal in $\mathbb{Z}[x]$ since \mathbb{Z} is not a field. \square

42. Let R be a non-zero ring with identity. Show that every proper ideal of R is contained in a maximal ideal.

Proof. Let $I \subsetneq R$ be a proper ideal. Define the set $P = \{A \mid I \subseteq A \subsetneq R \text{ is an ideal of } R\}$. Let \mathcal{C} be a chain of ideals in P . Then $U_{\mathcal{C}} = \bigcup_{A \in \mathcal{C}} A$ is an ideal of R containing I and is an upper bound for \mathcal{C} . Notice that $1 \notin U_{\mathcal{C}}$ since 1 was not in any of the ideals from \mathcal{C} as the ideals in \mathcal{C} are proper in R . Thus we have that $U_{\mathcal{C}} \in P$. Now we can apply Zorn's Lemma. So there exists a maximal element \mathcal{A} of the set P . It follows that $I \subseteq \mathcal{A} \subsetneq R$ and so I is contained in the maximal ideal \mathcal{A} . \square

43. Let R be a commutative ring with 1 and P a prime ideal of R . Show that if I and J are ideals of R such that $I \cap J \subseteq P$ and $J \not\subseteq P$, then $I \subseteq P$.
44. Let $M_1 \neq M_2$ be two maximal ideals in the commutative ring R and let $I = M_1 \cap M_2$. Prove that R/I is isomorphic to the direct sum of two fields.
45. Let R be a non-zero commutative ring with 1. Show that if I is an ideal of R such that $1 + a$ is a unit in R for all $a \in I$, then I is contained in every maximal ideal of R .
46. Let R be a commutative ring with identity. Suppose R contains an idempotent element a other than 0 or 1. Show that every prime ideal of R contains an idempotent element other than 0 or 1. (An element $a \in R$ is idempotent if $a^2 = a$)
47. Let R be a commutative ring with 1.

- (a) Prove that (x) is a prime ideal in $R[x]$ if and only if R is an integral domain.
(b) Prove that (x) is a maximal ideal in $R[x]$ if and only if R is a field.

48. Find all values of a in \mathbb{Z}_3 such that the quotient ring

$$\mathbb{Z}_3[x]/(x^3 + x^2 + ax + 1)$$

is a field. Justify your answer.

49. Find all values of a in \mathbb{Z}_5 such that the quotient ring

$$\mathbb{Z}_5[x]/(x^3 + 2x^2 + ax + 3)$$

is a field. Justify your answer.

50. Let R be a commutative ring with identity and let U be maximal among non-finitely generated ideals of R . Prove U is a prime ideal.
51. Let R be a commutative ring with identity and let U be a maximal among non-principal ideals of R . Prove U is a prime ideal.
52. Let R be a non-zero commutative ring with 1 and S a multiplicative subset of R not containing 0. Show that if P is maximal in the set of ideals of R not intersecting S , then P is a prime ideal.
53. Let R be a non-zero commutative ring with 1.

(a) Let S be a multiplicative subset of R not containing 0 and let P be maximal in the set of ideals of R not intersecting S . Show that P is a prime ideal.

(b) Show that the set of nilpotent elements of R is the intersection of all prime ideals.

54. Let R be a commutative ring with identity and let $x \in R$ be a non-nilpotent element. Prove that there exists a prime ideal P of R such that $x \notin P$.
55. Let R be a commutative ring with identity and let S be the set of all elements of R that are *not* zero-divisors. Show that there is a prime ideal P such that $P \cap S$ is empty. (Hint: Use Zorn's Lemma)
56. Let R be a commutative ring with identity and let \mathcal{C} be a chain of prime ideals of R . Show that $\bigcup_{P \in \mathcal{C}} P$ and $\bigcap_{P \in \mathcal{C}} P$ are prime ideals of R .
57. Let R be a commutative ring and P be a prime ideal of R . Show that there is a prime ideal $P_0 \subseteq P$ that does not properly contain any prime ideal.
58. Let R be a commutative ring with 1 such that every x in R there is an integer $n > 1$ (depending on x) such that $x^n = x$. Show that every prime ideal of R is maximal.
59. Let R be a commutative ring with 1 in which every ideal is a prime ideal. Prove that R is a field. (Hint: For $a \neq 0$ consider the ideals (a) and (a^2) .)
60. Let D be a principal ideal domain. Prove that every nonzero prime ideal of D is a maximal ideal.
61. Show that if R is a finite commutative ring with identity, then every prime ideal of R is a maximal ideal.
62. Let $R = C[0, 1]$ be the ring of all continuous real-valued functions on $[0, 1]$, with addition and multiplication defined as follows. For $f, g \in R$ and $x \in [0, 1]$,

$$(f + g)(x) = f(x) + g(x)$$

$$(fg)(x) = f(x)g(x).$$

Prove that if M is a maximal ideal of R , then there is a real number $x_0 \in [0, 1]$ such that $M = \{f \in R \mid f(x_0) = 0\}$.

63. Let R be a commutative ring with identity, and let $P \subset Q$ be prime ideals of R . Prove there exists prime ideals P^*, Q^* satisfying $P \subseteq P^* \subset Q^* \subseteq Q$, such that there are no prime ideals strictly between P^* and Q^* . (Hint: Fix $x \in Q \setminus P$ and show that there exists a prime ideal P^* containing P , contained in Q and maximal with respect to not containing x .)

64. Let R be a commutative ring with 1. An ideal I of R is called a *primary* ideal if $I \neq R$ and for all $x, y \in R$ with $xy \in I$, either $x \in I$ or $y^n \in I$ for some integer $n \geq 1$.
- (a) Show that an ideal I of R is primary if and only if $R/I \neq 0$ and every zero-divisor in R/I is nilpotent.
 - (b) Show that if I is a primary ideal of R then the radical $\text{Rad}(I)$ of I is a prime ideal. (Recall that $\text{Rad}(I) = \{x \in R \mid x^n \in I \text{ for some } n\}$.)

1.3 Commutative Rings

65. Let R be a commutative ring with identity. Show that R is an integral domain if and only if R is a subring of a field.
66. Let R be a commutative ring with identity. Show that if x and y are nilpotent elements of R then $x + y$ is nilpotent and the set of all nilpotent elements is an ideal in R .
67. Let R be a commutative ring with identity. An ideal I of R is *irreducible* if it cannot be expressed as the intersection of two ideals of R neither of which is contained in the other. Show the following.
- (a) If P is a prime ideal then P is irreducible.
 - (b) If x is a non-zero element of R , then there is an ideal I_x , maximal with respect to the property that $x \notin I_x$, and I_x is irreducible.
 - (c) If every irreducible ideal of R is a prime ideal, then 0 is the only nilpotent element of R .
68. Let R be a commutative ring with 1 and let I be an ideal of R satisfying $I^2 = \{0\}$. Show that if $a + I \in R/I$ is an idempotent element of R/I , then the coset $a + I$ contains an idempotent element of R .
69. Let R be a commutative ring with identity that has exactly one prime ideal P . Prove the following
- (a) R/P is a field.
 - (b) R is isomorphic to R_P , the ring of quotients of R with respect to the multiplicative set $R \setminus P = \{s \in R \mid s \notin P\}$
70. Let R be a commutative ring with identity and $\sigma : R \rightarrow R$ a ring automorphism.
- (a) Show that $F = \{r \in R \mid \sigma(r) = r\}$ is a subring of R and the identity of R is in F .
 - (b) Show that if σ^2 is the identity map on R , then each element of R is the root of a monic polynomial of degree two in $F[x]$.
71. Let R be a commutative ring with identity that has exactly three ideals $\{0\}$, I , and R .
- (a) Show that if $a \notin I$, then a is a unit of R .
 - (b) Show that if $a, b \in I$ then $ab = 0$
72. Let R be a commutative ring with 1. Show that if u is a unit in R and n is nilpotent, then $u + n$ is a unit.
73. Let R be a commutative ring with identity. Suppose that for every $a \in R$, either a or $1 - a$ is invertible. Prove that $N = \{a \in R \mid a \text{ is not invertible}\}$ is an ideal of R .
74. Let R be a commutative ring with 1. Show that the sum of any two principal ideals of R is principal if and only if every finitely generated ideal of R is principal.
75. Let R be a commutative ring with identity such that not every ideal is a principal ideal.
- (a) Show that there is an ideal I maximal with respect to the property that I is not a principal ideal.
 - (b) If I is the ideal of part (a), show that R/I is a principal ideal ring.

76. Recall that if $R \subseteq S$ is an inclusion of commutative rings (with the same identity) then an element $s \in S$ is *integral over R* if s satisfies some monic polynomial with coefficients in R . Prove the equivalence of the following statements.
- (a) s is integral over R .
 - (b) $R[s]$ is finitely generated as an R -module.
 - (c) There exists a faithful $R[s]$ module which is finitely generated as an R -module.
77. Recall that if $R \subseteq S$ is an inclusion of commutative rings (with the same identity) then S is an *integral extension* of R if every element of S satisfies some monic polynomial with coefficients in R . Prove that if $R \subseteq S \subseteq T$ are commutative rings with the same identity, then S is integral over R and T if and only if T is integral over R .
78. Let $R \subseteq S$ be commutative domains with the same identity, and assume that S is an integral Extension of R . Let I be a nonzero ideal of S . Prove the $I \cap R$ is a nonzero ideal of R .

1.4 Domains

79. Suppose R is a domain and I and J are ideals of R such that IJ is principal. Show that I (and by symmetry J) is finitely generated.
[Hint: If $IJ = (a)$, then $\sum_{i=1}^n x_i y_i$ for some $x_i \in I$ and $y_i \in J$. Show the x_i generate I .]
80. Prove that if D is a Euclidean Domain, then D is a Principal Ideal Domain.
81. Show that if p is a prime such that there is an integer b with $p = b^2 + 4$, then $\mathbb{Z}[\sqrt{p}]$ is not a unique factorization domain.
82. Show that if p is a prime such that $p \equiv 1 \pmod{4}$, then $\mathbb{Z}[\sqrt{p}]$ is not a unique factorization domain.
83. Let $D = \mathbb{Z}(\sqrt{5}) = \{m + n\sqrt{5} \mid m, n \in \mathbb{Z}\}$ - a subring of the field of real numbers and necessarily an integral domain (you need not show this) - and $F = \mathbb{Q}(\sqrt{5})$ its field of fractions. Show the following:
- (a) $x^2 + x - 1$ is irreducible in $D[x]$ but not in $F[x]$.
 - (b) D is not a unique factorization domain.
84. Let $D = \mathbb{Z}(\sqrt{21}) = \{m + n\sqrt{21} \mid m, n \in \mathbb{Z}\}$ and $F = \mathbb{Q}(\sqrt{21})$, the field of fractions. Show the following:
- (a) $x^2 - x - 5$ is irreducible in $D[x]$ but not in $F[x]$.
 - (b) D is not a unique factorization domain.
85. Let $D = \mathbb{Z}(\sqrt{-11}) = \{m + n\sqrt{-11} \mid m, n \in \mathbb{Z}\}$ and $F = \mathbb{Q}(\sqrt{-11})$, the field of fractions. Show the following:
- (a) $x^2 - x + 3$ is irreducible in $D[x]$ but not in $F[x]$.
 - (b) D is not a unique factorization domain.
86. Let $D = \mathbb{Z}(\sqrt{13}) = \{m + n\sqrt{13} \mid m, n \in \mathbb{Z}\}$ and $F = \mathbb{Q}(\sqrt{13})$, the field of fractions. Show the following:
- (a) $x^2 + 3x - 1$ is irreducible in $D[x]$ but not in $F[x]$.
 - (b) D is not a unique factorization domain.
87. Let D be an integral domain and F a subring of D that is a field. Show that if each element of D is algebraic over F , then D is a field.
88. Let R be an integral domain containing the subfield F and assume that R is finite dimensional over F when viewed as a vector space over F . Prove that R is a field.

89. Let D be an integral domain.
- (a) For $a, b \in D$ define a *greatest common divisor* of a and b .
 - (b) For $x \in D$ denote $(x) = \{dx \mid d \in D\}$. Prove that if $(a) + (b) = (d)$, then d is a greatest common divisor of a and b .
90. Let D be a principal ideal domain.
- (a) For $a, b \in D$, define a *least common multiple* of a and b .
 - (b) Show that $d \in D$ is a least common multiple of a and b if and only if $(a) \cap (b) = (d)$.
91. Let D be a principal ideal domain and let $a, b \in D$.
- (a) Show that there is an element $d \in D$ that satisfies the properties
 - i. $d \mid a$ and $d \mid b$ and
 - ii. if $e \mid a$ and $e \mid b$ then $e \mid d$
 - (b) Show that there is an element $m \in D$ that satisfies the properties
 - i. $a \mid m$ and $b \mid m$ and
 - ii. if $a \mid e$ and $b \mid e$ then $m \mid e$.
92. Let R be a principal ideal domain. Show that if (a) is a nonzero ideal in R , then there are only finitely many ideals in R containing (a) .
93. Let D be a unique factorization domain and F its field of fractions. Prove that if d is an irreducible element in D , then there are no $x \in F$ such that $x^2 = d$.
94. Let D be a Euclidean domain. Prove that every non-zero prime ideal is a maximal ideal.
95. Let π be an irreducible element of a principal ideal domain R . Prove that π is a prime element (that is, $\pi \mid ab$ implies $\pi \mid a$ or $\pi \mid b$).
96. Let D with $\phi : D \setminus \{0\} \rightarrow \mathbb{N}$ be a Euclidean domain. Suppose $\phi(a + b) \leq \max\{\phi(a), \phi(b)\}$ for all $a, b \in D$. Prove that D is either a field or isomorphic to a polynomial ring over a field.
97. Let D be an integral domain and F its field of fractions. Show that if g is an isomorphism of D onto itself, then there is a unique isomorphism h of F onto F such that $h(d) = g(d)$ for all $d \in D$. ($h|_D = g$).
98. Let D be a unique factorization domain such that if p and q are irreducible elements of D , then p and q are associates. Show that if A and B are ideals of D , then either $A \subseteq B$ or $B \subseteq A$.
99. Let D be a unique factorization domain and p a fixed irreducible element of D such that if q is any irreducible element of D , then q is an associate of p . Show the following.
- (a) If d is a nonzero element of D , then d is uniquely expressible in the form up^n , where u is a unit of D and n is a non-negative integer.
 - (b) D is a Euclidean domain.
100. Prove that $\mathbb{Z}[\sqrt{-2}] = \{a + b\sqrt{-2} \mid a, b \in \mathbb{Z}\}$ is a Euclidean domain.
101. Show that the ring $\mathbb{Z}[i]$ of Gaussian integers is a Euclidean ring and compute the greatest common divisor of $5 + i$ and 13 using the Euclidean algorithm.

1.5 Polynomial Rings

102. Show that the polynomial $f(x) = x^4 + 5x^2 + 3x + 2$ is irreducible over the field of rational numbers.
103. Let D be an integral domain and $D[x]$ the polynomial ring over D . Suppose $\phi : D[x] \rightarrow D$ is an isomorphism such that $\phi(d) = d$ for all $d \in D$. Show that $\phi(x) = ax + b$ for some $a, b \in D$ and that a is a unit of D .
104. Let $f(x) = a_0 + a_1x + \dots + a_kx^k + \dots + a_nx^n \in \mathbb{Z}[x]$ and p a prime such that $p \mid a_i$ for $i = 1, \dots, k-1$, $p \nmid a_k$, $p \nmid a_n$, and $p^2 \nmid a_0$. Show that $f(x)$ has an irreducible factor in $\mathbb{Z}[x]$ of degree at least k .
105. Let D be an integral domain and $D[x]$ the polynomial ring over D in the indeterminate x . Show that if every nonzero prime ideal of $D[x]$ is a maximal ideal, then D is a field.
106. Let R be a commutative ring with 1 and let $f(x) \in R[x]$ be nilpotent. Show that the coefficients of f are nilpotent.
107. Show that if R is an integral domain and $f(x)$ is a unit in the polynomial ring $R[x]$, then $f(x)$ is in R .
108. Let D be a unique factorization domain and F its field of fractions. Prove that if $f(x)$ is a monic polynomial in $D[x]$ and $\alpha \in F$ is a root of f , then $\alpha \in D$.
109. (a) Show that $x^4 + x^3 + x^2 + x + 1$ is irreducible in $\mathbb{Z}_3[x]$.
(b) Show that $x^4 + 1$ is not irreducible in $\mathbb{Z}_3[x]$.
110. Let $F[x, y]$ be the polynomial ring over a field F in two indeterminates x, y . Show that the ideal generated by $\{x, y\}$ is not a principal ideal.
111. Let F be a field. Prove that the polynomial ring $F[x]$ is a PID and that $F[x, y]$ is not a PID.
112. Let D be an integral domain and let c be an irreducible element in D . Show that the ideal (x, c) generated by x and c in the polynomial ring $D[x]$ is not a principal ideal.
113. Show that if R is a commutative ring with 1 that is not a field, then $R[x]$ is not a principal ideal domain.
114. (a) Let $\mathbb{Z}[\frac{1}{2}] = \{\frac{a}{2^n} \mid a, n \in \mathbb{Z}, n \geq 0\}$, the smallest subring of \mathbb{Q} containing \mathbb{Z} and $\frac{1}{2}$. Let $(2x - 1)$ be the ideal of $\mathbb{Z}[x]$ generated by the polynomial $2x - 1$. Show that $\mathbb{Z}[x]/(2x - 1) \cong \mathbb{Z}[\frac{1}{2}]$.
(b) Find an ideal I of $\mathbb{Z}[x]$ such that $(2x - 1) \subsetneq I \subsetneq \mathbb{Z}[x]$

1.6 Non-commutative Rings

115. Let R be a ring with identity such that the identity map is the only ring automorphism of R . Prove that the set N of all nilpotent elements of R is an ideal of R .
116. Let p be a prime. A ring S is called a p -ring if the characteristic of S is a power of p . Show that if R is a ring with identity of finite characteristic, then R is isomorphic to a finite direct product of p -rings for distinct primes.
117. If R is any ring with identity, let $J(R)$ denote the Jacobson radical of R . Show that if e is any idempotent of R , then $J(eRe) = eJ(R)e$.
118. If n is a positive integer and F is any field, let $M_n(F)$ denote the ring of $n \times n$ matrices with entries in F . Prove that $M_n(F)$ is a simple ring. Equivalently, $\text{End}_F(V)$ is a simple ring if V is a finite dimensional vector space over F .
119. Let R be a ring.
- (a) Show that there is a unique smallest (with respect to inclusion) ideal A such that R/A is a commutative ring.
- (b) Give an example of a ring R such that for every proper ideal I , R/I is not commutative. Verify your example.

- (c) For the ring $R = \left\{ \begin{bmatrix} a & b \\ 0 & c \end{bmatrix} \mid a, b, c \in \mathbb{Z} \right\}$ with the usual matrix operations, find the ideal of A of part (a).

120. A ring R is *nilpotent-free* if $a^n = 0$ for $a \in R$ and some positive integer n implies $a = 0$.
- (a) Suppose there is an ideal I such that R/I is nilpotent-free. Show there is a unique smallest (with respect to inclusion) ideal A such that R/A is nilpotent-free.
 - (b) Give an example of a ring R such that for every proper ideal I , R/I is not nilpotent-free. Verify your example.
 - (c) Show that if R is a commutative ring with identity, then there is a proper ideal I of R such that R/I is nilpotent-free, and find the ideal A of part (a).

1.7 Local Rings, Localization, Rings of Fractions

121. Let R be an integral domain. Construct the field of fractions F of R by defining the set F and the two binary operations, and show that the two operations are well-defined. Show that F has a multiplicative identity element and that every nonzero element of F has a multiplicative inverse.
122. A *local* ring is a commutative ring with 1 that has a unique maximal ideal. Show that a ring R is local if and only if the set of non-units in R is an ideal.
123. Let R be a commutative ring with $1 \neq 0$ in which the set of nonunits is closed under addition. Prove that R is local, i.e., has a unique maximal ideal.
124. Let D be an integral domain and F its field of fractions. Let P be a prime ideal in D and $D_P = \{ab^{-1} \mid a, b \in D, b \notin P\} \subseteq F$. Show that D_P has a unique maximal ideal.
125. Let R be a commutative ring with identity and M a maximal ideal of R . Let R_M be the ring of quotients of R with respect to the multiplicative set $R \setminus M = \{s \in R \mid s \notin M\}$. Show the following.
- (a) $M_M = \{\frac{a}{s} \mid a \in M, s \notin M\}$ is the unique maximal ideal of R_M .
 - (b) The fields R/M and R_M/M_M are isomorphic.
126. Let R be an integral domain, S a multiplicative set, and let $S^{-1}R = \{\frac{r}{s} \mid r \in R, s \in S\}$ (contained in the field of fractions of R). Show that if P is a prime ideal of R , then $S^{-1}P$ is either a prime ideal of $S^{-1}R$ or else equals $S^{-1}R$.
127. Let R be a commutative ring with identity and P a prime ideal of R . Let R_P be the ring of quotients of R with respect to the set $R \setminus P = \{s \in R \mid s \notin P\}$. Show that R_P/P_P is the field of fractions of the integral domain R/P .
128. Let D be an integral domain and F its field of fractions. Denote by \mathcal{M} the set of all maximal ideals of D . For $M \in \mathcal{M}$, let $D_M = \{\frac{a}{s} \mid a, s \in D, s \notin M\} \subset F$. Show that $\bigcap_{M \in \mathcal{M}} D_M = D$.
129. Let R be a commutative ring with 1 and D a multiplicative subset of R containing 1. Let J be an ideal in the ring of fractions $D^{-1}R$ and let

$$I = \left\{ a \in R \mid \frac{a}{d} \in J \text{ for some } d \in D \right\}.$$

Show that I is an ideal of R .

130. Let D be a principal ideal domain and let P be a non-zero prime ideal. Show that D_P , the localization of D at P , is a principal ideal domain and has a unique irreducible element, up to associates.

1.8 Chains and Chain Conditions

131. Let R be a commutative ring with identity. Prove that any non-empty set of prime ideals of R contains maximal *and* minimal elements.
132. Let R be a commutative ring with 1. We say R satisfies the *ascending chain condition* if whenever $I_1 \subseteq I_2 \subseteq I_3 \subseteq \dots$ is an ascending chain of ideals, there is an integer N such that $I_k = I_N$ for all $k \geq N$. Show that R satisfies the ascending chain condition if and only if every ideal of R is finitely generated.
133. Define *Noetherian ring* and prove that if R is Noetherian, then $R[x]$ is Noetherian.
134. Let R be a commutative Noetherian ring with identity. Prove that there are only finitely many *minimal* prime ideals of R .
135. Let R be a commutative Noetherian ring in which every 2-generated ideal is principal. Prove that R is a Principal Ideal Domain.
136. Let R be a commutative Noetherian ring with identity and let I be an ideal in R . Let $J = \text{Rad}(I)$. Prove that there exists a positive integer n such that $j^n \in I$ for all $j \in J$.
137. Let R be a commutative Noetherian domain with identity. Prove that every nonzero ideal of R contains a product of nonzero *prime* ideals of R .
138. Let R be a ring satisfying the *descending chain condition* on right ideals. If $J(R)$ denotes the Jacobson radical of R , prove that $J(R)$ is nilpotent.
139. Show that if R is a commutative Noetherian ring with identity, then the polynomial ring $R[x]$ is also Noetherian.
140. Let P be a nonzero prime ideal of the commutative Noetherian domain R . Assume P is principal. Prove that there does not exist a prime ideal Q satisfying $(0) < Q < P$.
141. Let R be a commutative Noetherian ring. Prove that every nonzero ideal A of R contains a product of prime ideals (not necessarily distinct) each of which contains A .
142. Let R be a commutative ring with 1 and let M be an R -module that is not Artinian (Noetherian, of finite composition length). Let \mathcal{I} be the set of ideals I of R such that there exists an R -submodule N of M with the property that N/NI is not Artinian (Noetherian, of finite composition length, respectively). Show that if $A \in \mathcal{I}$ is a maximal element of \mathcal{I} , then A is a prime ideal of R .