

ALGEBRA QUALIFYING EXAM PROBLEMS
RING THEORY

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RING THEORY

General Ring Theory

1. Give an example of each of the following.
 - (a) An irreducible polynomial of degree 3 in $\mathbf{Z}_3[x]$.
 - (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 or 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.
3. 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.
4. If p is a prime satisfying $p \equiv 1 \pmod{4}$, then p is a sum of two squares.
5. If (\cdot) denotes the Legendre symbol, prove Euler's Criterion: if p is a prime and a is any integer relatively prime to p , then $a^{(p-1)/2} \equiv \left(\frac{a}{p}\right) \pmod{p}$.
6. 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 $i = 1, 2$.
7. Show that a non-zero ring R in which $x^2 = x$ for all $x \in R$ is of characteristic 2 and is commutative.
8. Let R be a finite commutative ring with more than one element and no zero-divisors. Show that R is a field.

9. Determine for which integers n the ring $\mathbb{Z}/n\mathbb{Z}$ is a direct sum of fields. Prove your answer.
10. 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 two ideals of R , then either $I \subseteq J$ or $J \subseteq I$.
11. 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 .
12. 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.
13. Let m, n be positive integers such that m divides n . Then the natural map $\varphi : \mathbb{Z}_n \rightarrow \mathbb{Z}_m$ 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 $\varphi : U_n \rightarrow U_m$ is a surjective group homomorphism.
14. Let R be a ring with 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 $A + B = R$.
15. 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.
16. Let R be a commutative ring with 1 and let I and J be ideals of R such that $I + J = R$. Show that $R/(I \cap J) \cong R/I \oplus R/J$.
17. 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 $S/R \cong \mathbb{Z}/n\mathbb{Z}$.
18. 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 $b + (1 - xa) \in X$.
(b) If $\varphi : X \rightarrow X$ is the mapping given by $\varphi(x) = b + (1 - xa)$, then φ is one-to-one.
(c) If X has more than one element, then X is an infinite set.
19. 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.
20. 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.
21. 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.

22. 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 $\mathbb{Z}[\sqrt{p}]$.
23. 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.
24. 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 $I + K = J$.
25. 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.
26. Give an example of a field F and a one-to-one ring homomorphism $\varphi : F \rightarrow F$ which is not onto. Verify your example.
27. 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

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

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

28. 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 $f = 0_R$.
29. 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 $|t|$.
30. 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 .

31. Show that if p is a prime such that $p \equiv 1 \pmod{4}$, then $x^2 + 1$ is not irreducible in $\mathbb{Z}_p[x]$.
32. Show that if p is a prime such that $p \equiv 3 \pmod{4}$, then $x^2 + 1$ is irreducible in $\mathbb{Z}_p[x]$.
33. Show that if p is a prime such that $p \equiv 1 \pmod{6}$, then $x^3 + 1$ splits in $\mathbb{Z}_p[x]$.

Prime, Maximal, and Primary Ideals

34. 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.
35. (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.
36. Let R be a non-zero ring with identity. Show that every proper ideal of R is contained in a maximal ideal.
37. 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 .
38. 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.
39. 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.

40. 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.

41. 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.
42. Let R be a commutative ring with identity and let U be maximal among non-principal ideals of R . Prove U is a prime ideal.
43. 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.
44. 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.

45. 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.)
46. 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 .
47. Let R be a commutative ring and P a prime ideal of R . Show that there is a prime ideal $P_0 \subseteq P$ which does not properly contain any prime ideal.
48. Let R be a commutative ring with 1 such that for 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.
49. 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) .)
50. Let D be a principal ideal domain. Prove that every nonzero prime ideal of D is a maximal ideal.
51. Show that if R is a finite commutative ring with identity then every prime ideal of R is a maximal ideal.
52. 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 $M = \{f \in R \mid f(x_0) = 0\}$.
53. Let R be a commutative ring with identity, and let $P \subset Q$ be prime ideals of R . Prove that there exist 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 $x \in Q - P$ and show that there exists a prime ideal P^* containing P , contained in Q and maximal with respect to not containing x .
54. 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 $\text{Rad}(I) = \{x \in R \mid x^n \in I \text{ for some } n\}$.)

Commutative Rings

55. 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.
56. 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 .

57. 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.
- If P is a prime ideal then P is irreducible.
 - 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.
 - If every irreducible ideal of R is a prime ideal, then 0 is the only nilpotent element of R .
58. 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 .
59. Let R be a commutative ring with identity that has exactly one prime ideal P . Prove the following.
- R/P is a field.
 - R is isomorphic to R_P , the ring of quotients of R with respect to the multiplicative set $R - P = \{s \in R \mid s \notin P\}$.
60. Let R be a commutative ring with identity and $\sigma : R \rightarrow R$ a ring automorphism.
- Show that $F = \{r \in R \mid \sigma(r) = r\}$ is a subring of R and the identity of R is in F .
 - 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 $F[x]$.
61. Let R be a commutative ring with identity that has exactly three ideals, $\{0\}$, I , and R .
- Show that if $a \notin I$, then a is a unit of R .
 - Show that if $a, b \in I$ then $ab = 0$.
62. 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.
63. 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 .
64. 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.
65. Let R be a commutative ring with identity such that not every ideal is a principal ideal.
- Show that there is an ideal I maximal with respect to the property that I is not a principal ideal.
 - If I is the ideal of part (a), show that R/I is a principal ideal ring.
66. 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.
- s is integral over R .
 - $R[s]$ is finitely generated as an R -module.
 - There exists a faithful $R[s]$ module which is finitely generated as an R -module.

67. 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 is integral over S if and only if T is integral over R .
68. 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 that $I \cap R$ is a nonzero ideal of R .

Domains

69. Suppose R is a domain and I and J are ideals of R such that IJ is principal. Show that I (and hence J) is finitely generated.
 [Hint: If $IJ = (a)$, then $a = \sum_{i=1}^n x_i y_i$ for some $x_i \in I$ and $y_i \in J$. Show the x_i generate I .]
70. 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.
71. 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.
72. 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.
73. 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 of D . 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.
74. Let $D = \mathbb{Z}(\sqrt{-11}) = \{m + n\sqrt{-11} \mid m, n \in \mathbb{Z}\}$ and $F = \mathbb{Q}(\sqrt{-11})$ its 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.
75. **[NEW]**
 Let $D = \mathbb{Z}(\sqrt{13}) = \{m + n\sqrt{13} \mid m, n \in \mathbb{Z}\}$ and $F = \mathbb{Q}(\sqrt{13})$ its 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.
76. Let D be an integral domain and F a subring of D which is a field. Show that if each element of D is algebraic over F , then D is a field.
77. 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 .

78. Let D be a principal ideal domain.
- For $a, b \in D$, define a *least common multiple* of a and b .
 - Show that $d \in D$ is a least common multiple of a and b if and only if $(a) \cap (b) = (d)$.
79. Let D be a principal ideal domain and let $a, b \in D$.
- Show that there is an element $d \in D$ that satisfies the properties
 - $d|a$ and $d|b$ and
 - if $e|a$ and $e|b$ then $e|d$.
 - Show that there is an element $m \in D$ that satisfies the properties
 - $a|m$ and $b|m$ and
 - if $a|e$ and $b|e$ then $m|e$.
80. 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) .
81. 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 is no $x \in F$ such that $x^2 = d$.
82. Let D be a Euclidean domain. Prove that every non-zero prime ideal is a maximal ideal.
83. Let D with $\varphi : D - \{0\} \rightarrow \mathbb{N}$ be a Euclidean domain. Suppose $\varphi(a + b) \leq \max\{\varphi(a), \varphi(b)\}$ for all $a, b \in D$. Prove that D is either a field or isomorphic to a polynomial ring over a field.
84. 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 .
85. 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 $B \subseteq A$.
86. 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.
- 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.
 - D is a Euclidean domain.
87. Prove that $\mathbb{Z}[\sqrt{-2}] = \{a + b\sqrt{-2} \mid a, b \in \mathbb{Z}\}$ is a Euclidean domain.
88. 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.

Polynomial Rings

89. Show that the polynomial $f(x) = x^4 + 5x^2 + 3x + 2$ is irreducible over the field of rational numbers.
90. Let D be an integral domain and $D[x]$ the polynomial ring over D . Suppose $\varphi : D[x] \rightarrow D[x]$ is an isomorphism such that $\varphi(d) = d$ for all $d \in D$. Show that $\varphi(x) = ax + b$ for some $a, b \in D$ and that a is a unit of D .

91. Let $f(x) = a_0 + a_1x + \cdots + a_kx^k + \cdots + a_nx^n \in \mathbb{Z}[x]$ and p a prime such that $p|a_i$ 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 .
92. 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.
93. 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.
94. 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 .
95. 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 $\alpha \in D$.
96. (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 $\mathbb{Z}_3[x]$.
97. 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.
98. 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.
99. Show that if R is a commutative ring with 1 that is not a field, then $R[x]$ is not a principal ideal ring.
100. (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 $(2x-1) \subsetneq I \subsetneq \mathbb{Z}[x]$.

Non-commutative Rings

101. 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 .
102. 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.
103. 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 A of part (a).

104. If R is any ring with identity, let $J(R)$ denote the Jacobson radical of R . If e is any idempotent of R , show that $J(eRe) = eJ(R)e$.
105. 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 .
106. A ring R is *nilpotent-free* if $a^n = 0$ for $a \in R$ and some positive integer n implies $a = 0$.
- 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.
 - Give an example of a ring R such that for every proper ideal I , R/I is not nilpotent-free. Verify your example.
 - 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).

Local Rings, Localization, Rings of Fractions

107. 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.
108. 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.
109. 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.
110. 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.
111. 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 $R - M = \{s \in R \mid s \notin M\}$. Show the following.
- $M_M = \{\frac{a}{s} \mid a \in M, s \notin M\}$ is the unique maximal ideal of R_M .
 - The fields R/M and R_M/M_M are isomorphic.
112. 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 $S^{-1}R$.
113. 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 $R - P = \{s \in R \mid s \notin P\}$. Show that R_P/P_P is the field of fractions of the integral domain R/P .
114. 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 $\bigcap_{M \in \mathcal{M}} D_M = D$.

115. 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

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

Show that I is an ideal of R .

116. 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.

Chains and Chain Conditions

117. Let R be a commutative ring with identity. Prove that any non-empty set of prime ideals of R contains maximal *and* minimal elements.
118. 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.
119. Let R be a commutative Noetherian ring with identity. Prove that there are only finitely many *minimal* prime ideals of R .
120. 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 $j \in J$.
121. 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 .
122. 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.
123. Show that if R is a commutative Noetherian ring with identity, then the polynomial ring $R[x]$ is also Noetherian.
124. 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 $(0) < Q < P$.
125. 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 .
126. 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 .