

# Algebra Qualifying Exam Questions

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# 1 Group Theory

## 1.1 Spring 2020 #1

- Show that any group of order 2020 is solvable.
- Give (without proof) a classification of all abelian groups of order 2020.
- Describe one nonabelian group of order 2020.

## 1.2 Spring 2020 #2

Let  $H$  be a normal subgroup of a finite group  $G$  where the order of  $H$  and the index of  $H$  in  $G$  are relatively prime. Prove that no other subgroup of  $G$  has the same order as  $H$ .

**1.3 Fall 2019 #1**

Let  $G$  be a finite group with  $n$  distinct conjugacy classes. Let  $g_1 \cdots g_n$  be representatives of the conjugacy classes of  $G$ .

Prove that if  $g_i g_j = g_j g_i$  for all  $i, j$  then  $G$  is abelian.

**1.4 Fall 2019 #2**

Let  $G$  be a group of order 105 and let  $P, Q, R$  be Sylow 3, 5, 7 subgroups respectively.

- (a) Prove that at least one of  $Q$  and  $R$  is normal in  $G$ .
- (b) Prove that  $G$  has a cyclic subgroup of order 35.
- (c) Prove that both  $Q$  and  $R$  are normal in  $G$ .
- (d) Prove that if  $P$  is normal in  $G$  then  $G$  is cyclic.

**1.5 Spring 2019 #3**

How many isomorphism classes are there of groups of order 45?

Describe a representative from each class.

**1.6 Spring 2019 #4**

For a finite group  $G$ , let  $c(G)$  denote the number of conjugacy classes of  $G$ .

- (a) Prove that if two elements of  $G$  are chosen uniformly at random, then the probability they commute is precisely

$$\frac{c(G)}{|G|}.$$

- (b) State the class equation for a finite group.
- (c) Using the class equation (or otherwise) show that the probability in part (a) is at most

$$\frac{1}{2} + \frac{1}{2[G : Z(G)]}.$$

Here, as usual,  $Z(G)$  denotes the center of  $G$ .

**1.7 Fall 2012 #1**

Let  $G$  be a finite group and  $X$  a set on which  $G$  acts.

- a. Let  $x \in X$  and  $G_x := \{g \in G \mid g \cdot x = x\}$ . Show that  $G_x$  is a subgroup of  $G$ .
- b. Let  $x \in X$  and  $G \cdot x := \{g \cdot x \mid g \in G\}$ . Prove that there is a bijection between elements in  $G \cdot x$  and the left cosets of  $G_x$  in  $G$ .

**1.8 Fall 2012 #2**

Let  $G$  be a group of order 30.

- Show that  $G$  contains normal subgroups of orders 3, 5, and 15.
- Give all possible presentations and relations for  $G$ .
- Determine how many groups of order 30 there are up to isomorphism.

**1.9 Spring 2012 #2**

Let  $G$  be a finite group and  $p$  a prime number such that there is a normal subgroup  $H \trianglelefteq G$  with  $|H| = p^i > 1$ .

- Show that  $H$  is a subgroup of any Sylow  $p$ -subgroup of  $G$ .
- Show that  $G$  contains a nonzero abelian normal subgroup of order divisible by  $p$ .

**1.10 Spring 2012 #3**

Let  $G$  be a group of order 70.

- Show that  $G$  is not simple.
- Exhibit 3 nonisomorphic groups of order 70 and prove that they are not isomorphic.

**1.11 Fall 2018 #1**

Let  $G$  be a finite group whose order is divisible by a prime number  $p$ . Let  $P$  be a normal  $p$ -subgroup of  $G$  (so  $|P| = p^c$  for some  $c$ ).

- Show that  $P$  is contained in every Sylow  $p$ -subgroup of  $G$ .
- Let  $M$  be a maximal proper subgroup of  $G$ . Show that either  $P \subseteq M$  or  $|G/M| = p^b$  for some  $b \leq c$ .

**1.12 Fall 2018 #2**

- Suppose the group  $G$  acts on the set  $X$ . Show that the stabilizers of elements in the same orbit are conjugate.
- Let  $G$  be a finite group and let  $H$  be a proper subgroup. Show that the union of the conjugates of  $H$  is strictly smaller than  $G$ , i.e.

$$\bigcup_{g \in G} gHg^{-1} \subsetneq G$$

- Suppose  $G$  is a finite group acting transitively on a set  $S$  with at least 2 elements. Show that there is an element of  $G$  with no fixed points in  $S$ .

**1.13 Spring 2018 #1**

- (a) Use the Class Equation (equivalently, the conjugation action of a group on itself) to prove that any  $p$ -group (a group whose order is a positive power of a prime integer  $p$ ) has a nontrivial center.
- (b) Prove that any group of order  $p^2$  (where  $p$  is prime) is abelian.
- (c) Prove that any group of order  $5^2 \cdot 7^2$  is abelian.
- (d) Write down exactly one representative in each isomorphism class of groups of order  $5^2 \cdot 7^2$ .

**1.14 Fall 2017 #1**

Suppose the group  $G$  acts on the set  $A$ . Assume this action is faithful (recall that this means that the kernel of the homomorphism from  $G$  to  $\text{Sym}(A)$  which gives the action is trivial) and transitive (for all  $a, b$  in  $A$ , there exists  $g$  in  $G$  such that  $g \cdot a = b$ .)

- (a) For  $a \in A$ , let  $G_a$  denote the stabilizer of  $a$  in  $G$ . Prove that for any  $a \in A$ ,

$$\bigcap_{\sigma \in G} \sigma G_a \sigma^{-1} = \{1\}.$$

- (b) Suppose that  $G$  is abelian. Prove that  $|G| = |A|$ . Deduce that every abelian transitive subgroup of  $S_n$  has order  $n$ .

**1.15 Fall 2017 #2**

- (a) Classify the abelian groups of order 36.

For the rest of the problem, assume that  $G$  is a non-abelian group of order 36.

You may assume that the only subgroup of order 12 in  $S_4$  is  $A_4$  and that  $A_4$  has no subgroup of order 6.

- (b) Prove that if the 2-Sylow subgroup of  $G$  is normal,  $G$  has a normal subgroup  $N$  such that  $G/N$  is isomorphic to  $A_4$ .
- (c) Show that if  $G$  has a normal subgroup  $N$  such that  $G/N$  is isomorphic to  $A_4$  and a subgroup  $H$  isomorphic to  $A_4$  it must be the direct product of  $N$  and  $H$ .
- (d) Show that the dihedral group of order 36 is a non-abelian group of order 36 whose Sylow-2 subgroup is not normal.

**1.16 Spring 2017 #1**

Let  $G$  be a finite group and  $\pi : G \rightarrow \text{Sym}(G)$  the Cayley representation. (Recall that this means that for an element  $x \in G$ ,  $\pi(x)$  acts by left translation on  $G$ .)

Prove that  $\pi(x)$  is an odd permutation  $\iff$  the order  $|\pi(x)|$  of  $\pi(x)$  is even and  $|G|/|\pi(x)|$  is odd.

**1.17 Spring 2017 #2**

- How many isomorphism classes of abelian groups of order 56 are there? Give a representative for one of each class.
- Prove that if  $G$  is a group of order 56, then either the Sylow-2 subgroup or the Sylow-7 subgroup is normal.
- Give two non-isomorphic groups of order 56 where the Sylow-7 subgroup is normal and the Sylow-2 subgroup is *not* normal. Justify that these two groups are not isomorphic.

**1.18 Fall 2016 #1**

Let  $G$  be a finite group and  $s, t \in G$  be two distinct elements of order 2. Show that subgroup of  $G$  generated by  $s$  and  $t$  is a dihedral group.

Recall that the dihedral groups of order  $2m$  for  $m \geq 2$  are of the form

$$D_{2m} = \langle \sigma, \tau \mid \sigma^m = 1 = \tau^2, \tau\sigma = \sigma^{-1}\tau \rangle.$$

**1.19 Fall 2016 #3**

How many groups are there up to isomorphism of order  $pq$  where  $p < q$  are prime integers?

**1.20 ★ Fall 2016 #7**

- Define what it means for a group  $G$  to be *solvable*.
- Show that every group  $G$  of order 36 is solvable.

Hint: you can use that  $S_4$  is solvable.

**1.21 Spring 2016 #3**

- State the three Sylow theorems.
- Prove that any group of order 1225 is abelian.
- Write down exactly one representative in each isomorphism class of abelian groups of order 1225.

**1.22 Spring 2016 #5**

Let  $G$  be a finite group acting on a set  $X$ . For  $x \in X$ , let  $G_x$  be the stabilizer of  $x$  and  $G \cdot x$  be the orbit of  $x$ .

- Prove that there is a bijection between the left cosets  $G/G_x$  and  $G \cdot x$ .
- Prove that the center of every finite  $p$ -group  $G$  is nontrivial by considering that action of  $G$  on  $X = G$  by conjugation.



**1.23 Fall 2015 #1**

Let  $G$  be a group containing a subgroup  $H$  not equal to  $G$  of finite index. Prove that  $G$  has a normal subgroup which is contained in every conjugate of  $H$  which is of finite index.

**1.24 Fall 2015 #2**

Let  $G$  be a finite group,  $H$  a  $p$ -subgroup, and  $P$  a Sylow  $p$ -subgroup for  $p$  a prime. Let  $H$  act on the left cosets of  $P$  in  $G$  by left translation.

Prove that this is an orbit under this action of length 1.

Prove that  $xP$  is an orbit of length 1  $\iff H$  is contained in  $xPx^{-1}$ .

**1.25 Spring 2015 #1**

For a prime  $p$ , let  $G$  be a finite  $p$ -group and let  $N$  be a normal subgroup of  $G$  of order  $p$ . Prove that  $N$  is contained in the center of  $G$ .

**1.26 Spring 2015 #4**

Let  $N$  be a positive integer, and let  $G$  be a finite group of order  $N$ .

- a. Let  $\text{Sym}G$  be the set of all bijections from  $G \rightarrow G$  viewed as a group under composition. Note that  $\text{Sym}G \cong S_N$ . Prove that the Cayley map

$$\begin{aligned} C : G &\longrightarrow \text{Sym}G \\ g &\mapsto (x \mapsto gx) \end{aligned}$$

is an injective homomorphism.

- b. Let  $\Phi : \text{Sym}G \rightarrow S_N$  be an isomorphism. For  $a \in G$  define  $\varepsilon(a) \in \{\pm 1\}$  to be the sign of the permutation  $\Phi(C(a))$ . Suppose that  $a$  has order  $d$ . Prove that  $\varepsilon(a) = -1 \iff d$  is even and  $N/d$  is odd.
- c. Suppose  $N > 2$  and  $n \equiv 2 \pmod{4}$ . Prove that  $G$  is not simple.

Hint: use part (b).

**1.27 Fall 2014 #2**

Let  $G$  be a group of order 96.

- a. Show that  $G$  has either one or three 2-Sylow subgroups.
- b. Show that either  $G$  has a normal subgroup of order 32, or a normal subgroup of order 16.

**1.28 Fall 2014 #6**

Let  $G$  be a group and  $H, K < G$  be subgroups of finite index. Show that

$$[G : H \cap K] \leq [G : H] [G : K].$$

**1.29 Spring 2014 #1**

Let  $p, n$  be integers such that  $p$  is prime and  $p$  does not divide  $n$ . Find a real number  $k = k(p, n)$  such that for every integer  $m \geq k$ , every group of order  $p^m n$  is not simple.

**1.30 Spring 2014 #2**

Let  $G \subset S_9$  be a Sylow-3 subgroup of the symmetric group on 9 letters.

- Show that  $G$  contains a subgroup  $H$  isomorphic to  $\mathbb{Z}_3 \times \mathbb{Z}_3 \times \mathbb{Z}_3$  by exhibiting an appropriate set of cycles.
- Show that  $H$  is normal in  $G$ .
- Give generators and relations for  $G$  as an abstract group, such that all generators have order 3. Also exhibit elements of  $S_9$  in cycle notation corresponding to these generators.
- Without appealing to the previous parts of the problem, show that  $G$  contains an element of order 9.

**1.31 Fall 2013 #1**

Let  $p, q$  be distinct primes.

- Let  $\bar{q} \in \mathbb{Z}_p$  be the class of  $q \pmod p$  and let  $k$  denote the order of  $\bar{q}$  as an element of  $\mathbb{Z}_p^\times$ . Prove that no group of order  $pq^k$  is simple.
- Let  $G$  be a group of order  $pq$ , and prove that  $G$  is not simple.

**1.32 Fall 2013 #2**

Let  $G$  be a group of order 30.

- Show that  $G$  has a subgroup of order 15.
- Show that every group of order 15 is cyclic.
- Show that  $G$  is isomorphic to some semidirect product  $\mathbb{Z}_{15} \rtimes \mathbb{Z}_2$ .
- Exhibit three nonisomorphic groups of order 30 and prove that they are not isomorphic. You are not required to use your answer to (c).

**1.33 Spring 2013 #3**

Let  $P$  be a finite  $p$ -group. Prove that every nontrivial normal subgroup of  $P$  intersects the center of  $P$  nontrivially.

**1.34 Spring 2013 #4**

Define a *simple group*. Prove that a group of order 56 can not be simple.

**1.35 Fall 2019 Midterm #1**

Let  $G$  be a group of order  $p^2q$  for  $p, q$  prime. Show that  $G$  has a nontrivial normal subgroup.

**1.36 Fall 2019 Midterm #2**

Let  $G$  be a finite group and let  $P$  be a Sylow  $p$ -subgroup for  $p$  prime. Show that  $N(N(P)) = N(P)$  where  $N$  is the normalizer in  $G$ .

**1.37 Fall 2019 Midterm #3**

Show that there exist no simple groups of order 148.

**1.38 Fall 2019 Midterm #4**

Let  $p$  be a prime. Show that  $S_p = \langle \tau, \sigma \rangle$  where  $\tau$  is a transposition and  $\sigma$  is a  $p$ -cycle.

**1.39 Fall 2019 Midterm #5**

Let  $G$  be a nonabelian group of order  $p^3$  for  $p$  prime. Show that  $Z(G) = [G, G]$

**2 Commutative Algebra****2.1 Spring 2020 #5**

Let  $R$  be a ring and  $f : M \rightarrow N$  and  $g : N \rightarrow M$  be  $R$ -module homomorphisms such that  $g \circ f = \text{id}_M$ . Show that  $N \cong \text{im } f \oplus \ker g$ .

**2.2 Fall 2019 #3**

Let  $R$  be a ring with the property that for every  $a \in R$ ,  $a^2 = a$ .

- (a) Prove that  $R$  has characteristic 2.
- (b) Prove that  $R$  is commutative.

**2.3 Fall 2019 #6**

Let  $R$  be a commutative ring with multiplicative identity. Assume Zorn's Lemma.

- (a) Show that

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

is an ideal which is contained in any prime ideal.

- (b) Let  $r$  be an element of  $R$  not in  $N$ . Let  $S$  be the collection of all proper ideals of  $R$  not containing any positive power of  $r$ . Use Zorn's Lemma to prove that there is a prime ideal in  $S$ .

- (c) Suppose that  $R$  has exactly one prime ideal  $P$ . Prove that every element  $r$  of  $R$  is either nilpotent or a unit.

## 2.4 Spring 2019 #6

Let  $R$  be a commutative ring with 1.

Recall that  $x \in R$  is nilpotent iff  $x^n = 0$  for some positive integer  $n$ .

- (a) Show that every proper ideal of  $R$  is contained within a maximal ideal.  
 (b) Let  $J(R)$  denote the intersection of all maximal ideals of  $R$ .

Show that  $x \in J(R) \iff 1 + rx$  is a unit for all  $r \in R$ .

- (c) Suppose now that  $R$  is finite. Show that in this case  $J(R)$  consists precisely of the nilpotent elements in  $R$ .

## 2.5 Fall 2018 #7

Let  $R$  be a commutative ring.

- (a) Let  $r \in R$ . Show that the map

$$\begin{aligned} r \bullet : R &\longrightarrow R \\ x &\mapsto rx. \end{aligned}$$

is an  $R$ -module endomorphism of  $R$ .

- (b) We say that  $r$  is a **zero-divisor** if  $r \bullet$  is not injective. Show that if  $r$  is a zero-divisor and  $r \neq 0$ , then the kernel and image of  $R$  each consist of zero-divisors.  
 (c) Let  $n \geq 2$  be an integer. Show: if  $R$  has exactly  $n$  zero-divisors, then  $\#R \leq n^2$ .  
 (d) Show that up to isomorphism there are exactly two commutative rings  $R$  with precisely 2 zero-divisors.

You may use without proof the following fact: every ring of order 4 is isomorphic to exactly one of the following:

$$\frac{\mathbb{Z}}{4\mathbb{Z}}, \quad \frac{\frac{\mathbb{Z}}{2\mathbb{Z}}[t]}{(t^2 + t + 1)}, \quad \frac{\frac{\mathbb{Z}}{2\mathbb{Z}}[t]}{(t^2 - t)}, \quad \frac{\frac{\mathbb{Z}}{2\mathbb{Z}}[t]}{(t^2)}.$$

## 2.6 Spring 2018 #5

Let

$$M = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \quad \text{and} \quad N = \begin{pmatrix} x & u \\ -y & -v \end{pmatrix}$$

over a commutative ring  $R$ , where  $b$  and  $x$  are units of  $R$ . Prove that

$$MN = \begin{pmatrix} 0 & 0 \\ 0 & * \end{pmatrix} \implies MN = 0.$$

**2.7 Spring 2018 #8**

Let  $R = C[0, 1]$  be the ring of continuous real-valued functions on the interval  $[0, 1]$ . Let  $I$  be an ideal of  $R$ .

- (a) Show that if  $f \in I$ ,  $a \in [0, 1]$  are such that  $f(a) \neq 0$ , then there exists  $g \in I$  such that  $g(x) \geq 0$  for all  $x \in [0, 1]$ , and  $g(x) > 0$  for all  $x$  in some open neighborhood of  $a$ .
- (b) If  $I \neq R$ , show that the set  $Z(I) = \{x \in [0, 1] \mid f(x) = 0 \text{ for all } f \in I\}$  is nonempty.
- (c) Show that if  $I$  is maximal, then there exists  $x_0 \in [0, 1]$  such that  $I = \{f \in R \mid f(x_0) = 0\}$ .

**2.8 Fall 2017 #5**

A ring  $R$  is called *simple* if its only two-sided ideals are  $0$  and  $R$ .

- (a) Suppose  $R$  is a commutative ring with  $1$ . Prove  $R$  is simple if and only if  $R$  is a field.
- (b) Let  $k$  be a field. Show the ring  $M_n(k)$ ,  $n \times n$  matrices with entries in  $k$ , is a simple ring.

**2.9 Fall 2017 #6**

For a ring  $R$ , let  $U(R)$  denote the multiplicative group of units in  $R$ . Recall that in an integral domain  $R$ ,  $r \in R$  is called *irreducible* if  $r$  is not a unit in  $R$ , and the only divisors of  $r$  have the form  $ru$  with  $u$  a unit in  $R$ .

We call a non-zero, non-unit  $r \in R$  *prime* in  $R$  if  $r \mid ab \implies r \mid a$  or  $r \mid b$ . Consider the ring  $R = \{a + b\sqrt{-5} \mid a, b \in \mathbb{Z}\}$ .

- (a) Prove  $R$  is an integral domain.
- (b) Show  $U(R) = \{\pm 1\}$ .
- (c) Show  $3$ ,  $2 + \sqrt{-5}$ , and  $2 - \sqrt{-5}$  are irreducible in  $R$ .
- (d) Show  $3$  is not prime in  $R$ .
- (e) Conclude  $R$  is not a PID.

**2.10 Spring 2017 #3**

Let  $R$  be a commutative ring with  $1$ . Suppose that  $M$  is a free  $R$ -module with a finite basis  $X$ .

- a. Let  $I \trianglelefteq R$  be a proper ideal. Prove that  $M/IM$  is a free  $R/I$ -module with basis  $X'$ , where  $X'$  is the image of  $X$  under the canonical map  $M \rightarrow M/IM$ .
- b. Prove that any two bases of  $M$  have the same number of elements. You may assume that the result is true when  $R$  is a field.

**2.11 Spring 2017 #4**

- a. Let  $R$  be an integral domain with quotient field  $F$ . Suppose that  $p(x), a(x), b(x)$  are monic polynomials in  $F[x]$  with  $p(x) = a(x)b(x)$  and with  $p(x) \in R[x]$ ,  $a(x)$  not in  $R[x]$ , and both  $a(x), b(x)$  not constant. Prove that  $R$  is not a UFD. (You may assume Gauss' lemma)
- b. Prove that  $\mathbb{Z}[2\sqrt{2}]$  is not a UFD.

Hint: let  $p(x) = x^2 - 2$ .

**2.12 Spring 2016 #8**

Let  $R$  be a simple rng (a nonzero ring which is not assumed to have a 1, whose only two-sided ideals are  $(0)$  and  $R$ ) satisfying the following two conditions:

- i.  $R$  has no zero divisors, and  
ii. If  $x \in R$  with  $x \neq 0$  then  $2x \neq 0$ , where  $2x := x + x$ .

Prove the following:

- a. For each  $x \in R$  there is one and only one element  $y \in R$  such that  $x = 2y$ .  
b. Suppose  $x, y \in R$  such that  $x \neq 0$  and  $2(xy) = x$ , then  $yz = zy$  for all  $z \in R$ .

You can get partial credit for (b) by showing it in the case  $R$  has a 1.

**2.13 Fall 2015 #3**

Let  $R$  be a rng (a ring without 1) which contains an element  $u$  such that for all  $y \in R$ , there exists an  $x \in R$  such that  $xu = y$ .

Prove that  $R$  contains a maximal left ideal.

Hint: imitate the proof (using Zorn's lemma) in the case where  $R$  does have a 1.

**2.14 Fall 2015 #4**

Let  $R$  be a PID and  $(a_1) < (a_2) < \cdots$  be an ascending chain of ideals in  $R$ . Prove that for some  $n$ , we have  $(a_j) = (a_n)$  for all  $j \geq n$ .

**2.15 Spring 2015 #7**

Let  $R$  be a commutative ring, and  $S \subset R$  be a nonempty subset that does not contain 0 such that for all  $x, y \in S$  we have  $xy \in S$ . Let  $\mathcal{I}$  be the set of all ideals  $I \trianglelefteq R$  such that  $I \cap S = \emptyset$ .

Show that for every ideal  $I \in \mathcal{I}$ , there is an ideal  $J \in \mathcal{I}$  such that  $I \subset J$  and  $J$  is not properly contained in any other ideal in  $\mathcal{I}$ .

Prove that every such ideal  $J$  is prime.

**2.16 Fall 2014 #7**

Give a careful proof that  $\mathbb{C}[x, y]$  is not a PID.

**2.17 Fall 2014 #8**

Let  $R$  be a nonzero commutative ring without unit such that  $R$  does not contain a proper maximal ideal. Prove that for all  $x \in R$ , the ideal  $xR$  is proper. You may assume the axiom of choice.

**2.18 Spring 2014 #5**

Let  $R$  be a commutative ring and  $a \in R$ . Prove that  $a$  is not nilpotent  $\iff$  there exists a commutative ring  $S$  and a ring homomorphism  $\varphi : R \rightarrow S$  such that  $\varphi(a)$  is a unit.

Note: by definition,  $a$  is nilpotent  $\iff$  there is a natural number  $n$  such that  $a^n = 0$ .

**2.19 Spring 2014 #6**

Let  $R$  be a commutative ring with identity and let  $n$  be a positive integer.

- Prove that every surjective  $R$ -linear endomorphism  $T : R^n \rightarrow R^n$  is injective.
- Show that an injective  $R$ -linear endomorphism of  $R^n$  need not be surjective.

**2.20 Fall 2013 #3**

- Define *prime ideal*, give an example of a nontrivial ideal in the ring  $\mathbb{Z}$  that is not prime, and prove that it is not prime.
- Define *maximal ideal*, give an example of a nontrivial maximal ideal in  $\mathbb{Z}$  and prove that it is maximal.

**2.21 Fall 2013 #4**

Let  $R$  be a commutative ring with  $1 \neq 0$ . Recall that  $x \in R$  is *nilpotent* iff  $x^n = 0$  for some positive integer  $n$ .

- Show that the collection of nilpotent elements in  $R$  forms an ideal.
- Show that if  $x$  is nilpotent, then  $x$  is contained in every prime ideal of  $R$ .
- Suppose  $x \in R$  is not nilpotent and let  $S = \{x^n \mid n \in \mathbb{N}\}$ . There is at least one ideal of  $R$  disjoint from  $S$ , namely  $(0)$ . By Zorn's lemma the set of ideals disjoint from  $S$  has a maximal element with respect to inclusion, say  $I$ . In other words,  $I$  is disjoint from  $S$  and if  $J$  is any ideal disjoint from  $S$  with  $I \subseteq J \subseteq R$  then  $J = I$  or  $J = R$ .

Show that  $I$  is a prime ideal.

- Deduce from (a) and (b) that the set of nilpotent elements of  $R$  is the intersection of all prime ideals of  $R$ .

**2.22 Spring 2013 #1**

Let  $R$  be a commutative ring.

- Define a *maximal ideal* and prove that  $R$  has a maximal ideal.

- b. Show that an element  $r \in R$  is not invertible  $\iff r$  is contained in a maximal ideal.
- c. Let  $M$  be an  $R$ -module, and recall that for  $0 \neq \mu \in M$ , the *annihilator* of  $\mu$  is the set

$$\text{Ann}(\mu) = \{r \in R \mid r\mu = 0\}.$$

Suppose that  $I$  is an ideal in  $R$  which is maximal with respect to the property that there exists an element  $\mu \in M$  such that  $I = \text{Ann}(\mu)$  for some  $\mu \in M$ . In other words,  $I = \text{Ann}(\mu)$  but there does not exist  $\nu \in M$  with  $J = \text{Ann}(\nu) \subsetneq R$  such that  $I \subsetneq J$ .

Prove that  $I$  is a prime ideal.

## 2.23 Spring 2013 #2

- a. Define a *Euclidean domain*.
- b. Define a *unique factorization domain*.
- c. Is a Euclidean domain an UFD? Give either a proof or a counterexample with justification.
- d. Is a UFD a Euclidean domain? Give either a proof or a counterexample with justification.

## 3 Fields and Galois Theory

### 3.1 Spring 2020 #3

Let  $E$  be an extension field of  $F$  and  $\alpha \in E$  be algebraic of odd degree over  $F$ .

- a. Show that  $F(\alpha) = F(\alpha^2)$ .
- b. Prove that  $\alpha^{2020}$  is algebraic of odd degree over  $F$ .

### 3.2 Spring 2020 #4

Let  $f(x) = x^4 - 2 \in \mathbb{Q}[x]$ .

- a. Define what it means for a finite extension field  $E$  of a field  $F$  to be a Galois extension.
- b. Determine the Galois group  $\text{Gal}(E/\mathbb{Q})$  for the polynomial  $f(x)$ , and justify your answer carefully.
- c. Exhibit a subfield  $K$  in (b) such that  $\mathbb{Q} \leq K \leq E$  with  $K$  not a Galois extension over  $\mathbb{Q}$ . Explain.

### 3.3 Fall 2019 #4

Let  $F$  be a finite field with  $q$  elements.

Let  $n$  be a positive integer relatively prime to  $q$  and let  $\omega$  be a primitive  $n$ th root of unity in an extension field of  $F$ .

Let  $E = F[\omega]$  and let  $k = [E : F]$ .

- (a) Prove that  $n$  divides  $q^k - 1$ .



- (b) Let  $m$  be the order of  $q$  in  $\mathbb{Z}/n\mathbb{Z}$ . Prove that  $m$  divides  $k$ .
- (c) Prove that  $m = k$ .

### 3.4 Fall 2019 #7

Let  $\zeta_n$  denote a primitive  $n$ th root of  $1 \in \mathbb{Q}$ . You may assume the roots of the minimal polynomial  $p_n(x)$  of  $\zeta_n$  are exactly the primitive  $n$ th roots of 1.

Show that the field extension  $\mathbb{Q}(\zeta_n)$  over  $\mathbb{Q}$  is Galois and prove its Galois group is  $(\mathbb{Z}/n\mathbb{Z})^\times$ .

How many subfields are there of  $\mathbb{Q}(\zeta_{20})$ ?

### 3.5 Spring 2019 #2

Let  $F = \mathbb{F}_p$ , where  $p$  is a prime number.

- (a) Show that if  $\pi(x) \in F[x]$  is irreducible of degree  $d$ , then  $\pi(x)$  divides  $x^{p^d} - x$ .
- (b) Show that if  $\pi(x) \in F[x]$  is an irreducible polynomial that divides  $x^{p^n} - x$ , then  $\deg \pi(x)$  divides  $n$ .

### 3.6 Spring 2019 #8

Let  $\zeta = e^{2\pi i/8}$ .

- (a) What is the degree of  $\mathbb{Q}(\zeta)/\mathbb{Q}$ ?
- (b) How many quadratic subfields of  $\mathbb{Q}(\zeta)$  are there?
- (c) What is the degree of  $\mathbb{Q}(\zeta, \sqrt[4]{2})$  over  $\mathbb{Q}$ ?

### 3.7 Fall 2018 #3

Let  $F \subset K \subset L$  be finite degree field extensions. For each of the following assertions, give a proof or a counterexample.

- (a) If  $L/F$  is Galois, then so is  $K/F$ .
- (b) If  $L/F$  is Galois, then so is  $L/K$ .
- (c) If  $K/F$  and  $L/K$  are both Galois, then so is  $L/F$ .

### 3.8 Spring 2018 #2

Let  $f(x) = x^4 - 4x^2 + 2 \in \mathbb{Q}[x]$ .

- (a) Find the splitting field  $K$  of  $f$ , and compute  $[K : \mathbb{Q}]$ .
- (b) Find the Galois group  $G$  of  $f$ , both as an explicit group of automorphisms, and as a familiar abstract group to which it is isomorphic.
- (c) Exhibit explicitly the correspondence between subgroups of  $G$  and intermediate fields between  $\mathbb{Q}$  and  $K$ .

**3.9 Spring 2018 #3**

Let  $K$  be a Galois extension of  $\mathbb{Q}$  with Galois group  $G$ , and let  $E_1, E_2$  be intermediate fields of  $K$  which are the splitting fields of irreducible  $f_i(x) \in \mathbb{Q}[x]$ .

Let  $E = E_1 E_2 \subset K$ .

Let  $H_i = \text{Gal}(K/E_i)$  and  $H = \text{Gal}(K/E)$ .

- (a) Show that  $H = H_1 \cap H_2$ .
- (b) Show that  $H_1 H_2$  is a subgroup of  $G$ .
- (c) Show that

$$\text{Gal}(K/(E_1 \cap E_2)) = H_1 H_2.$$

**3.10 Fall 2017 #3**

Let  $F$  be a field. Let  $f(x)$  be an irreducible polynomial in  $F[x]$  of degree  $n$  and let  $g(x)$  be any polynomial in  $F[x]$ . Let  $p(x)$  be an irreducible factor (of degree  $m$ ) of the polynomial  $f(g(x))$ .

Prove that  $n$  divides  $m$ . Use this to prove that if  $r$  is an integer which is not a perfect square, and  $n$  is a positive integer then every irreducible factor of  $x^{2n} - r$  over  $\mathbb{Q}[x]$  has even degree.

**3.11 Fall 2017 #4**

- (a) Let  $f(x)$  be an irreducible polynomial of degree 4 in  $\mathbb{Q}[x]$  whose splitting field  $K$  over  $\mathbb{Q}$  has Galois group  $G = S_4$ .

Let  $\theta$  be a root of  $f(x)$ . Prove that  $\mathbb{Q}[\theta]$  is an extension of  $\mathbb{Q}$  of degree 4 and that there are no intermediate fields between  $\mathbb{Q}$  and  $\mathbb{Q}[\theta]$ .

- (b) Prove that if  $K$  is a Galois extension of  $\mathbb{Q}$  of degree 4, then there is an intermediate subfield between  $K$  and  $\mathbb{Q}$ .

**3.12 Spring 2017 #7**

Let  $F$  be a field and let  $f(x) \in F[x]$ .

- a. Define what a splitting field of  $f(x)$  over  $F$  is.
- b. Let  $F$  now be a finite field with  $q$  elements. Let  $E/F$  be a finite extension of degree  $n > 0$ . Exhibit an explicit polynomial  $g(x) \in F[x]$  such that  $E/F$  is a splitting field of  $g(x)$  over  $F$ . Fully justify your answer.
- c. Show that the extension  $E/F$  in (b) is a Galois extension.

**3.13 Spring 2017 #8**

- a. Let  $K$  denote the splitting field of  $x^5 - 2$  over  $\mathbb{Q}$ . Show that the Galois group of  $K/\mathbb{Q}$  is isomorphic to the group of invertible matrices

$$\begin{pmatrix} a & b \\ 0 & 1 \end{pmatrix} \quad \text{where } a \in \mathbb{F}_5^\times \text{ and } b \in \mathbb{F}_5.$$

- b. Determine all intermediate fields between  $K$  and  $\mathbb{Q}$  which are Galois over  $\mathbb{Q}$ .

### 3.14 Fall 2016 #4

Set  $f(x) = x^3 - 5 \in \mathbb{Q}[x]$ .

- Find the splitting field  $K$  of  $f(x)$  over  $\mathbb{Q}$ .
- Find the Galois group  $G$  of  $K$  over  $\mathbb{Q}$ .
- Exhibit explicitly the correspondence between subgroups of  $G$  and intermediate fields between  $\mathbb{Q}$  and  $K$ .

### 3.15 ★ Fall 2016 #5

How many monic irreducible polynomials over  $\mathbb{F}_p$  of prime degree  $\ell$  are there? Justify your answer.

### 3.16 Spring 2016 #2

Let  $K = \mathbb{Q}[\sqrt{2} + \sqrt{5}]$ .

- Find  $[K : \mathbb{Q}]$ .
- Show that  $K/\mathbb{Q}$  is Galois, and find the Galois group  $G$  of  $K/\mathbb{Q}$ .
- Exhibit explicitly the correspondence between subgroups of  $G$  and intermediate fields between  $\mathbb{Q}$  and  $K$ .

### 3.17 Spring 2016 #6

Let  $K$  be a Galois extension of a field  $F$  with  $[K : F] = 2015$ . Prove that  $K$  is an extension by radicals of the field  $F$ .

### 3.18 Fall 2015 #5

Let  $u = \sqrt{2 + \sqrt{2}}$ ,  $v = \sqrt{2 - \sqrt{2}}$ , and  $E = \mathbb{Q}(u)$ .

- Find (with justification) the minimal polynomial  $f(x)$  of  $u$  over  $\mathbb{Q}$ .
- Show  $v \in E$ , and show that  $E$  is a splitting field of  $f(x)$  over  $\mathbb{Q}$ .
- Determine the Galois group of  $E$  over  $\mathbb{Q}$  and determine all of the intermediate fields  $F$  such that  $\mathbb{Q} \subset F \subset E$ .

**3.19 Fall 2015 #6**

- a. Let  $G$  be a finite group. Show that there exists a field extension  $K/F$  with  $\text{Gal}(K/F) = G$ .

You may assume that for any natural number  $n$  there is a field extension with Galois group  $S_n$ .

- b. Let  $K$  be a Galois extension of  $F$  with  $|\text{Gal}(K/F)| = 12$ . Prove that there exists an intermediate field  $E$  of  $K/F$  with  $[E : F] = 3$ .
- c. With  $K/F$  as in (b), does an intermediate field  $L$  necessarily exist satisfying  $[L : F] = 2$ ? Give a proof or counterexample.

**3.20 Spring 2015 #2**

Let  $\mathbb{F}$  be a finite field.

- a. Give (with proof) the decomposition of the additive group  $(\mathbb{F}, +)$  into a direct sum of cyclic groups.
- b. The *exponent* of a finite group is the least common multiple of the orders of its elements. Prove that a finite abelian group has an element of order equal to its exponent.
- c. Prove that the multiplicative group  $(\mathbb{F}^\times, \cdot)$  is cyclic.

**3.21 Spring 2015 #5**

Let  $f(x) = x^4 - 5 \in \mathbb{Q}[x]$ .

- a. Compute the Galois group of  $f$  over  $\mathbb{Q}$ .
- b. Compute the Galois group of  $f$  over  $\mathbb{Q}(\sqrt{5})$ .

**3.22 Fall 2014 #1**

Let  $f \in \mathbb{Q}[x]$  be an irreducible polynomial and  $L$  a finite Galois extension of  $\mathbb{Q}$ . Let  $f(x) = g_1(x)g_2(x) \cdots g_r(x)$  be a factorization of  $f$  into irreducibles in  $L[x]$ .

- a. Prove that each of the factors  $g_i(x)$  has the same degree.
- b. Give an example showing that if  $L$  is not Galois over  $\mathbb{Q}$ , the conclusion of part (a) need not hold.

**3.23 Fall 2014 #3**

Consider the polynomial  $f(x) = x^4 - 7 \in \mathbb{Q}[x]$  and let  $E/\mathbb{Q}$  be the splitting field of  $f$ .

- a. What is the structure of the Galois group of  $E/\mathbb{Q}$ ?
- b. Give an explicit description of all of the intermediate subfields  $\mathbb{Q} \subset K \subset E$  in the form  $K = \mathbb{Q}(\alpha), \mathbb{Q}(\alpha, \beta), \dots$  where  $\alpha, \beta$ , etc are complex numbers. Describe the corresponding subgroups of the Galois group.

**3.24 Spring 2014 #3**

Let  $F \subset C$  be a field extension with  $C$  algebraically closed.

- Prove that the intermediate field  $C_{\text{alg}} \subset C$  consisting of elements algebraic over  $F$  is algebraically closed.
- Prove that if  $F \rightarrow E$  is an algebraic extension, there exists a homomorphism  $E \rightarrow C$  that is the identity on  $F$ .

**3.25 Spring 2014 #4**

Let  $E \subset \mathbb{C}$  denote the splitting field over  $\mathbb{Q}$  of the polynomial  $x^3 - 11$ .

- Prove that if  $n$  is a squarefree positive integer, then  $\sqrt{n} \notin E$ .

Hint: you can describe all quadratic extensions of  $\mathbb{Q}$  contained in  $E$ .

- Find the Galois group of  $(x^3 - 11)(x^2 - 2)$  over  $\mathbb{Q}$ .
- Prove that the minimal polynomial of  $11^{1/3} + 2^{1/2}$  over  $\mathbb{Q}$  has degree 6.

**3.26 Fall 2013 #5**

Let  $L/K$  be a finite extension of fields.

- Define what it means for  $L/K$  to be *separable*.
- Show that if  $K$  is a finite field, then  $L/K$  is always separable.
- Give an example of a finite extension  $L/K$  that is not separable.

**3.27 Fall 2013 #6**

Let  $K$  be the splitting field of  $x^4 - 2$  over  $\mathbb{Q}$  and set  $G = \text{Gal}(K/\mathbb{Q})$ .

- Show that  $K/\mathbb{Q}$  contains both  $\mathbb{Q}(i)$  and  $\mathbb{Q}(\sqrt[4]{2})$  and has degree 8 over  $\mathbb{Q}$ .
- Let  $N = \text{Gal}(K/\mathbb{Q}(i))$  and  $H = \text{Gal}(K/\mathbb{Q}(\sqrt[4]{2}))$ . Show that  $N$  is normal in  $G$  and  $NH = G$ .

Hint: what field is fixed by  $NH$ ?

- Show that  $\text{Gal}(K/\mathbb{Q})$  is generated by elements  $\sigma, \tau$ , of orders 4 and 2 respectively, with  $\tau\sigma\tau^{-1} = \sigma^{-1}$ .

Equivalently, show it is the dihedral group of order 8.

- How many distinct quartic subfields of  $K$  are there? Justify your answer.

**3.28 ★ Fall 2013 #7**

Let  $F = \mathbb{F}_2$  and let  $\bar{F}$  denote its algebraic closure.

- Show that  $\bar{F}$  is not a finite extension of  $F$ .
- Suppose that  $\alpha \in \bar{F}$  satisfies  $\alpha^{17} = 1$  and  $\alpha \neq 1$ . Show that  $F(\alpha)/F$  has degree 8.

**3.29 Spring 2013 #7**

Let  $f(x) = g(x)h(x) \in \mathbb{Q}[x]$  and  $E, B, C/\mathbb{Q}$  be the splitting fields of  $f, g, h$  respectively.

- Prove that  $\text{Gal}(E/B)$  and  $\text{Gal}(E/C)$  are normal subgroups of  $\text{Gal}(E/\mathbb{Q})$ .
- Prove that  $\text{Gal}(E/B) \cap \text{Gal}(E/C) = \{1\}$ .
- If  $B \cap C = \mathbb{Q}$ , show that  $\text{Gal}(E/B)\text{Gal}(E/C) = \text{Gal}(E/\mathbb{Q})$ .
- Under the hypothesis of (c), show that  $\text{Gal}(E/\mathbb{Q}) \cong \text{Gal}(E/B) \times \text{Gal}(E/C)$ .
- Use (d) to describe  $\text{Gal}(\mathbb{Q}[\alpha]/\mathbb{Q})$  where  $\alpha = \sqrt{2} + \sqrt{3}$ .

**3.30 Spring 2013 #8**

Let  $F$  be the field with 2 elements and  $K$  a splitting field of  $f(x) = x^6 + x^3 + 1$  over  $F$ . You may assume that  $f$  is irreducible over  $F$ .

- Show that if  $r$  is a root of  $f$  in  $K$ , then  $r^9 = 1$  but  $r^3 \neq 1$ .
- Find  $\text{Gal}(K/F)$  and express each intermediate field between  $F$  and  $K$  as  $F(\beta)$  for an appropriate  $\beta \in K$ .

**3.31 Fall 2012 #3**

Let  $f(x) \in \mathbb{Q}[x]$  be an irreducible polynomial of degree 5. Assume that  $f$  has all but two roots in  $\mathbb{R}$ . Compute the Galois group of  $f(x)$  over  $\mathbb{Q}$  and justify your answer.

**3.32 Fall 2012 #4**

Let  $f(x) \in \mathbb{Q}[x]$  be a polynomial and  $K$  be a splitting field of  $f$  over  $\mathbb{Q}$ . Assume that  $[K : \mathbb{Q}] = 1225$  and show that  $f(x)$  is solvable by radicals.

**3.33 Spring 2012 #1**

Suppose that  $F \subset E$  are fields such that  $E/F$  is Galois and  $|\text{Gal}(E/F)| = 14$ .

- Show that there exists a unique intermediate field  $K$  with  $F \subset K \subset E$  such that  $[K : F] = 2$ .
- Assume that there are at least two distinct intermediate subfields  $F \subset L_1, L_2 \subset E$  with  $[L_i : F] = 7$ . Prove that  $\text{Gal}(E/F)$  is nonabelian.

**3.34 Spring 2012 #4**

Let  $f(x) = x^7 - 3 \in \mathbb{Q}[x]$  and  $E/\mathbb{Q}$  be a splitting field of  $f$  with  $\alpha \in E$  a root of  $f$ .

- Show that  $E$  contains a primitive 7th root of unity.
- Show that  $E \neq \mathbb{Q}(\alpha)$ .

**3.35 Fall 2019 Midterm #6**

Compute the Galois group of  $f(x) = x^3 - 3x - 3 \in \mathbb{Q}[x]/\mathbb{Q}$ .

**3.36 Fall 2019 Midterm #7**

Show that a field  $k$  of characteristic  $p \neq 0$  is perfect  $\iff$  for every  $x \in k$  there exists a  $y \in k$  such that  $y^p = x$ .

**3.37 Fall 2019 Midterm #8**

Let  $k$  be a field of characteristic  $p \neq 0$  and  $f \in k[x]$  irreducible. Show that  $f(x) = g(x^{p^d})$  where  $g(x) \in k[x]$  is irreducible and separable. Conclude that every root of  $f$  has the same multiplicity  $p^d$  in the splitting field of  $f$  over  $k$ .

**3.38 Fall 2019 Midterm #9**

Let  $n \geq 3$  and  $\zeta_n$  be a primitive  $n$ th root of unity. Show that  $[\mathbb{Q}(\zeta_n + \zeta_n^{-1}) : \mathbb{Q}] = \varphi(n)/2$  for  $\varphi$  the totient function. 10. Let  $L/K$  be a finite normal extension - Show that if  $L/K$  is cyclic and  $E/K$  is normal with  $L/E/K$  then  $L/E$  and  $E/K$  are cyclic. - Show that if  $L/K$  is cyclic then there exists exactly one extension  $E/K$  of degree  $n$  with  $L/E/K$  for each divisor  $n$  of  $[L : K]$ .

**4 Modules****4.0.1 Fall 2019 Final #2**

Consider the  $\mathbb{Z}$ -submodule  $N$  of  $\mathbb{Z}^3$  spanned by  $f_1 = [-1, 0, 1], f_2 = [2, -3, 1], f_3 = [0, 3, 1], f_4 = [3, 1, 5]$ . Find a basis for  $N$  and describe  $\mathbb{Z}^3/N$ .

**4.0.2 Spring 2018 #6.**

Let

$$M = \{(w, x, y, z) \in \mathbb{Z}^4 \mid w + x + y + z \in 2\mathbb{Z}\},$$

and

$$N = \{(w, x, y, z) \in \mathbb{Z}^4 \mid 4 \mid (w - x), 4 \mid (x - y), 4 \mid (y - z)\}.$$

- (a) Show that  $N$  is a  $\mathbb{Z}$ -submodule of  $M$ .
- (b) Find vectors  $u_1, u_2, u_3, u_4 \in \mathbb{Z}^4$  and integers  $d_1, d_2, d_3, d_4$  such that

$$\{u_1, u_2, u_3, u_4\}$$

is a free basis for  $M$ , and

$$\{d_1 u_1, d_2 u_2, d_3 u_3, d_4 u_4\}$$

is a free basis for  $N$ .

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(c) Use the previous part to describe  $M/N$  as a direct sum of cyclic  $\mathbb{Z}$ -modules.

#### 4.0.3 Fall 2018 #6.

Let  $R$  be a commutative ring, and let  $M$  be an  $R$ -module. An  $R$ -submodule  $N$  of  $M$  is maximal if there is no  $R$ -module  $P$  with  $N \subsetneq P \subsetneq M$ .

- (a) Show that an  $R$ -submodule  $N$  of  $M$  is maximal  $\iff M/N$  is a simple  $R$ -module: i.e.,  $M/N$  is nonzero and has no proper, nonzero  $R$ -submodules.
- (b) Let  $M$  be a  $\mathbb{Z}$ -module. Show that a  $\mathbb{Z}$ -submodule  $N$  of  $M$  is maximal  $\iff \#M/N$  is a prime number.
- (c) Let  $M$  be the  $\mathbb{Z}$ -module of all roots of unity in  $\mathbb{C}$  under multiplication. Show that there is no maximal  $\mathbb{Z}$ -submodule of  $M$ .

#### 4.0.4 Spring 2018 #7.

Let  $R$  be a PID and  $M$  be an  $R$ -module. Let  $p$  be a prime element of  $R$ . The module  $M$  is called  $\langle p \rangle$ -primary if for every  $m \in M$  there exists  $k > 0$  such that  $p^k m = 0$ .

- (a) Suppose  $M$  is  $\langle p \rangle$ -primary. Show that if  $m \in M$  and  $t \in R$ ,  $t \notin \langle p \rangle$ , then there exists  $a \in R$  such that  $atm = m$ .
- (b) A submodule  $S$  of  $M$  is said to be *pure* if  $S \cap rM = rS$  for all  $r \in R$ . Show that if  $M$  is  $\langle p \rangle$ -primary, then  $S$  is pure if and only if  $S \cap p^k M = p^k S$  for all  $k \geq 0$ .

#### 4.0.5 Fall 2016 #6

Let  $R$  be a ring and  $f : M \rightarrow N$  and  $g : N \rightarrow M$  be  $R$ -module homomorphisms such that  $g \circ f = \text{id}_M$ . Show that  $N \cong \text{im } f \oplus \ker g$ .

#### 4.0.6 Spring 2016 #4

Let  $R$  be a ring with the following commutative diagram of  $R$ -modules, where each row represents a short exact sequence of  $R$ -modules:

$$\begin{array}{ccccccccc} 0 & \longrightarrow & A & \xrightarrow{f} & B & \xrightarrow{g} & C & \longrightarrow & 0 \\ & & \downarrow \alpha & & \downarrow \beta & & \downarrow \gamma & & \\ 0 & \longrightarrow & A' & \xrightarrow{f'} & B' & \xrightarrow{g'} & C' & \longrightarrow & 0 \end{array}$$

Prove that if  $\alpha$  and  $\gamma$  are isomorphisms then  $\beta$  is an isomorphism.

#### 4.0.7 Spring 2015 #8

Let  $R$  be a PID and  $M$  a finitely generated  $R$ -module.

- a. Prove that there are  $R$ -submodules

$$0 = M_0 \subset M_1 \subset \cdots \subset M_n = M$$



such that for all  $0 \leq i \leq n-1$ , the module  $M_{i+1}/M_i$  is cyclic.

- b. Is the integer  $n$  in part (a) uniquely determined by  $M$ ? Prove your answer.

#### 4.0.8 Fall 2012 #6

Let  $R$  be a ring and  $M$  an  $R$ -module. Recall that  $M$  is *Noetherian* iff any strictly increasing chain of submodule  $M_1 \subsetneq M_2 \subsetneq \cdots$  is finite. Call a proper submodule  $M' \subsetneq M$  *intersection-decomposable* if it can not be written as the intersection of two proper submodules  $M' = M_1 \cap M_2$  with  $M_i \subsetneq M$ .

Prove that for every Noetherian module  $M$ , any proper submodule  $N \subsetneq M$  can be written as a finite intersection  $N = N_1 \cap \cdots \cap N_k$  of intersection-indecomposable modules.

#### 4.0.9 Fall 2019 Final #1

Let  $A$  be an abelian group, and show  $A$  is a  $\mathbb{Z}$ -module in a unique way.

### 4.1 Torsion and the Structure Theorem

#### 4.1.1 Spring 2012 #5

Let  $M$  be a finitely generated module over a PID  $R$ .

- $M_t$  be the set of torsion elements of  $M$ , and show that  $M_t$  is a submodule of  $M$ .
- Show that  $M/M_t$  is torsion free.
- Prove that  $M \cong M_t \oplus F$  where  $F$  is a free module.

#### 4.1.2 Spring 2017 #5

Let  $R$  be an integral domain and let  $M$  be a nonzero torsion  $R$ -module.

- Prove that if  $M$  is finitely generated then the annihilator in  $R$  of  $M$  is nonzero.
- Give an example of a non-finitely generated torsion  $R$ -module whose annihilator is  $(0)$ , and justify your answer.

#### 4.1.3 ★ Fall 2019 #5

Let  $R$  be a ring and  $M$  an  $R$ -module.

Recall that the set of torsion elements in  $M$  is defined by

$$\text{Tor}(M) = \{m \in M \mid \exists r \in R, r \neq 0, rm = 0\}.$$

- Prove that if  $R$  is an integral domain, then  $\text{Tor}(M)$  is a submodule of  $M$ .
- Give an example where  $\text{Tor}(M)$  is not a submodule of  $M$ .
- If  $R$  has zero-divisors, prove that every non-zero  $R$ -module has non-zero torsion elements.

**4.1.4 ★ Spring 2019 #5.**

Let  $R$  be an integral domain. Recall that if  $M$  is an  $R$ -module, the *rank* of  $M$  is defined to be the maximum number of  $R$ -linearly independent elements of  $M$ .

- (a) Prove that for any  $R$ -module  $M$ , the rank of  $\text{Tor}(M)$  is 0.
- (b) Prove that the rank of  $M$  is equal to the rank of  $M/\text{Tor}(M)$ .
- (c) Suppose that  $M$  is a non-principal ideal of  $R$ .

Prove that  $M$  is torsion-free of rank 1 but not free.

**4.1.5 ★ Spring 2020 #6**

Let  $R$  be a ring with unity.

- a. Give a definition for a free module over  $R$ .
- b. Define what it means for an  $R$ -module to be torsion free.
- c. Prove that if  $F$  is a free module, then any short exact sequence of  $R$ -modules of the following form splits:

$$0 \longrightarrow N \longrightarrow M \longrightarrow F \longrightarrow 0.$$

- d. Let  $R$  be a PID. Show that any finitely generated  $R$ -module  $M$  can be expressed as a direct sum of a torsion module and a free module. You may assume that a finitely generated torsionfree module over a PID is free.

**4.1.6 Fall 2019 Final #3**

Let  $R = k[x]$  for  $k$  a field and let  $M$  be the  $R$ -module given by

$$M = \frac{k[x]}{(x-1)^3} \oplus \frac{k[x]}{(x^2+1)^2} \oplus \frac{k[x]}{(x-1)(x^2+1)^4} \oplus \frac{k[x]}{(x+2)(x^2+1)^2}.$$

Describe the elementary divisors and invariant factors of  $M$ .

**4.1.7 Fall 2019 Final #4**

Let  $I = (2, x)$  be an ideal in  $R = \mathbb{Z}[x]$ , and show that  $I$  is not a direct sum of nontrivial cyclic  $R$ -modules.

**4.1.8 Fall 2019 Final #5**

Let  $R$  be a PID. - Classify irreducible  $R$ -modules up to isomorphism. - Classify indecomposable  $R$ -modules up to isomorphism.

**4.1.9 Fall 2019 Final #6**

Let  $V$  be a finite-dimensional  $k$ -vector space and  $T : V \longrightarrow V$  a non-invertible  $k$ -linear map. Show that there exists a  $k$ -linear map  $S : V \longrightarrow V$  with  $T \circ S = 0$  but  $S \circ T \neq 0$ .

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#### 4.1.10 Fall 2019 Final #7

Let  $A \in M_n(\mathbb{C})$  with  $A^2 = A$ . Show that  $A$  is similar to a diagonal matrix, and exhibit an explicit diagonal matrix similar to  $A$ .

#### 4.1.11 Fall 2019 Final #8

Exhibit the rational canonical form for -  $A \in M_6(\mathbb{Q})$  with minimal polynomial  $(x-1)(x^2+1)^2$ . -  $A \in M_{10}(\mathbb{Q})$  with minimal polynomial  $(x^2+1)^2(x^3+1)$ .

#### 4.1.12 Fall 2019 Final #9

Exhibit the rational and Jordan canonical forms for the following matrix  $A \in M_4(\mathbb{C})$ :

$$A = \begin{pmatrix} 2 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ -2 & -2 & 0 & 1 \\ -2 & 0 & -1 & -2 \end{pmatrix}.$$

#### 4.1.13 Fall 2019 Final #10

Show that the eigenvalues of a Hermitian matrix  $A$  are real and that  $A = PDP^{-1}$  where  $P$  is an invertible matrix with orthogonal columns.

## 5 Linear Algebra: Canonical Forms

### 5.1 Spring 2020 #7

Let

$$A = \begin{bmatrix} 2 & 0 & 0 \\ 4 & 6 & 1 \\ -16 & -16 & -2 \end{bmatrix} \in M_3(\mathbb{C}).$$

- Find the Jordan canonical form  $J$  of  $A$ .
- Find an invertible matrix  $P$  such that  $P^{-1}AP = J$ . You should not need to compute  $P^{-1}$ .
- Write down the minimal polynomial of  $A$ .

### 5.2 Spring 2020 #8

Let  $T : V \rightarrow V$  be a linear transformation where  $V$  is a finite-dimensional vector space over  $\mathbb{C}$ . Prove the Cayley-Hamilton theorem: if  $p(x)$  is the characteristic polynomial of  $T$ , then  $p(T) = 0$ . You may use canonical forms.

**5.3 Spring 2012 #8**

Let  $V$  be a finite-dimensional vector space over a field  $k$  and  $T : V \rightarrow V$  a linear transformation.

- Provide a definition for the *minimal polynomial* in  $k[x]$  for  $T$ .
- Define the *characteristic polynomial* for  $T$ .
- Prove the Cayley-Hamilton theorem: the linear transformation  $T$  satisfies its characteristic polynomial.

**5.4 Spring 2019 #7**

Let  $p$  be a prime number. Let  $A$  be a  $p \times p$  matrix over a field  $F$  with 1 in all entries except 0 on the main diagonal.

Determine the Jordan canonical form (JCF) of  $A$

- When  $F = \mathbb{Q}$ ,
- When  $F = \mathbb{F}_p$ .

Hint: In both cases, all eigenvalues lie in the ground field. In each case find a matrix  $P$  such that  $P^{-1}AP$  is in JCF.

**5.5 Spring 2018 #4**

Let

$$A = \begin{bmatrix} 0 & 1 & -2 \\ 1 & 1 & -3 \\ 1 & 2 & -4 \end{bmatrix} \in M_3(\mathbb{C})$$

- Find the Jordan canonical form  $J$  of  $A$ .
- Find an invertible matrix  $P$  such that  $P^{-1}AP = J$ .

You should not need to compute  $P^{-1}$ .

**5.6 Spring 2017 #6**

Let  $A$  be an  $n \times n$  matrix with all entries equal to 0 except for the  $n - 1$  entries just above the diagonal being equal to 2.

- What is the Jordan canonical form of  $A$ , viewed as a matrix in  $M_n(\mathbb{C})$ ?
- Find a nonzero matrix  $P \in M_n(\mathbb{C})$  such that  $P^{-1}AP$  is in Jordan canonical form.

**5.7 Spring 2016 #1**

Let

$$A = \begin{pmatrix} -3 & 3 & -2 \\ -7 & 6 & -3 \\ 1 & -1 & 2 \end{pmatrix} \in M_3(\mathbb{C}).$$

- Find the Jordan canonical form  $J$  of  $A$ .
- Find an invertible matrix  $P$  such that  $P^{-1}AP = J$ . You do not need to compute  $P^{-1}$ .

**5.8 Spring 2016 #7**

Let  $D = \mathbb{Q}[x]$  and let  $M$  be a  $\mathbb{Q}[x]$ -module such that

$$M \cong \frac{\mathbb{Q}[x]}{(x-1)^3} \oplus \frac{\mathbb{Q}[x]}{(x^2+1)^3} \oplus \frac{\mathbb{Q}[x]}{(x-1)(x^2+1)^5} \oplus \frac{\mathbb{Q}[x]}{(x+2)(x^2+1)^2}.$$

Determine the elementary divisors and invariant factors of  $M$ .

**5.9 Spring 2015 #6**

Let  $F$  be a field and  $n$  a positive integer, and consider

$$A = \begin{bmatrix} 1 & \dots & 1 \\ & \ddots & \\ 1 & \dots & 1 \end{bmatrix} \in M_n(F).$$

Show that  $A$  has a Jordan normal form over  $F$  and find it.

Hint: treat the cases  $n \cdot 1 \neq 0$  in  $F$  and  $n \cdot 1 = 0$  in  $F$  separately.

**5.10 Fall 2014 #5**

Let  $T$  be a  $5 \times 5$  complex matrix with characteristic polynomial  $\chi(x) = (x-3)^5$  and minimal polynomial  $m(x) = (x-3)^2$ . Determine all possible Jordan forms of  $T$ .

**5.11 Spring 2013 #5**

Let  $T : V \rightarrow V$  be a linear map from a 5-dimensional  $\mathbb{C}$ -vector space to itself and suppose  $f(T) = 0$  where  $f(x) = x^2 + 2x + 1$ .

- Show that there does not exist any vector  $v \in V$  such that  $Tv = v$ , but there *does* exist a vector  $w \in V$  such that  $T^2w = w$ .
- Give all of the possible Jordan canonical forms of  $T$ .

**5.12 ★ Spring 2012 #7**

Consider the following matrix as a linear transformation from  $V := \mathbb{C}^5$  to itself:

$$A = \begin{pmatrix} -1 & 1 & 0 & 0 & 0 \\ -4 & 3 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 2 \end{pmatrix}.$$

- Find the invariant factors of  $A$ .
- Express  $V$  in terms of a direct sum of indecomposable  $\mathbb{C}[x]$ -modules.
- Find the Jordan canonical form of  $A$ .

**6 Linear Algebra: Diagonalizability****6.1 Spring 2015 #3**

Let  $F$  be a field and  $V$  a finite dimensional  $F$ -vector space, and let  $A, B : V \rightarrow V$  be commuting  $F$ -linear maps. Suppose there is a basis  $\mathcal{B}_1$  with respect to which  $A$  is diagonalizable and a basis  $\mathcal{B}_2$  with respect to which  $B$  is diagonalizable.

Prove that there is a basis  $\mathcal{B}_3$  with respect to which  $A$  and  $B$  are both diagonalizable.

**6.2 Spring 2013 #6**

Let  $V$  be a finite dimensional vector space over a field  $F$  and let  $T : V \rightarrow V$  be a linear operator with characteristic polynomial  $f(x) \in F[x]$ .

- Show that  $f(x)$  is irreducible in  $F[x] \iff$  there are no proper nonzero subspaces  $W < V$  with  $T(W) \subseteq W$ .
- If  $f(x)$  is irreducible in  $F[x]$  and the characteristic of  $F$  is 0, show that  $T$  is diagonalizable when we extend the field to its algebraic closure.

**6.3 Spring 2019 #1**

Let  $A$  be a square matrix over the complex numbers. Suppose that  $A$  is nonsingular and that  $A^{2019}$  is diagonalizable over  $\mathbb{C}$ .

Show that  $A$  is also diagonalizable over  $\mathbb{C}$ .

**6.4 Fall 2017 #7**

Let  $F$  be a field and let  $V$  and  $W$  be vector spaces over  $F$ .

Make  $V$  and  $W$  into  $F[x]$ -modules via linear operators  $T$  on  $V$  and  $S$  on  $W$  by defining  $X \cdot v = T(v)$  for all  $v \in V$  and  $X \cdot w = S(w)$  for all  $w \in W$ .

Denote the resulting  $F[x]$ -modules by  $V_T$  and  $W_S$  respectively.

- (a) Show that an  $F[x]$ -module homomorphism from  $V_T$  to  $W_S$  consists of an  $F$ -linear transformation  $R : V \rightarrow W$  such that  $RT = SR$ .
- (b) Show that  $VT \cong WS$  as  $F[x]$ -modules  $\iff$  there is an  $F$ -linear isomorphism  $P : V \rightarrow W$  such that  $T = P^{-1}SP$ .
- (c) Recall that a module  $M$  is *simple* if  $M \neq 0$  and any proper submodule of  $M$  must be zero. Suppose that  $V$  has dimension 2. Give an example of  $F, T$  with  $V_T$  simple.
- (d) Assume  $F$  is algebraically closed. Prove that if  $V$  has dimension 2, then any  $V_T$  is not simple.

## 6.5 Fall 2016 #2

Let  $A, B$  be two  $n \times n$  matrices with the property that  $AB = BA$ . Suppose that  $A$  and  $B$  are diagonalizable. Prove that  $A$  and  $B$  are *simultaneously* diagonalizable.

## 7 Linear Algebra: Misc

### 7.1 Fall 2012 #7

Let  $k$  be a field of characteristic zero and  $A, B \in M_n(k)$  be two square  $n \times n$  matrices over  $k$  such that  $AB - BA = A$ . Prove that  $\det A = 0$ .

Moreover, when the characteristic of  $k$  is 2, find a counterexample to this statement.

### 7.2 Fall 2012 #8

Prove that any nondegenerate matrix  $X \in M_n(\mathbb{R})$  can be written as  $X = UT$  where  $U$  is orthogonal and  $T$  is upper triangular.

### 7.3 Fall 2012 #5

Let  $U$  be an infinite-dimensional vector space over a field  $k$ ,  $f : U \rightarrow U$  a linear map, and  $\{u_1, \dots, u_m\} \subset U$  vectors such that  $U$  is generated by  $\{u_1, \dots, u_m, f^d(u_1), \dots, f^d(u_m)\}$  for some  $d \in \mathbb{N}$ .

Prove that  $U$  can be written as a direct sum  $U \cong V \oplus W$  such that

1.  $V$  has a basis consisting of some vector  $v_1, \dots, v_n, f^d(v_1), \dots, f^d(v_n)$  for some  $d \in \mathbb{N}$ , and
2.  $W$  is finite-dimensional.

Moreover, prove that for any other decomposition  $U \cong V' \oplus W'$ , one has  $W' \cong W$ .

### 7.4 Fall 2015 #7

- a. Show that two  $3 \times 3$  matrices over  $\mathbb{C}$  are similar  $\iff$  their characteristic polynomials are equal and their minimal polynomials are equal.
- b. Does the conclusion in (a) hold for  $4 \times 4$  matrices? Justify your answer with a proof or counterexample.

**7.5 Fall 2018 #4**

Let  $V$  be a finite dimensional vector space over a field (the field is not necessarily algebraically closed).

Let  $\varphi : V \rightarrow V$  be a linear transformation. Prove that there exists a decomposition of  $V$  as  $V = U \oplus W$ , where  $U$  and  $W$  are  $\varphi$ -invariant subspaces of  $V$ ,  $\varphi|_U$  is nilpotent, and  $\varphi|_W$  is nonsingular.

**7.6 Fall 2018 #5**

Let  $A$  be an  $n \times n$  matrix.

- (a) Suppose that  $v$  is a column vector such that the set  $\{v, Av, \dots, A^{n-1}v\}$  is linearly independent. Show that any matrix  $B$  that commutes with  $A$  is a polynomial in  $A$ .
- (b) Show that there exists a column vector  $v$  such that the set  $\{v, Av, \dots, A^{n-1}v\}$  is linearly independent  $\iff$  the characteristic polynomial of  $A$  equals the minimal polynomial of  $A$ .

**7.7 Fall 2019 #8**

Let  $\{e_1, \dots, e_n\}$  be a basis of a real vector space  $V$  and let

$$\Lambda := \left\{ \sum r_i e_i \mid r_i \in \mathbb{Z} \right\}$$

Let  $\cdot$  be a non-degenerate ( $v \cdot w = 0$  for all  $w \in V \iff v = 0$ ) symmetric bilinear form on  $V$  such that the Gram matrix  $M = (e_i \cdot e_j)$  has integer entries.

Define the dual of  $\Lambda$  to be

$$\Lambda^\vee := \{v \in V \mid v \cdot x \in \mathbb{Z} \text{ for all } x \in \Lambda\}.$$

- (a) Show that  $\Lambda \subset \Lambda^\vee$ .
- (b) Prove that  $\det M \neq 0$  and that the rows of  $M^{-1}$  span  $\Lambda^\vee$ .
- (c) Prove that  $\det M = |\Lambda^\vee / \Lambda|$ .

**7.8 Spring 2012 #6**

Let  $k$  be a field and let the group  $G = \text{GL}(m, k) \times \text{GL}(n, k)$  acts on the set of  $m \times n$  matrices  $M_{m,n}(k)$  as follows:

$$(A, B) \cdot X = AXB^{-1}$$

where  $(A, B) \in G$  and  $X \in M_{m,n}(k)$ .

- a. State what it means for a group to act on a set. Prove that the above definition yields a group action.
- b. Exhibit with justification a subset  $S$  of  $M_{m,n}(k)$  which contains precisely one element of each orbit under this action.



**7.9 Spring 2014 #7**

Let  $G = \text{GL}(3, \mathbb{Q}[x])$  be the group of invertible  $3 \times 3$  matrices over  $\mathbb{Q}[x]$ . For each  $f \in \mathbb{Q}[x]$ , let  $S_f$  be the set of  $3 \times 3$  matrices  $A$  over  $\mathbb{Q}[x]$  such that  $\det(A) = cf(x)$  for some nonzero constant  $c \in \mathbb{Q}$ .

- a. Show that for  $(P, Q) \in G \times G$  and  $A \in S_f$ , the formula

$$(P, Q) \cdot A := PAQ^{-1}$$

gives a well defined map  $G \times G \times S_f \rightarrow S_f$  and show that this map gives a group action of  $G \times G$  on  $S_f$ .

- b. For  $f(x) = x^3(x^2 + 1)^2$ , give one representative from each orbit of the group action in (a), and justify your assertion.

**7.10 Fall 2014 #4**

Let  $F$  be a field and  $T$  an  $n \times n$  matrix with entries in  $F$ . Let  $I$  be the ideal consisting of all polynomials  $f \in F[x]$  such that  $f(T) = 0$ .

Show that the following statements are equivalent about a polynomial  $g \in I$ :

- a.  $g$  is irreducible.  
b. If  $k \in F[x]$  is nonzero and of degree strictly less than  $g$ , then  $k[T]$  is an invertible matrix.

**7.11 Fall 2015 #8**

Let  $V$  be a vector space over a field  $F$  and  $V^\vee$  its dual. A *symmetric bilinear form*  $(\cdot, \cdot)$  on  $V$  is a map  $V \times V \rightarrow F$  satisfying

$$(av_1 + bv_2, w) = a(v_1, w) + b(v_2, w) \quad \text{and} \quad (v_1, v_2) = (v_2, v_1)$$

for all  $a, b \in F$  and  $v_1, v_2 \in V$ . The form is *nondegenerate* if the only element  $w \in V$  satisfying  $(v, w) = 0$  for all  $v \in V$  is  $w = 0$ .

Suppose  $(\cdot, \cdot)$  is a nondegenerate symmetric bilinear form on  $V$ . If  $W$  is a subspace of  $V$ , define

$$W^\perp := \{v \in V \mid (v, w) = 0 \text{ for all } w \in W\}.$$

- a. Show that if  $X, Y$  are subspaces of  $V$  with  $Y \subset X$ , then  $X^\perp \subseteq Y^\perp$ .  
b. Define an injective linear map

$$\psi : Y^\perp / X^\perp \hookrightarrow (X/Y)^\vee$$

which is an isomorphism if  $V$  is finite dimensional.