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1 Exercise 3.15

Verify that if $K = \mathbb{Q}(\sqrt{-2}, \sqrt{-5})$ then an integral basis is given by $\{1, \sqrt{-2}, \sqrt{-5}, \frac{\sqrt{-2} + \sqrt{10}}{2}\}$.

See proposition 2.34 that integral elements of $\mathbb{Z}[\sqrt{d}]$ have the form $\mathbb{Z} + \mathbb{Z}\sqrt{d}$ when $d \equiv 2, 3 \pmod{4}$.

Adding α with its conjugates creates elements of the form $2a + 2k\sqrt{d} \in \mathbb{Z}_K$ where $d \in \{-2, -5, 10\}$. $-2 \equiv 2 \pmod{4}$, $-5 \equiv 3 \pmod{4}$, $10 \equiv 2 \pmod{4}$. So we know by above that these elements are from $\mathbb{Z} + \mathbb{Z}\sqrt{d}$. So $2a, 2k \in \mathbb{Z}$.

Follow method of previous section.

$$A = 2a, B = 2b, C = 2c, D = 2d \in \mathbb{Z}$$

$$a = \frac{A}{2}, b = \frac{B}{2}, c = \frac{C}{2}, d = \frac{D}{2}$$

$$\begin{aligned} \alpha &= a + b\sqrt{-2} + c\sqrt{-5} + d\sqrt{10} \\ &= \frac{A}{2} + \frac{B}{2}\sqrt{-2} + \frac{C}{2}\sqrt{-5} + \frac{D}{2}\sqrt{10} \\ \alpha_2 &= a - b\sqrt{-2} + c\sqrt{-5} - d\sqrt{10} \\ \alpha\alpha_2 &= ((a + c\sqrt{-5}) - (b\sqrt{-2} + d\sqrt{10}))((a + c\sqrt{-5}) + (b\sqrt{-2} + d\sqrt{10})) \\ &= (a + c\sqrt{-5})^2 - (b\sqrt{-2} + d\sqrt{10})^2 \\ &= a^2 + 2\sqrt{-5}ac - 5c^2 + 2b^2 - 2\sqrt{-20}bd - 10d^2 \\ &= \frac{A^2 - 5C^2 + 2B^2 - 10D^2}{4} + \frac{AC - 2BD}{2}\sqrt{-5} \end{aligned}$$

First note that $AC - 2BD \equiv AC \equiv 0 \pmod{2}$, which means either A or C are even.

$$\begin{aligned} A^2 - 5C^2 + 2B^2 - 10D^2 &\equiv 0 \pmod{2} \\ &\equiv A^2 - 5C^2 \pmod{2} \\ &\equiv A + C \pmod{2} \end{aligned}$$

| $A \pmod{2}$ | $C \pmod{2}$ | $A + C \pmod{2}$ |
|--------------|--------------|------------------|
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |

So A and C are both even.

Now we look at B and D. Note that by the last step $A^2 \equiv 0 \pmod{4}$ and $C^2 \equiv 0 \pmod{4}$.

$$A^2 - 5C^2 + 2B^2 - 10D^2 \equiv 2B^2 - 10D^2 \equiv 0 \pmod{4}$$

$$\begin{aligned}
2B^2 - 10D^2 = 4p &\implies B^2 - 5D^2 = 2p \\
B^2 - 5D^2 &\equiv B^2 + D^2 \equiv 0 \pmod{2} \\
&\implies B + D \equiv 0 \pmod{2}
\end{aligned}$$

| $B \pmod{2}$ | $D \pmod{2}$ | $B + D \pmod{2}$ |
|--------------|--------------|------------------|
| 0 | 0 | 0 |
| 0 | 1 | 1 |
| 1 | 0 | 1 |
| 1 | 1 | 0 |

So $B \equiv D \equiv 0 \pmod{2}$ or $B \equiv D \equiv 1 \pmod{2}$. Remembering $A \equiv C \equiv 0 \pmod{2}$, we now have 2 cases.

1.1 Case 1: A, B, C, D are all even

$$\begin{aligned}
A &\equiv C \equiv 0 \pmod{2} \\
B &\equiv D \equiv 0 \pmod{2}
\end{aligned}$$

$$A = 2a, B = 2b, C = 2c, D = 2d \in \mathbb{Z}$$

Earlier we found

$$2\alpha = A + B\sqrt{-2} + C\sqrt{-5} + D\sqrt{10}$$

with $A, B, C, D \in \mathbb{Z}$.

But now we know $A, B, C, D \in 2\mathbb{Z}$. So $a, b, c, d \in \mathbb{Z}$.

Which is integral over $\{1, \sqrt{-2}, \sqrt{-5}, \sqrt{10}\}$ and so also over $\{1, \sqrt{-2}, \sqrt{-5}, \frac{\sqrt{-2}+\sqrt{10}}{2}\}$ since $\sqrt{10} = 0 \cdot 1 - 1 \cdot \sqrt{-2} + 0\sqrt{-5} + 2\frac{\sqrt{-2}+\sqrt{10}}{2}$

1.2 Case 2: A, B are even, C, D are odd

Now we do the other case.

$$\begin{aligned}
A &\equiv C \equiv 0 \pmod{2} \\
B &\equiv D \equiv 1 \pmod{2}
\end{aligned}$$

$$A = 2a, B = 2b, C = 2c, D = 2d$$

Here $A, C \in 2\mathbb{Z}$ so $a, c \in \mathbb{Z}$. But this is not true for B, D which are odd integers.

a, c are integers, but b, d are halves of odd integers.

$$\alpha = a + b\sqrt{-2} + c\sqrt{-5} + d\sqrt{10}$$

which has as basis $\{1, \sqrt{-2}, \sqrt{-5}, \frac{\sqrt{-2}+\sqrt{10}}{2}\}$

So we managed to reduce all elements of \mathbb{Z}_K which both have the same basis. We therefore conclude that the entire ring has that integral basis too.

2 Prove that $\mathbb{Z}_K \neq \mathbb{Z}[\gamma]$

$$\gamma = \frac{\sqrt{-2} + \sqrt{10}}{2}$$

```
sage: var("a b c d")
(a, b, c, d)
sage: y = (sqrt(-2) + sqrt(10))/2
sage: e = a + b*y + c*y^2 + d*y^3 == 0
sage: e = e.expand()
sage: e
1/2*sqrt(10)*sqrt(-2)*c + 1/2*sqrt(10)*b + 1/2*sqrt(-2)*b + 1/2*sqrt(10)*d + 7/2*sqrt(-2)*d + a + 2*c =
```

$$\frac{1}{2} \sqrt{10} \sqrt{-2} c + \frac{1}{2} \sqrt{10} b + \frac{1}{2} \sqrt{-2} b + \frac{1}{2} \sqrt{10} d + \frac{7}{2} \sqrt{-2} d + a + 2c = 0$$

Tidying up

$$\frac{1}{2} \sqrt{-2} \sqrt{-5} \sqrt{-2} c + \frac{1}{2} \sqrt{10} b + \frac{1}{2} \sqrt{-2} b + \frac{1}{2} \sqrt{10} d + \frac{7}{2} \sqrt{-2} d + a + 2c = 0$$

$$a + 2c + \frac{1}{2} \sqrt{-2} b + \frac{7}{2} \sqrt{-2} d - \sqrt{-5} c + \frac{1}{2} \sqrt{10} b + \frac{1}{2} \sqrt{10} d = 0$$

$$(a + 2c) + \left(\frac{b + 7d}{2} \right) \sqrt{-2} - c \sqrt{-5} + \frac{b + d}{2} \sqrt{10} = 0$$

We will now search for basis elements which cannot be computed from powers of γ . We can use the last equation before to convert elements from the basis $\{1, \gamma, \gamma^2, \gamma^3\}$ to $\{1, \sqrt{-2}, \sqrt{-5}, \sqrt{10}\}$. We are interested to in reverse, and see if there are elements from the $\langle \sqrt{-2}, \sqrt{-5} \rangle$ basis to $\langle \gamma \rangle$.

Let M be a 4x4 matrix transform that takes the basis for $\langle \gamma \rangle$ to $\langle \sqrt{-2}, \sqrt{-5} \rangle$.

$$M\mathbf{v} = \mathbf{A}$$

A is the result of the change of basis. So we can actually compute values from $\langle \sqrt{-2}, \sqrt{-5} \rangle$ in terms of γ . But these elements must be integers, otherwise it is not $\mathbb{Z}[\gamma]$.

$$\begin{pmatrix} 1 & 0 & 2 & 0 \\ 0 & 1 & 0 & 7 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix} \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} = \begin{pmatrix} a + 2c \\ b + 7d \\ c \\ b + d \end{pmatrix}$$

where A is our basis. We are interested in

$$\begin{pmatrix} 0 \\ 2 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ -1 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ 0 \\ 2 \end{pmatrix}$$

Which correspond to the basis over $\langle \sqrt{-2}, \sqrt{-5} \rangle$.

$$(a + 2c) + \left(\frac{b + 7d}{2} \right) \sqrt{-2} - c \sqrt{-5} + \frac{b + d}{2} \sqrt{10} = 0$$

Trying the first one, we get

```
sage: M = matrix([
.....:      [1, 0, 2, 0],
.....:      [0, 1, 0, 7],
.....:      [0, 0, 1, 0],
.....:      [0, 1, 0, 1]
.....: ])
sage: v = vector([0, 2, 0, 0])
sage: M^-1*v
(0, -1/3, 0, 1/3)
```

So therefore $\sqrt{-2} \notin \mathbb{Z}[\gamma]$.

3 Exercise 3.16

$$f(\gamma) = 0$$

$$3 \mid g(\gamma) \implies g(\gamma) \equiv 0 \pmod{3}$$

$$g(X) \equiv f(X)u(X) \pmod{3}$$

likewise

$$g(X) \equiv f(X)u(X) \pmod{3}$$

$$\implies g(\gamma) \equiv f(\gamma)u(\gamma) \equiv 0 \pmod{3}$$

$$g(X) = 3a(X) + f(X)u(X)$$

4 $\mathbb{Q}[\sqrt[3]{175}]$

Note there's a mistake on the first page. $\alpha' = \alpha^2/5$. The book erroneously shows 7.

```
sage: K.<a> = NumberField(x^3 - 175)
sage: L.<X> = K[]
sage: K2.<w> = K.extension(X^2 + X + 1)
sage: K3.<j, k> = K2[]
sage: b = a^2/5
sage: c1 = (j*a + k*b)/5
sage: c2 = (j*a*w + k*b*w^2)/5
sage: c3 = (j*a*w^2 + k*b*w)/5
sage: c1*c2*c3
7/5*j^3 + 49/25*k^3
```