MATH 601 (DUE 9/25)

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Exercise. (Problem 1) Define $\gamma : \mathbb{Z}[\sqrt{2}] \to \mathbb{Z}[\sqrt{2}]$ by $\gamma(a + b\sqrt{2}) = a - b\sqrt{2}$. Show that γ is a ring isomorphism and compute its inverse.

Proof. Let $a + b\sqrt{2}, c + d\sqrt{2} \in \mathbb{Z}[\sqrt{2}]$ be given.

$$\begin{aligned}
\gamma((a + b\sqrt{2}) + (c + d\sqrt{2})) &= \gamma((a + c) + (b + d)\sqrt{2}) \\
&= (a + c) - (b + d)\sqrt{2} \\
&= (a - b\sqrt{2}) + (c - d\sqrt{2}) \\
&= \gamma(a + b\sqrt{2}) + \gamma(c + d\sqrt{2}). \\
\gamma((a + b\sqrt{2})(c + d\sqrt{2})) &= \gamma((ac + 2bd) + (ad + bc)\sqrt{2}) \\
&= (ac + 2bd) - (ad + bc)\sqrt{2} \\
&= (ac + 2(-b)(-d)) + (a(-d) + (-b)c)\sqrt{2} \\
&= (a - b\sqrt{2})(c - d\sqrt{2}) \\
&= \gamma(a + b\sqrt{2})\gamma(c + d\sqrt{2}).
\end{aligned}$$

Moreover, $\gamma(1) = 1 - 0\sqrt{2} = 1$. Therefore, γ is a ring homomorphism. For any $a + b\sqrt{2}$, $\gamma(\gamma(a + b\sqrt{2})) = \gamma(a - b\sqrt{2}) = a + b\sqrt{2}$. Therefore, γ has an inverse, and the inverse of γ is γ. This implies that γ is bijective.

In conclusion, γ is an isomorphism and its inverse is itself. $\square$

Exercise. (Problem 2) Define $N : \mathbb{Z}[\sqrt{2}] \to \mathbb{Z}$ by $N(a+b\sqrt{2}) = (a+b\sqrt{2})\gamma(a+b\sqrt{2})$. Show that $N(\alpha\beta) = N(\alpha)N(\beta)$.

Proof. Let $a + b\sqrt{2}, c + d\sqrt{2}$ be given.

$$\begin{aligned}
N((a + b\sqrt{2})(c + d\sqrt{2})) &= N((ac + 2bd) + (ad + bc)\sqrt{2}) \\
&= ((ac + 2bd) + (ad + bc)\sqrt{2})\gamma((ac + 2bd) + (ad + bc)\sqrt{2}) \\
&= (a + b\sqrt{2})(c + d\sqrt{2})\gamma((a + b\sqrt{2})(c + d\sqrt{2})) \\
&= (a + b\sqrt{2})(c + d\sqrt{2})\gamma(a + b\sqrt{2})\gamma(c + d\sqrt{2}) \\
&= (a + b\sqrt{2})\gamma(a + b\sqrt{2})(c + d\sqrt{2})\gamma(c + d\sqrt{2}) \\
&= N(a + b\sqrt{2})N(c + d\sqrt{2}).
\end{aligned}$$

$\square$

Exercise. (Problem 3) Write $\mathbb{Z}[\sqrt{2}]^*$ for the group of units in $\mathbb{Z}[\sqrt{2}]$. Show that $\alpha \in \mathbb{Z}[\sqrt{2}]^*$ if and only if $N(\alpha) = \pm 1$.

Proof. We have $N(1) = 1\gamma(1) = 1$.

Let α be a unit and β be the inverse. Then $N(\alpha\beta) = N(1) = 1$. Thus $1 = N(\alpha)N(\beta)$. Since $N(\alpha), N(\beta) \in \mathbb{Z}$, $N(\alpha) = \pm 1$.

On the other hand, suppose that $N(\alpha) = \pm 1$ for some α.

- Case 1: $N(\alpha) = 1$. Then $\alpha\gamma(\alpha) = 1$, so $\gamma(\alpha)$ is an inverse of α. Therefore, α is a unit.
- Case 2: $N(\alpha) = -1$. Then $\alpha\gamma(\alpha) = -1$, so $-\gamma(\alpha)$ is an inverse of α. Therefore, α is a unit.

In each case, α is a unit.

Therefore, $N(\alpha) = \pm 1$ if and only if α is a unit. $\square$

Exercise. (Problem 4) What does finding the units in $\mathbb{Z}[\sqrt{2}]$ have to do with solving the equation $x^2 - 2y^2 = \pm 1$?

Proof. Let (a, b) be a solution to the equation. Then $a^2 - 2b^2 = \pm 1$, so $(a + b\sqrt{2})(a - b\sqrt{2}) = \pm 1$. This implies that $a \pm b\sqrt{2}$ is a unit in $\mathbb{Z}[\sqrt{2}]$.

On the other hand, let $a + b\sqrt{2}$ be a unit in $\mathbb{Z}[\sqrt{2}]$. By Problem 3, $N(a + b\sqrt{2}) = \pm 1$. Thus $\pm 1 = N(a + b\sqrt{2}) = (a + b\sqrt{2})(a - b\sqrt{2}) = a^2 - b^2$. Hence, (a, b) is a solution to $x^2 - 2y^2 = \pm 1$.

In conclusion, there exists a bijective correspondence between the units in $\mathbb{Z}[\sqrt{2}]$ and the solutions to $x^2 - 2y^2 = \pm 1$. $\square$

Exercise. (Problem 5) Show that $\mathbb{Z}[\sqrt{2}]$ has no smallest positive element.

Proof. We have $0 < \sqrt{2} - 1 < 1$. Since $\forall n \in \mathbb{N}, (\sqrt{2} - 1)^n \in \mathbb{Z}[\sqrt{2}]$ and $\lim_{n \to \infty} (\sqrt{2} - 1)^n = 0$, there exists no smallest positive element in $\mathbb{Z}[\sqrt{2}]$. $\square$

Exercise. (Problem 6) Find an element $u \in \mathbb{Z}[\sqrt{2}]^*$ with $u > 1$.

Proof. $(\sqrt{2} + 1)(\sqrt{2} - 1) = 2 - 1 = 1$. Thus $u = \sqrt{2} + 1$ is a unit such that $u > 1$. $\square$

Exercise. (Problem 7) Let $u \in \mathbb{Z}[\sqrt{2}]^*$ with $u > 1$. Write $u = a + b\sqrt{2}$ with $a, b \in \mathbb{Z}$. Show $a > 0$ and $b > 0$.

Proof. Since u is a unit, $N(u) = \pm 1$ from Problem 3. In other words, $(a + b\sqrt{2})(a - b\sqrt{2}) = a^2 - 2b^2 = \pm 1$. Then $a^2 = \pm 1 + 2b^2 \equiv 1 \pmod 2$, so a is odd. Specifically, $a \neq 0$.

- Case 1: $a < 0$. Since a is an integer, $a \leq -1$. Since $u = a + b\sqrt{2} > 1$, $b > 0$. Since b is an integer, $b \geq 1$. This implies that $a - b\sqrt{2} \leq -1 - \sqrt{2} < -1$.

  This means $(a + b\sqrt{2})(a - b\sqrt{2}) < -1$ because $a + b\sqrt{2} > 1$. However, this is impossible because $(a + b\sqrt{2})(a - b\sqrt{2}) = \pm 1$. This is a contradiction, so a is not negative.
- Case 2: $a > 0$ and $b < 0$. Since a, b are integers, this implies $a \geq 1$ and $b \leq -1$. Then $a - b\sqrt{2} \geq 1 + \sqrt{2} > 2$. Since $a + b\sqrt{2} > 1$, this implies $(a + b\sqrt{2})(a - b\sqrt{2}) > 1 \cdot 2 = 2$. This is a contradiction because we have $(a + b\sqrt{2})(a - b\sqrt{2}) = \pm 1$.

Therefore, both a and b must be positive. $\square$

Exercise. (Problem 8) Show that among all u satisfying the conditions of 7, there is a least element u_0. What is u_0?

Proof. Since we know that $a \geq 1$ and $b \geq 1$, $1+\sqrt{2}$ is less than or equal to all such u. Since $(1+\sqrt{2})(\sqrt{2}-1) = 1$, $1+\sqrt{2}$ is indeed a unit. Therefore, $1+\sqrt{2}$ is the least element in $\mathbb{Z}[\sqrt{2}]^*$. □

Exercise. (Problem 9) Show that every element of $\mathbb{Z}[\sqrt{2}]^*$ is of the form $\pm u_0^n$, $n \in \mathbb{Z}$.

Proof. Let $u \in \mathbb{Z}[\sqrt{2}]^*$.

- Case 1: $1 < u$. Since $1+\sqrt{2}$ is the least element among all units greater than 1, there must exist an $n \in \mathbb{N}$ such that $(1+\sqrt{2})^n \leq u < (1+\sqrt{2})^{n+1}$. This implies that $1 \leq \frac{u}{(1+\sqrt{2})^n} < 1+\sqrt{2}$. Since u and $1+\sqrt{2}$ are both units, $\frac{u}{(1+\sqrt{2})^n}$ is a unit in $\mathbb{Z}[\sqrt{2}]$ as well. Since $1+\sqrt{2}$ is the least element among all units greater than 1, $u/(1+\sqrt{2})^n = 1$. Therefore, $u = (1+\sqrt{2})^n$.
- Case 2: $u = 1$. Then $u = (1+\sqrt{2})^0$.
- Case 3: $0 < u < 1$. Then $1/u \in \mathbb{Z}[\sqrt{2}]^*$, and $1 < 1/u$. By Case 1, $1/u = (1+\sqrt{2})^n$ for some $n \in \mathbb{Z}$. Therefore, $u = (1+\sqrt{2})^{-n}$.
- Case 4: $-1 < u < 0$. Then $-u \in \mathbb{Z}[\sqrt{2}]^*$ and $0 < -u < 1$. By Case 3, $-u = (1+\sqrt{2})^n$ for some $n \in \mathbb{Z}$. Thus $u = -(1+\sqrt{2})^n$.
- Case 5: $u = -1$. Then $u = -(1+\sqrt{2})^0$.
- Case 6: $u < -1$. Then $-u \in \mathbb{Z}[\sqrt{2}]^*$ and $1 < -u$. By Case 1, $-u = (1+\sqrt{2})^n$ for some $n \in \mathbb{Z}$. Therefore, $u = -(1+\sqrt{2})^n$.

Therefore, u is indeed of the form $\pm(1+\sqrt{2})^n$ with $n \in \mathbb{Z}$. □

Exercise. (Problem 10) Describe all solutions to $x^2 - 2y^2 = 1$.

Proof. We claim that $(x, y) \in \mathbb{Z}^2$ is a solution to $x^2 - 2y^2 = 1$ if and only if $x + y\sqrt{2} = (1+\sqrt{2})^{2n}$ for some $n \in \mathbb{Z}$.

Let $x, y \in \mathbb{Z}$.

- $x^2 - 2y^2 = 1$ if and only if $N(x+\sqrt{2}y) = 1$.
- We showed in Problem 3 that $x+\sqrt{2}y \in \mathbb{Z}[\sqrt{2}]^*$ if and only if $N(x+\sqrt{2}y) = \pm 1$.
- We showed in Problem 9 that every element in $\mathbb{Z}[\sqrt{2}]^*$ is of the form $\pm u_0^n$ for some $n \in \mathbb{Z}$.

Therefore, we will first check which $\pm u_0^n$ satisfies $N(\pm u_0^n) = 1$. We claim that $N(u_0^{2n}) = N(-u_0^{2n}) = 1$ for all $n \in \mathbb{Z}$.

- When $n = 0$, this is clearly true.
- Suppose that $N(u_0^{2n}) = 1$ for some $n \in \mathbb{N}$. Let $x+\sqrt{2}y = u_0^{2n}$ where $x, y \in \mathbb{Z}$. Then $u_0^{2n+2} = (x+\sqrt{2}y)(1+\sqrt{2})^2 = (x+\sqrt{2}y)(3+2\sqrt{2}) = (3x+4y)+(2x+3y)\sqrt{2}$.

$$\begin{aligned}
N(u_0^{2n+2}) &= ((3x+4y)+(2x+3y)\sqrt{2})((3x+4y)-(2x+3y)\sqrt{2}) \\
&= (9x^2+24xy+16y^2) - 2(4x^2+12xy+9y^2) \\
&= x^2 - 2y^2 \\
&= N(u_0^{2n}) = 1.
\end{aligned}$$

By mathematical induction, $N(u_0^{2n}) = 1$ for all $n \in \mathbb{N}$.

- Let $n \in \mathbb{N}$. Let $x + y\sqrt{2} = u_0^{2n}$ where $x, y \in \mathbb{Z}$.

$$\begin{aligned}\frac{1}{u_0^{2n}} &= \frac{1}{x + y\sqrt{2}} \\ &= \frac{x - y\sqrt{2}}{x^2 - 2y^2} \\ &= \frac{x - y\sqrt{2}}{N(x + y\sqrt{2})} \\ &= \frac{x - y\sqrt{2}}{N(u_0^{2n})} \\ &= x - y\sqrt{2}.\end{aligned}$$

  Since $N(x - y\sqrt{2}) = N(x + y\sqrt{2}) = 1$, $N(u_0^{-2n}) = 1$ for all $n \in \mathbb{N}$.
- Let $k \in \mathbb{Z}$. Let $x + y\sqrt{2} = u_0^{2n}$.

$$\begin{aligned}N(-u_0^{2n}) &= N(-x - y\sqrt{2}) \\ &= (-x - y\sqrt{2})(-x + y\sqrt{2}) \\ &= (x + y\sqrt{2})(x - y\sqrt{2}) \\ &= N(x + y\sqrt{2}) \\ &= N(u_0^{2n}) = 1.\end{aligned}$$

Therefore, $N(\pm u_0^{2n}) = 1$ for any sign and $n \in \mathbb{Z}$. We now claim that $N(\pm u_0^{2n+1}) = -1$ for any sign and $n \in \mathbb{Z}$. Let $x + y\sqrt{2} = \pm u_0^{2n}$ for some sign and $n \in \mathbb{Z}$. Then $(x + y\sqrt{2})(1 + \sqrt{2}) = (x + 2y) + (x + y)\sqrt{2}$.

$$\begin{aligned}N((x + y\sqrt{2})(1 + \sqrt{2})) &= N((x + 2y) + (x + y)\sqrt{2}) \\ &= ((x + 2y) + (x + y)\sqrt{2})((x + 2y) - (x + y)\sqrt{2}) \\ &= (x + 2y)^2 - 2(x + y)^2 \\ &= (x^2 + 4xy + 4y^2) - (2x^2 + 4xy + 2y^2) \\ &= -x^2 + 2y^2 \\ &= -(x^2 - 2y^2) \\ &= -N(x + y\sqrt{2}) \\ &= -1.\end{aligned}$$

Therefore, $N(\pm u_0^{2n+1})$ for any sign and any $n \in \mathbb{Z}$. Hence, $\{(x, y) \in \mathbb{Z}^2 \mid x + \sqrt{2}y \in \{-u_0^{2n}, u_0^{2n} \mid n \in \mathbb{Z}\}\}$ is the set of all solutions to $x^2 - 2y^2 = 1$. $\square$

Exercise. (Problem 11) Construct a group isomorphism $\mathbb{Z}[\sqrt{2}]^* \to \mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$.

Proof. By Problem 9, every element in $\mathbb{Z}[\sqrt{2}]^*$ can be represented as $(-1)^a(1+\sqrt{2})^{2k}$ for some $(k, a) \in \mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$. Let $\phi : \mathbb{Z}[\sqrt{2}]^* \to \mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$ be defined such that $\phi((-1)^a(1 + \sqrt{2})^{2k}) = (k, a)$.

- Well-defined? Every element in $\mathbb{Z}[\sqrt{2}]^*$ can be expressed unique as $(-1)^a(1+\sqrt{2})^{2k}$ for some $(k, a) \in \mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$. Thus ϕ is well defined.
- Group homomorphism?

$$\begin{aligned}\phi((-1)^a(1+\sqrt{2})^{2k}(-1)^b(1+\sqrt{2})^{2l}) &= \phi((-1)^{a+b}(1+\sqrt{2})^{2(k+l)}) \\ &= (k+l, a+b) \\ &= (k, a) + (l, b) \\ &= \phi((-1)^a(1+\sqrt{2})^{2k})\phi((-1)^b(1+\sqrt{2})^{2l}).\end{aligned}$$

- Injective? $\phi((-1)^a(1+\sqrt{2})^k) = (0, 0)$ implies that $k = a = 0$. Therefore, 1 is the only number in the kernel of ϕ. Since the kernel of ϕ only contains the identity element, ϕ is injective.
- Surjective? For any $(k, a) \in \mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$, $(-1)^a(1+\sqrt{2})^{2k} \in \mathbb{Z}[\sqrt{2}]^*$.

Therefore, ϕ is a group isomorphism. □

Exercise. (Problem 12) Show that $\mathbb{Z}[\sqrt{2}]$ is an integral domain.

Proof. $\mathbb{Z}[\sqrt{2}]$ is a commutative ring because multiplication of real numbers is commutative. Moreover, $\mathbb{Z}[\sqrt{2}] \subset \mathbb{R}$ where $\mathbb{R}$ is a field. Thus $\mathbb{Z}[\sqrt{2}]$ has no zero divisors. Therefore, $\mathbb{Z}[\sqrt{2}]$ is an integral domain. □

Exercise. (Problem 14) Conclude that $\mathbb{Z}[\sqrt{2}]$ is a principal ideal domain and a unique factorization domain.

Proof. In class, we proved that every principal ideal domain is a unique factorization domain. Therefore, it suffices to show that $\mathbb{Z}[\sqrt{2}]$ is a principal ideal domain. Let I be an ideal of $\mathbb{Z}[\sqrt{2}]$. If $I = (0)$, we are done. Suppose otherwise. Let $S = \{|N(\alpha)| \mid \alpha \in I, \alpha \neq 0\}$. Since S is a nonempty set of positive integers, there exists a minimum value m. Let $\beta \in I$ be an element such that $|N(\beta)| = m$. We claim that $I = (\beta)$.

Suppose otherwise. Let $\alpha \in I \setminus (\beta)$. By Problem 13, there exist $\delta, \epsilon \in \mathbb{Z}[\sqrt{2}]$ such that $\alpha = \beta\delta + \epsilon$ with $|N(\epsilon)| < |N(\beta)|$. ϵ cannot be 0 because $\alpha \notin (\beta)$. Since I is an ideal, $\beta\delta \in I$. This implies that $\epsilon = \alpha - \beta\delta \in I$. However, this is a contradiction because β was chosen because $|N(\beta)| \leq |N(\beta')|$ for all $\beta' \in I$. Therefore, $I = (\beta)$, and thus $\mathbb{Z}[\sqrt{2}]$ is a principal ideal domain and a unique factorization domain. □