

Math 395
Homework 2
Due: 2/8/2024

Name: Avinash Iyer

Collaborators: Nate Hall, Nora Manukyan, Gianluca Crescenzo, Isaac Ochoa, Jamie Perez-Schere, Timothy Rainone

Problem 1

Let R be a ring with identity and I an ideal in R .

- (a) We will prove that if I contains a unit, then $I = R$.

Specifically, by the definition of a unit u , for all $a \in R$, $ua = au = u$.

If $u \in I$, then by the definition of ideal, $au \in I$ and $ua \in I$ for all $a \in R$. Therefore, $a \in I$ for all $a \in R$, meaning $I = R$.

- (b) Let F be a field. We will show that if I is an ideal in F , then $I = \{0_F\}$ or $I = F$.

Clearly, $I = \{0_F\}$ is an ideal — I is closed under subtraction, multiplication, and multiplication by elements of F (as for $a \in F$, $a \cdot 0_F = 0_F \cdot a = 0_F$).

Suppose that I contains at least one element, a , where $a \neq 0_F$. Then, since $a \neq 0_F$, there is a multiplicative identity for a , $1/a$ such that $a \cdot 1/a = 1/a \cdot a = 1_F$. Since I is an ideal, this means I contains $a \cdot 1/a$ as I is closed under multiplication by elements of the ring.

Therefore, I contains a unit of F (namely, 1_F), meaning $I = F$ by the result from (a).

Problem 2

Let I, J be ideals in ring R . Define $I + J = \{i + j \mid i \in I, j \in J\}$. This is referred to as the sum of the ideals.

- (a) We will prove that $I + J$ is an ideal in R that contains I and J .

To start, since I and J are ideals in R , I and J are each subrings of R , meaning both I and J contain 0_R . Therefore, taking $j = 0_R$, we find that $\{i + 0_R \mid i \in I\} \subseteq I + J$, and similarly, taking $i = 0_R$, we find that $\{0_R + j \mid j \in J\} \subseteq I + J$. These sets are, respectively, I and J , meaning I and J are both subsets of $I + J$.

We will now show $I + J$ is an ideal in R . First, $I + J$ is non-empty since, as exhibited earlier, both I and J are subrings, meaning $0_R \in I$ and $0_R \in J$, so $0_R + 0_R = 0_R \in I + J$. Let $x, y \in I + J$. Then, $x = x_i + x_j$ and $y = y_i + y_j$ for some $x_i, y_i \in I$ and $x_j, y_j \in J$. Then,

$$\begin{aligned} x - y &= (x_i + x_j) - (y_i + y_j) \\ &= (x_i - y_i) + (x_j - y_j), \end{aligned}$$

which is an element of $I + J$. Similarly,

$$\begin{aligned} xy &= (x_i + x_j)(y_i + y_j) \\ &= (x_i y_i) + (x_j y_j + x_i y_j + x_j y_i). \end{aligned}$$

Since $x_i y_i \in I$, as I is a subring, and $x_j y_j \in J$, as J is a subring, as well as $x_i y_j \in J$ and $x_j y_i \in J$ as J is an ideal, we have that $x_j y_j + x_i y_j + x_j y_i \in J$, so $xy \in I + J$.

Finally, we will show that $I + J$ is closed under multiplication by elements from R . Let $r \in R$, $a \in I + J$. Then, $a = a_i + a_j$ for $a_i \in I$ and $a_j \in J$. So,

$$\begin{aligned} ra &= r(a_i + a_j) \\ &= ra_i + ra_j, \end{aligned}$$

and

$$\begin{aligned} ar &= (a_i + a_j)r \\ &= a_i r + a_j r, \end{aligned}$$

and since I and J are both ideals, $ra_i, a_i r \in I$ and $ra_j, a_j r \in J$, so $ar, ra \in I + J$.

Therefore, $I + J$ is an ideal that contains I and J .

- (b) Let $a, b \in \mathbf{Z}$. We will show that $a\mathbf{Z} + b\mathbf{Z} = \gcd(a, b)\mathbf{Z}$.

By Bezout's identity, it is the case that there are integers x and y such that $xa + yb = \gcd(a, b)$. Since $xa \in a\mathbf{Z}$, and $yb \in b\mathbf{Z}$, as $a\mathbf{Z}$ and $b\mathbf{Z}$ are ideals in \mathbf{Z} , it is the case that for any $n \in \mathbf{Z}$, $n(xa + yb) \in a\mathbf{Z} + b\mathbf{Z}$. Therefore, $\gcd(a, b)\mathbf{Z} \subseteq a\mathbf{Z} + b\mathbf{Z}$.

For any $na + mb \in a\mathbf{Z} + b\mathbf{Z}$, there exist $k, \ell \in \mathbf{Z}$ such that $na = k \gcd(a, b)$ and $mb = \ell \gcd(a, b)$, by definition of greatest common divisor. Therefore, $na + mb = (k + \ell) \gcd(a, b) \in \gcd(a, b)\mathbf{Z}$, so $a\mathbf{Z} + b\mathbf{Z} \subseteq \gcd(a, b)\mathbf{Z}$.

Since $\gcd(a, b)\mathbf{Z} \subseteq a\mathbf{Z} + b\mathbf{Z}$, and $a\mathbf{Z} + b\mathbf{Z} \subseteq \gcd(a, b)\mathbf{Z}$, it is the case that $a\mathbf{Z} + b\mathbf{Z} = \gcd(a, b)\mathbf{Z}$.

- (c) We will prove that if $\gcd(a, b) = 1$, then $a\mathbf{Z} \cap b\mathbf{Z} = ab\mathbf{Z}$.

To start, since a divides all members of $ab\mathbf{Z}$, $ab\mathbf{Z} \subseteq a\mathbf{Z}$, and since b divides all members of $ab\mathbf{Z}$, $ab\mathbf{Z} \subseteq b\mathbf{Z}$, meaning $ab\mathbf{Z} \subseteq a\mathbf{Z} \cap b\mathbf{Z}$.

Let $k \in a\mathbf{Z} \cap b\mathbf{Z}$. Then, k is a common multiple of a and b . Therefore, k is an integer multiple of $\text{lcm}(a, b)$, or $\frac{ab}{\gcd(a, b)}$. Since $\gcd(a, b) = 1$, k is an integer multiple of ab . Therefore, $k \in ab\mathbf{Z}$, meaning $a\mathbf{Z} \cap b\mathbf{Z} \subseteq ab\mathbf{Z}$.

Since $ab\mathbf{Z} \subseteq a\mathbf{Z} \cap b\mathbf{Z}$, and $a\mathbf{Z} \cap b\mathbf{Z} \subseteq ab\mathbf{Z}$, it is the case that $ab\mathbf{Z} = a\mathbf{Z} \cap b\mathbf{Z}$.

Problem 3

Let p be a prime number and let T denote the set of rational numbers in reduced form whose denominators are not divisible by p .

- (a) We will prove that T is a ring by showing closure under addition, identity and inverse under addition, commutativity of addition, closure under multiplication, associativity under multiplication, and distribution of multiplication over addition.

Let $\frac{a}{b}, \frac{c}{d} \in T$ denote such rational numbers in lowest terms that satisfy the condition that p does not divide b and d , meaning that p is not a prime factor of either b or d . Then,

$$\frac{a}{b} + \frac{c}{d} = \frac{ad + bc}{bd},$$

and since the prime factors of bd are precisely the prime factors multiplied by the prime factors of d , and p is not a prime factor of b or d , p is not a prime factor of bd , meaning p does not divide bd . Therefore, T is closed under addition.

The additive identity in lowest terms in T is inherited from the rational numbers — namely, 0. Since p does not divide 0, it is the case that T contains the additive identity.

The additive inverse to $\frac{a}{b} \in T$ is $\frac{-a}{b} \in T$; since p does not divide b by definition, it is the case that $\frac{-a}{b}$ satisfies the necessary condition for T .

Since addition under T is inherited from addition under the rational numbers, addition in T is commutative, meaning T is an abelian group under addition.

Let $\frac{a}{b}, \frac{c}{d} \in T$, meaning p does not divide c and p does not divide d . Then,

$$\left(\frac{a}{b}\right) \left(\frac{c}{d}\right) = \frac{ac}{bd},$$

so by the same logic as with addition, p does not divide bd , meaning T is closed under multiplication.

Since multiplication is associative and distributive under the rational numbers, and T inherits these properties, it is the case that multiplication is associative and distributes over the rational numbers.

Therefore, T satisfies the necessary requirements for a ring.

- (b) Let I be the set of elements in T such that the numerator is divisible by p . We will show that I is an ideal by showing that I is a subring and multiplication by any element of T yields an element of I .

Since $0 \in I$, as the rational number 0 is divisible by every number, it is the case that I is non-empty. Let $\frac{a}{b}, \frac{c}{d} \in I$. Then, $a = pk$ and $c = p\ell$ for some k and ℓ . Thus,

$$\begin{aligned} \frac{a}{b} - \frac{c}{d} &= \frac{pk}{b} - \frac{p\ell}{d} \\ &= \frac{pkd - p\ell b}{bd} \\ &= \frac{p(kd - \ell b)}{bd}, \end{aligned}$$

meaning that I is closed under subtraction. Similarly,

$$\begin{aligned} \left(\frac{a}{b}\right) \left(\frac{c}{d}\right) &= \frac{(pk)(p\ell)}{bd} \\ &= \frac{p(pk\ell)}{bd}, \end{aligned}$$

meaning I is closed under multiplication.

- (c) We will show that T/I has p distinct cosets.

To start, we will show that for some $p \nmid b$, we will show that, modulo p , $\{0, b, 2b, \dots, (p-1)b\}$ are distinct. Suppose toward contradiction that $kb \equiv \ell b$ modulo p for some $k, \ell \in \{0, 1, \dots, p-1\}$. Then, $kb - \ell b \equiv 0$ modulo p , implying that $p|b(k - \ell)$. However, since $p \nmid b$, it is the case that $p|(k - \ell)$. However, since $k, \ell \in \{0, 1, \dots, p-1\}$, $p|(k - \ell)$ if and only if $k = \ell$.

By the definition of the equivalence relation of ideals,

$$\frac{a}{b} \sim \frac{k}{1}$$

if

$$\frac{a}{b} - \frac{k}{1} \in I$$

for some $k \in \{0, 1, \dots, p-1\}$. Therefore, $\frac{a-kb}{b} \in I$, so $p|a - kb$, so $a - kb \equiv 0$ modulo p . Therefore, $a \equiv kb$ modulo p . Since p is prime, and $p \nmid b$, we can take inverses to find $\frac{a}{b} \equiv k$ modulo p .

Therefore, the cosets of T/I are the $\left[\frac{k}{1}\right]_{T/I}$ that each $\frac{a}{b} \in T$ is equal to within the quotient ring.

(d) Let $\varphi : T/I \rightarrow \mathbf{Z}/p\mathbf{Z}$ be defined as $\varphi\left(\frac{a}{b}\right) = \left[\frac{a}{b}\right]_p$. We will show that φ is an isomorphism.

Let $\left[\frac{a}{b}\right]_{T/I} = \left[\frac{c}{d}\right]_{T/I}$. Then, $ad - bc \equiv 0$ modulo p . Applying φ to both sides, we get that $\left[\frac{a}{b}\right]_p = \left[\frac{c}{d}\right]_p$, meaning $ad - bc \equiv 0$ modulo p . Therefore, φ is well-defined.

We will now show that φ is a ring homomorphism. Let $\frac{a}{b}, \frac{c}{d} \in T/I$. Then,

$$\varphi\left(\left(\frac{a}{b}\right)\left(\frac{c}{d}\right)\right) = \left[\frac{a}{b} \frac{c}{d}\right]_p,$$

and by the properties of $\mathbf{Z}/p\mathbf{Z}$,

$$\begin{aligned} &= \left[\frac{a}{b}\right]_p \left[\frac{c}{d}\right]_p \\ &= \varphi\left(\frac{a}{b}\right) \varphi\left(\frac{c}{d}\right). \end{aligned}$$

Similarly,

$$\varphi\left(\frac{a}{b} + \frac{c}{d}\right) = \left[\frac{a}{b} + \frac{c}{d}\right]_p,$$

and by the properties of $\mathbf{Z}/p\mathbf{Z}$,

$$\begin{aligned} &= \left[\frac{a}{b}\right]_p + \left[\frac{c}{d}\right]_p \\ &= \varphi\left(\frac{a}{b}\right) + \varphi\left(\frac{c}{d}\right). \end{aligned}$$

Therefore, φ is a ring homomorphism.

We will now show that φ is a bijection. Clearly, φ is surjective, as we can select any $\frac{a}{b} \in T/I$ such that $\frac{a}{b} \in \mathbf{Z}/p\mathbf{Z}$. To show that φ is injective, let $\varphi\left(\frac{a}{b}\right) = \varphi\left(\frac{c}{d}\right)$. Then,

$$\left[\frac{a}{b}\right]_p = \left[\frac{c}{d}\right]_p,$$

so

$$\frac{a}{b} \equiv \frac{c}{d} \text{ modulo } p.$$

Therefore, by the definition of equivalence modulo p ,

$$ad - bc \equiv 0 \text{ modulo } p,$$

so

$$\frac{a}{d} \sim_I \frac{c}{d}.$$

Since φ is a bijective ring homomorphism, φ is an isomorphism, meaning $T/I \cong \mathbf{Z}/p\mathbf{Z}$.

Problem 5

Let $\varphi : R \rightarrow S$ be a ring homomorphism. We will prove that φ is injective if and only if $\ker \varphi = \{0_R\}$.

In the forwards direction, we let φ be injective. Then, $\varphi(0_R) = 0_S$ by the definition of a ring homomorphism. Since, for any $a \in R, a \neq 0_R$, $\varphi(a)$ cannot equal 0_S (or else φ would not be injective), this means $\ker \varphi = \{0_R\}$.

In the reverse direction, we let $\ker \varphi = \{0_R\}$. Let $\varphi(a) = \varphi(b)$. Then, $\varphi(a) - \varphi(b) = \varphi(b) - \varphi(b)$, meaning $\varphi(a) - \varphi(b) = 0_S$. By the definition of a ring homomorphism, this is equivalent to $\varphi(a - b) = 0_S$. Since $\ker \varphi = \{0_R\}$, we have $a - b = 0_R$, or $a = b$. Thus, φ is injective.