

Divisible \mathbb{Z} -modules

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Summary. In this article, we formalize the definition of divisible \mathbb{Z} -module and its properties in the Mizar system [3]. We formally prove that any non-trivial divisible \mathbb{Z} -modules are not finitely-generated. We introduce a divisible \mathbb{Z} -module, equivalent to a vector space of a torsion-free \mathbb{Z} -module with a coefficient ring \mathbb{Q} . \mathbb{Z} -modules are important for lattice problems, LLL (Lenstra, Lenstra and Lovász) base reduction algorithm [15], cryptographic systems with lattices [16] and coding theory [8].

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1. DIVISIBLE MODULE

Let a, b be elements of $\mathbb{F}_{\mathbb{Q}}$ and x, y be rational numbers. We identify $x + y$ with $a + b$. We identify $x \cdot y$ with $a \cdot b$. Let V be a \mathbb{Z} -module and v be a vector of V . We say that v is divisible if and only if

(Def. 1) for every element a of $\mathbb{Z}^{\mathbb{R}}$ such that $a \neq 0_{\mathbb{Z}^{\mathbb{R}}}$ there exists a vector u of V such that $a \cdot u = v$.

Let us observe that 0_V is divisible and there exists a vector of V which is divisible.

Now we state the propositions:

(1) Let us consider a \mathbb{Z} -module V , and divisible vectors v, u of V . Then $v + u$ is divisible.

- (2) Let us consider a \mathbb{Z} -module V , and a divisible vector v of V . Then $-v$ is divisible.

PROOF: For every element a of $\mathbb{Z}^{\mathbb{R}}$ such that $a \neq 0_{\mathbb{Z}^{\mathbb{R}}}$ there exists a vector w of V such that $-v = a \cdot w$ by [9, (6)]. \square

- (3) Let us consider a \mathbb{Z} -module V , a divisible vector v of V , and an element i of $\mathbb{Z}^{\mathbb{R}}$. Then $i \cdot v$ is divisible.

Let V be a \mathbb{Z} -module. We say that V is divisible if and only if

- (Def. 2) every vector of V is divisible.

Observe that $\mathbf{0}_V$ is divisible and \mathbb{Z} -module \mathbb{Q} is divisible and there exists a \mathbb{Z} -module which is divisible.

Let V be a \mathbb{Z} -module. Let us note that there exists a submodule of V which is divisible and there exists a divisible \mathbb{Z} -module which is non finitely generated.

Now we state the propositions:

- (4) (The left integer multiplication of $\mathbb{F}_{\mathbb{Q}} \upharpoonright (\mathbb{Z} \times \mathbb{Z}) =$
the left integer multiplication of $\mathbb{Z}^{\mathbb{R}}$.)

PROOF: Set $a = (\text{the left integer multiplication of } \mathbb{F}_{\mathbb{Q}} \upharpoonright (\mathbb{Z} \times \mathbb{Z}))$. For every object z such that $z \in \text{dom } a$ holds $a(z) = (\text{the left integer multiplication of } \mathbb{Z}^{\mathbb{R}})(z)$ by [5, (49)], [13, (15)], [12, (14)]. \square

- (5) \langle the carrier of $\mathbb{Z}^{\mathbb{R}}$, the addition of $\mathbb{Z}^{\mathbb{R}}$, the zero of $\mathbb{Z}^{\mathbb{R}}$, the left integer multiplication of $\mathbb{Z}^{\mathbb{R}}$ \rangle is a submodule of \mathbb{Z} -module \mathbb{Q} . The theorem is a consequence of (4).
- (6) Let us consider a divisible \mathbb{Z} -module V , and a submodule W of V . Then $\mathbb{Z}\text{-ModuleQuot}(V, W)$ is divisible.

Let us note that there exists a divisible \mathbb{Z} -module which is non trivial.

Now we state the proposition:

- (7) Let us consider a \mathbb{Z} -module V . Then V is divisible if and only if Ω_V is divisible.

Let us consider a \mathbb{Z} -module V and a vector v of V . Now we state the propositions:

- (8) If v is not torsion, then $\text{Lin}(\{v\})$ is not divisible.
- (9) If v is torsion and $v \neq 0_V$, then $\text{Lin}(\{v\})$ is not divisible.

Let V be a non trivial \mathbb{Z} -module and v be a non zero vector of V . Observe that $\text{Lin}(\{v\})$ is non divisible and there exists a submodule of V which is non divisible.

Now we state the propositions:

- (10) Every non trivial, finitely generated, torsion-free \mathbb{Z} -module is not divisible.

PROOF: Consider I being a finite subset of V such that I is a basis of V . Consider v being an object such that $v \in I$. v is not divisible by [9, (92)], [12, (19)], [19, (15)], [9, (9)]. \square

(11) Let us consider a non trivial, finitely generated, torsion \mathbb{Z} -module V . Then there exists an element i of \mathbb{Z}^R such that

- (i) $i \neq 0$, and
- (ii) for every vector v of V , $i \cdot v = 0_V$.

PROOF: Define $\mathcal{P}[\text{natural number}] \equiv$ for every finite subset I of V such that $\bar{I} = \$_1$ there exists an element i of \mathbb{Z}^R such that $i \neq 0$ and for every vector v of V such that $v \in \text{Lin}(I)$ holds $i \cdot v = 0_V$. $\mathcal{P}[0]$ by [10, (67)], [9, (1)]. For every natural number n such that $\mathcal{P}[n]$ holds $\mathcal{P}[n+1]$ by [7, (40)], [10, (72)], [1, (44)], [7, (31)]. For every natural number n , $\mathcal{P}[n]$ from [2, Sch. 2]. Consider I being a finite subset of V such that $\text{Lin}(I) =$ the vector space structure of V . Consider i being an element of \mathbb{Z}^R such that $i \neq 0$ and for every vector v of V such that $v \in \text{Lin}(I)$ holds $i \cdot v = 0_V$. For every vector v of V , $i \cdot v = 0_V$. \square

(12) Let us consider a non trivial, finitely generated, torsion \mathbb{Z} -module V , and an element i of \mathbb{Z}^R . Suppose $i \neq 0$ and for every vector v of V , $i \cdot v = 0_V$. Then V is not divisible.

(13) Every non trivial, finitely generated, torsion \mathbb{Z} -module is not divisible. The theorem is a consequence of (11) and (12).

One can verify that there exists a non trivial, finitely generated, torsion \mathbb{Z} -module which is non divisible.

Now we state the proposition:

(14) Every non trivial, finitely generated \mathbb{Z} -module is not divisible. The theorem is a consequence of (13), (6), and (10).

Let us note that every non trivial, divisible \mathbb{Z} -module is non finitely generated.

Let V be a non trivial, non divisible \mathbb{Z} -module. One can verify that there exists a non zero vector of V which is non divisible.

Let V be a non trivial, finite rank, free \mathbb{Z} -module. Observe that $\text{rank } V$ is non zero.

Now we state the propositions:

(15) Let us consider a non trivial, free \mathbb{Z} -module V , a non zero vector v of V , and a basis I of V . Then there exists a linear combination L of I and there exists a vector u of V such that $v = \sum L$ and $u \in I$ and $L(u) \neq 0$.

PROOF: Consider L being a linear combination of I such that $v = \sum L$. The support of $L \neq \emptyset$ by [10, (23)]. Consider u_1 being an object such that

$u_1 \in$ the support of L . Consider u being a vector of V such that $u = u_1$ and $L(u) \neq 0$. \square

- (16) Let us consider a non trivial, free \mathbb{Z} -module V . Then every non zero vector of V is not divisible. The theorem is a consequence of (15).

Let us observe that every non trivial, free \mathbb{Z} -module is non divisible.

Let us consider a non trivial, free \mathbb{Z} -module V and a non zero vector v of V .

Now we state the propositions:

- (17) There exists an element a of $\mathbb{Z}^{\mathbb{R}}$ such that
- (i) $a \in \mathbb{N}$, and
 - (ii) for every element b of $\mathbb{Z}^{\mathbb{R}}$ and for every vector u of V such that $b > a$ holds $v \neq b \cdot u$.

PROOF: Set $I =$ the basis of V . Consider L being a linear combination of I , w being a vector of V such that $v = \sum L$ and $w \in I$ and $L(w) \neq 0$. Reconsider $a = |L(w)|$ as an element of $\mathbb{Z}^{\mathbb{R}}$. For every element b of $\mathbb{Z}^{\mathbb{R}}$ and for every vector u of V such that $b > a$ holds $v \neq b \cdot u$ by [10, (64), (31), (53)], [11, (3)]. \square

- (18) There exists an element a of $\mathbb{Z}^{\mathbb{R}}$ and there exists a vector u of V such that $a \in \mathbb{N}$ and $a \neq 0$ and $v = a \cdot u$ and for every element b of $\mathbb{Z}^{\mathbb{R}}$ and for every vector w of V such that $b > a$ holds $v \neq b \cdot w$.

PROOF: Define $\mathcal{P}[\text{natural number}] \equiv$ there exists a vector u of V and there exists an element k of $\mathbb{Z}^{\mathbb{R}}$ such that $k = \$_1$ and $v = k \cdot u$. Consider a being an element of $\mathbb{Z}^{\mathbb{R}}$ such that $a \in \mathbb{N}$ and for every element b of $\mathbb{Z}^{\mathbb{R}}$ and for every vector u of V such that $b > a$ holds $v \neq b \cdot u$. There exists a natural number k such that $\mathcal{P}[k]$. Consider a_0 being a natural number such that $\mathcal{P}[a_0]$ and for every natural number n such that $\mathcal{P}[n]$ holds $n \leq a_0$ from [2, Sch. 6]. Reconsider $a = a_0$ as an element of $\mathbb{Z}^{\mathbb{R}}$. Consider u being a vector of V such that $v = a \cdot u$. $a \neq 0$ by [9, (1)]. For every element b of $\mathbb{Z}^{\mathbb{R}}$ and for every vector w of V such that $b > a$ holds $v \neq b \cdot w$ by [18, (3)]. \square

2. DIVISIBLE MODULE FOR TORSION-FREE \mathbb{Z} -MODULE

Let V be a torsion-free \mathbb{Z} -module. The functor $\text{Embedding}(V)$ yielding a strict \mathbb{Z} -module is defined by

- (Def. 3) the carrier of $it = \text{rng MorphsZQ}(V)$ and the zero of $it = \text{zeroCoset}(V)$ and the addition of $it = \text{addCoset}(V) \upharpoonright \text{rng MorphsZQ}(V)$ and the left multiplication of $it = \text{lmultCoset}(V) \upharpoonright (\mathbb{Z} \times \text{rng MorphsZQ}(V))$.

Let us consider a torsion-free \mathbb{Z} -module V . Now we state the propositions:

- (19) (i) every vector of $\text{Embedding}(V)$ is a vector of $\mathbb{Z}\text{-MQVectSp}(V)$, and

- (ii) $0_{\text{Embedding}(V)} = 0_{\mathbb{Z}\text{-MQVectSp}(V)}$, and
- (iii) for every vectors x, y of $\text{Embedding}(V)$ and for every vectors v, w of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $x = v$ and $y = w$ holds $x + y = v + w$, and
- (iv) for every element i of $\mathbb{Z}^{\mathbb{R}}$ and for every element j of $\mathbb{F}_{\mathbb{Q}}$ and for every vector x of $\text{Embedding}(V)$ and for every vector v of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $i = j$ and $x = v$ holds $i \cdot x = j \cdot v$.

PROOF: Set $Z = \mathbb{Z}\text{-MQVectSp}(V)$. Set $E = \text{Embedding}(V)$. For every vectors x, y of E and for every vectors v, w of Z such that $x = v$ and $y = w$ holds $x + y = v + w$ by [5, (49)]. For every element i of $\mathbb{Z}^{\mathbb{R}}$ and for every element j of $\mathbb{F}_{\mathbb{Q}}$ and for every vector x of E and for every vector v of Z such that $i = j$ and $x = v$ holds $i \cdot x = j \cdot v$ by [5, (49)]. \square

- (20) (i) for every vectors v, w of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $v, w \in \text{Embedding}(V)$ holds $v + w \in \text{Embedding}(V)$, and
- (ii) for every element j of $\mathbb{F}_{\mathbb{Q}}$ and for every vector v of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $j \in \mathbb{Z}$ and $v \in \text{Embedding}(V)$ holds $j \cdot v \in \text{Embedding}(V)$.

The theorem is a consequence of (19).

- (21) There exists a linear transformation T from V to $\text{Embedding}(V)$ such that
 - (i) T is bijective, and
 - (ii) $T = \text{MorphsZQ}(V)$, and
 - (iii) for every vector v of V , $T(v) = [\{v, 1\}]_{\text{EQRZM}(V)}$.

The theorem is a consequence of (19).

Now we state the proposition:

- (22) Let us consider a torsion-free \mathbb{Z} -module V , and a vector v_1 of $\text{Embedding}(V)$. Then there exists a vector v of V such that $(\text{MorphsZQ}(V))(v) = v_1$. The theorem is a consequence of (21).

Let V be a torsion-free \mathbb{Z} -module. The functor $\text{DivisibleMod}(V)$ yielding a strict \mathbb{Z} -module is defined by

- (Def. 4) the carrier of $it = \text{Classes EQRZM}(V)$ and the zero of $it = \text{zeroCoset}(V)$ and the addition of $it = \text{addCoset}(V)$ and the left multiplication of $it = \text{lmultCoset}(V) \upharpoonright (\mathbb{Z} \times \text{Classes EQRZM}(V))$.

Now we state the proposition:

- (23) Let us consider a torsion-free \mathbb{Z} -module V , a vector v of $\text{DivisibleMod}(V)$, and an element a of $\mathbb{Z}^{\mathbb{R}}$. Suppose $a \neq 0$. Then there exists a vector u of $\text{DivisibleMod}(V)$ such that $a \cdot u = v$.

PROOF: For every vector v of $\text{DivisibleMod}(V)$ and for every element a of \mathbb{Z}^R such that $a \neq 0$ there exists a vector u of $\text{DivisibleMod}(V)$ such that $a \cdot u = v$ by [5, (49)], [7, (87)]. \square

Let V be a torsion-free \mathbb{Z} -module. Let us observe that $\text{DivisibleMod}(V)$ is divisible.

Now we state the proposition:

(24) Let us consider a torsion-free \mathbb{Z} -module V . Then $\text{Embedding}(V)$ is a submodule of $\text{DivisibleMod}(V)$.

PROOF: Set $E = \text{Embedding}(V)$. Set $D = \text{DivisibleMod}(V)$. For every object x such that $x \in$ the carrier of E holds $x \in$ the carrier of D by [6, (11), (5)]. The left multiplication of $E =$ (the left multiplication of D) \upharpoonright ((the carrier of \mathbb{Z}^R) \times $\text{rng MorphsZQ}(V)$) by [20, (74)], [7, (96)]. \square

Let V be a finitely generated, torsion-free \mathbb{Z} -module. One can check that $\text{Embedding}(V)$ is finitely generated.

Let V be a non trivial, torsion-free \mathbb{Z} -module. Observe that $\text{Embedding}(V)$ is non trivial.

Let G be a field, V be a vector space over G , W be a subset of V , and a be an element of G . The functor $a \cdot W$ yielding a subset of V is defined by the term (Def. 5) $\{a \cdot u, \text{ where } u \text{ is a vector of } V : u \in W\}$.

Let V be a torsion-free \mathbb{Z} -module and r be an element of \mathbb{F}_Q . The functor $\text{Embedding}(r, V)$ yielding a strict \mathbb{Z} -module is defined by

(Def. 6) the carrier of $it = r \cdot \text{rng MorphsZQ}(V)$ and the zero of $it = \text{zeroCoset}(V)$ and the addition of $it = \text{addCoset}(V) \upharpoonright (r \cdot \text{rng MorphsZQ}(V))$ and the left multiplication of $it = \text{lmultCoset}(V) \upharpoonright ((\text{the carrier of } \mathbb{Z}^R) \times (r \cdot \text{rng MorphsZQ}(V)))$.

Let us consider a torsion-free \mathbb{Z} -module V and an element r of \mathbb{F}_Q . Now we state the propositions:

- (25) (i) every vector of $\text{Embedding}(r, V)$ is a vector of $\mathbb{Z}\text{-MQVectSp}(V)$, and
- (ii) $0_{\text{Embedding}(r, V)} = 0_{\mathbb{Z}\text{-MQVectSp}(V)}$, and
- (iii) for every vectors x, y of $\text{Embedding}(r, V)$ and for every vectors v, w of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $x = v$ and $y = w$ holds $x + y = v + w$, and
- (iv) for every element i of \mathbb{Z}^R and for every element j of \mathbb{F}_Q and for every vector x of $\text{Embedding}(r, V)$ and for every vector v of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $i = j$ and $x = v$ holds $i \cdot x = j \cdot v$.

PROOF: Set $Z = \mathbb{Z}\text{-MQVectSp}(V)$. Set $E = \text{Embedding}(r, V)$. For every vectors x, y of E and for every vectors v, w of Z such that $x = v$ and

$y = w$ holds $x + y = v + w$ by [5, (49)]. For every element i of $\mathbb{Z}^{\mathbb{R}}$ and for every element j of $\mathbb{F}_{\mathbb{Q}}$ and for every vector x of E and for every vector v of Z such that $i = j$ and $x = v$ holds $i \cdot x = j \cdot v$ by [5, (49)]. \square

- (26) (i) for every vectors v, w of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $v, w \in \text{Embedding}(r, V)$ holds $v + w \in \text{Embedding}(r, V)$, and
 (ii) for every element j of $\mathbb{F}_{\mathbb{Q}}$ and for every vector v of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $j \in \mathbb{Z}$ and $v \in \text{Embedding}(r, V)$ holds $j \cdot v \in \text{Embedding}(r, V)$.
 The theorem is a consequence of (25).

- (27) Suppose $r \neq 0_{\mathbb{F}_{\mathbb{Q}}}$. Then there exists a linear transformation T from $\text{Embedding}(V)$ to $\text{Embedding}(r, V)$ such that

- (i) for every element v of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $v \in \text{Embedding}(V)$ holds $T(v) = r \cdot v$, and
 (ii) T is bijective.

PROOF: Set $Z = \mathbb{Z}\text{-MQVectSp}(V)$. Define $\mathcal{F}(\text{vector of } Z) = r \cdot \1 . Consider T being a function from the carrier of Z into the carrier of Z such that for every element x of the carrier of Z , $T(x) = \mathcal{F}(x)$ from [6, Sch. 4]. Set $T_0 = T \upharpoonright (\text{the carrier of } \text{Embedding}(V))$. For every object $y, y \in \text{rng } T_0$ iff $y \in \text{the carrier of } \text{Embedding}(r, V)$ by [5, (49)]. T_0 is additive by (19), (20), [5, (49)], (25). For every element x of $\text{Embedding}(V)$ and for every element i of $\mathbb{Z}^{\mathbb{R}}$, $T_0(i \cdot x) = i \cdot T_0(x)$ by (19), (20), [5, (49)], (25). For every element v of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $v \in \text{Embedding}(V)$ holds $T_0(v) = r \cdot v$ by [5, (49)]. For every objects x_1, x_2 such that $x_1, x_2 \in \text{the carrier of } \text{Embedding}(V)$ and $T_0(x_1) = T_0(x_2)$ holds $x_1 = x_2$ by [14, (20)]. \square

Now we state the propositions:

- (28) Let us consider a torsion-free \mathbb{Z} -module V , and a vector v of V . Then $[\langle v, 1 \rangle]_{\text{EQRZM}(V)} \in \text{Embedding}(V)$.
 (29) Let us consider a torsion-free \mathbb{Z} -module V , and a vector v of $\text{DivisibleMod}(V)$. Then there exists an element a of $\mathbb{Z}^{\mathbb{R}}$ such that
 (i) $a \neq 0$, and
 (ii) $a \cdot v \in \text{Embedding}(V)$.

The theorem is a consequence of (28).

Let V be a torsion-free \mathbb{Z} -module. One can check that $\text{DivisibleMod}(V)$ is torsion-free and $\text{Embedding}(V)$ is torsion-free.

Let V be a free \mathbb{Z} -module. Let us note that $\text{Embedding}(V)$ is free.

Let us consider a torsion-free \mathbb{Z} -module V . Now we state the propositions:

- (30) (i) every vector of $\mathbb{Z}\text{-MQVectSp}(V)$ is a vector of $\text{DivisibleMod}(V)$, and

- (ii) every vector of $\text{DivisibleMod}(V)$ is a vector of $\mathbb{Z}\text{-MQVectSp}(V)$, and
 - (iii) $0_{\text{DivisibleMod}(V)} = 0_{\mathbb{Z}\text{-MQVectSp}(V)}$.
- (31) (i) for every vectors x, y of $\text{DivisibleMod}(V)$ and for every vectors v, u of $\mathbb{Z}\text{-MQVectSp}(V)$ such that $x = v$ and $y = u$ holds $x + y = v + u$, and
- (ii) for every vector z of $\text{DivisibleMod}(V)$ and for every vector w of $\mathbb{Z}\text{-MQVectSp}(V)$ and for every element a of $\mathbb{Z}^{\mathbb{R}}$ and for every element a_1 of $\mathbb{F}_{\mathbb{Q}}$ such that $z = w$ and $a = a_1$ holds $a \cdot z = a_1 \cdot w$, and
- (iii) for every vector z of $\text{DivisibleMod}(V)$ and for every vector w of $\mathbb{Z}\text{-MQVectSp}(V)$ and for every element a_1 of $\mathbb{F}_{\mathbb{Q}}$ and for every element a of $\mathbb{Z}^{\mathbb{R}}$ such that $a \neq 0$ and $a_1 = a$ and $a \cdot z = a_1 \cdot w$ holds $z = w$, and
- (iv) for every vector x of $\text{DivisibleMod}(V)$ and for every vector v of $\mathbb{Z}\text{-MQVectSp}(V)$ and for every element r of $\mathbb{F}_{\mathbb{Q}}$ and for every elements m, n of $\mathbb{Z}^{\mathbb{R}}$ and for every integers m_1, n_1 such that $m = m_1$ and $n = n_1$ and $x = v$ and $r \neq 0_{\mathbb{F}_{\mathbb{Q}}}$ and $n \neq 0$ and $r = \frac{m_1}{n_1}$ there exists a vector y of $\text{DivisibleMod}(V)$ such that $x = n \cdot y$ and $r \cdot v = m \cdot y$.

PROOF: For every vector z of $\text{DivisibleMod}(V)$ and for every vector w of $\mathbb{Z}\text{-MQVectSp}(V)$ and for every element a of $\mathbb{Z}^{\mathbb{R}}$ and for every element a_1 of $\mathbb{F}_{\mathbb{Q}}$ such that $z = w$ and $a = a_1$ holds $a \cdot z = a_1 \cdot w$ by [5, (49)], [7, (87)]. For every vector z of $\text{DivisibleMod}(V)$ and for every vector w of $\mathbb{Z}\text{-MQVectSp}(V)$ and for every element a_1 of $\mathbb{F}_{\mathbb{Q}}$ and for every element a of $\mathbb{Z}^{\mathbb{R}}$ such that $a \neq 0$ and $a_1 = a$ and $a \cdot z = a_1 \cdot w$ holds $z = w$ by (30), [9, (8)], [19, (15), (21)]. For every vector x of $\text{DivisibleMod}(V)$ and for every vector v of $\mathbb{Z}\text{-MQVectSp}(V)$ and for every element r of $\mathbb{F}_{\mathbb{Q}}$ and for every elements m, n of $\mathbb{Z}^{\mathbb{R}}$ and for every integers m_1, n_1 such that $m = m_1$ and $n = n_1$ and $x = v$ and $r \neq 0_{\mathbb{F}_{\mathbb{Q}}}$ and $n \neq 0$ and $r = \frac{m_1}{n_1}$ there exists a vector y of $\text{DivisibleMod}(V)$ such that $x = n \cdot y$ and $r \cdot v = m \cdot y$. \square

Now we state the proposition:

- (32) Let us consider a torsion-free \mathbb{Z} -module V , and an element r of $\mathbb{F}_{\mathbb{Q}}$. Then $\text{Embedding}(r, V)$ is a submodule of $\text{DivisibleMod}(V)$. The theorem is a consequence of (25) and (30).

Let V be a finitely generated, torsion-free \mathbb{Z} -module and r be an element of $\mathbb{F}_{\mathbb{Q}}$. Observe that $\text{Embedding}(r, V)$ is finitely generated.

Let V be a non trivial, torsion-free \mathbb{Z} -module and r be a non zero element of $\mathbb{F}_{\mathbb{Q}}$. One can verify that $\text{Embedding}(r, V)$ is non trivial.

Let V be a torsion-free \mathbb{Z} -module and r be an element of $\mathbb{F}_{\mathbb{Q}}$. Observe that $\text{Embedding}(r, V)$ is torsion-free.

Let V be a free \mathbb{Z} -module and r be a non zero element of $\mathbb{F}_{\mathbb{Q}}$. One can check that $\text{Embedding}(r, V)$ is free.

Now we state the propositions:

- (33) Let us consider a non trivial, free \mathbb{Z} -module V , and a vector v of $\text{DivisibleMod}(V)$. Then there exists an element a of $\mathbb{Z}^{\mathbb{R}}$ such that
- (i) $a \in \mathbb{N}$, and
 - (ii) $a \neq 0$, and
 - (iii) $a \cdot v \in \text{Embedding}(V)$, and
 - (iv) for every element b of $\mathbb{Z}^{\mathbb{R}}$ such that $b \in \mathbb{N}$ and $b < a$ and $b \neq 0$ holds $b \cdot v \notin \text{Embedding}(V)$.

PROOF: Consider a_1 being an element of $\mathbb{Z}^{\mathbb{R}}$ such that $a_1 \neq 0$ and $a_1 \cdot v \in \text{Embedding}(V)$. $|a_1| \cdot v \in \text{Embedding}(V)$ by (24), [9, (16), (30)]. Define $\mathcal{P}[\text{natural number}] \equiv$ there exists an element n of $\mathbb{Z}^{\mathbb{R}}$ such that $n = \$_1$ and $n \in \mathbb{N}$ and $n \neq 0$ and $n \cdot v \in \text{Embedding}(V)$. There exists a natural number k such that $\mathcal{P}[k]$ and for every natural number n such that $\mathcal{P}[n]$ holds $k \leq n$ from [2, Sch. 5]. Consider a_0 being a natural number such that $\mathcal{P}[a_0]$ and for every natural number b_0 such that $\mathcal{P}[b_0]$ holds $a_0 \leq b_0$. \square

- (34) Let us consider a finite rank, free \mathbb{Z} -module V . Then $\text{rank Embedding}(V) = \text{rank } V$. The theorem is a consequence of (21).

Let us consider a finite rank, free \mathbb{Z} -module V and a non zero element r of $\mathbb{F}_{\mathbb{Q}}$. Now we state the propositions:

- (35) $\text{rank Embedding}(r, V) = \text{rank Embedding}(V)$. The theorem is a consequence of (27).
- (36) $\text{rank Embedding}(r, V) = \text{rank } V$. The theorem is a consequence of (35) and (34).

Observe that every non trivial, torsion-free \mathbb{Z} -module is infinite.

Now we state the propositions:

- (37) Let us consider a \mathbb{Z} -module V . Then there exists a subset A of V such that
- (i) A is linearly independent, and
 - (ii) for every vector v of V , there exists an element a of $\mathbb{Z}^{\mathbb{R}}$ such that $a \in \mathbb{N}$ and $a > 0$ and $a \cdot v \in \text{Lin}(A)$.

PROOF: Consider A being a subset of V such that $\emptyset \subseteq A$ and A is linearly independent and for every vector v of V , there exists an element a_1 of $\mathbb{Z}^{\mathbb{R}}$ such that $a_1 \neq 0$ and $a_1 \cdot v \in \text{Lin}(A)$. For every vector v of V , there exists

an element a of $\mathbb{Z}^{\mathbb{R}}$ such that $a \in \mathbb{N}$ and $a > 0$ and $a \cdot v \in \text{Lin}(A)$ by [17, (2)], [4, (46)], [18, (3)], [9, (16), (38)]. \square

- (38) Let us consider a non trivial, torsion-free \mathbb{Z} -module V , a non zero vector v of V , a subset A of V , and an element a of $\mathbb{Z}^{\mathbb{R}}$. Suppose $a \in \mathbb{N}$ and A is linearly independent and $a > 0$ and $a \cdot v \in \text{Lin}(A)$. Then there exists a linear combination L of A and there exists a vector u of V such that $a \cdot v = \sum L$ and $u \in A$ and $L(u) \neq 0$.

PROOF: Consider L being a linear combination of A such that $a \cdot v = \sum L$. The support of $L \neq \emptyset$ by [10, (23)]. Consider u_1 being an object such that $u_1 \in$ the support of L . Consider u being a vector of V such that $u = u_1$ and $L(u) \neq 0$. \square

- (39) Let us consider a torsion-free \mathbb{Z} -module V , a non zero integer i , and non zero elements r_1, r_2 of $\mathbb{F}_{\mathbb{Q}}$. Suppose $r_2 = \frac{r_1}{i}$. Then $\text{Embedding}(r_1, V)$ is a submodule of $\text{Embedding}(r_2, V)$.

PROOF: For every vector x of $\text{DivisibleMod}(V)$ such that $x \in \text{Embedding}(r_1, V)$ holds $x \in \text{Embedding}(r_2, V)$ by (27), [6, (11)], (19), [6, (5)]. $\text{Embedding}(r_1, V)$ is a submodule of $\text{DivisibleMod}(V)$ and $\text{Embedding}(r_2, V)$ is a submodule of $\text{DivisibleMod}(V)$. \square

- (40) Let us consider a finite rank, free \mathbb{Z} -module V , and a submodule Z of $\text{DivisibleMod}(V)$. Then Z is finitely generated if and only if there exists a non zero element r of $\mathbb{F}_{\mathbb{Q}}$ such that Z is a submodule of $\text{Embedding}(r, V)$. The theorem is a consequence of (32), (29), (19), (27), (31), and (39).

REFERENCES

- [1] Grzegorz Bancerek. Cardinal arithmetics. *Formalized Mathematics*, 1(3):543–547, 1990.
- [2] Grzegorz Bancerek. The fundamental properties of natural numbers. *Formalized Mathematics*, 1(1):41–46, 1990.
- [3] Grzegorz Bancerek, Czesław Byliński, Adam Grabowski, Artur Korniłowicz, Roman Matuszewski, Adam Naumowicz, Karol Pąk, and Josef Urban. Mizar: State-of-the-art and beyond. In Manfred Kerber, Jacques Carette, Cezary Kaliszyk, Florian Rabe, and Volker Sorge, editors, *Intelligent Computer Mathematics*, volume 9150 of *Lecture Notes in Computer Science*, pages 261–279. Springer International Publishing, 2015. ISBN 978-3-319-20614-1. doi:10.1007/978-3-319-20615-8_17.
- [4] Czesław Byliński. The complex numbers. *Formalized Mathematics*, 1(3):507–513, 1990.
- [5] Czesław Byliński. Functions and their basic properties. *Formalized Mathematics*, 1(1):55–65, 1990.
- [6] Czesław Byliński. Functions from a set to a set. *Formalized Mathematics*, 1(1):153–164, 1990.
- [7] Czesław Byliński. Some basic properties of sets. *Formalized Mathematics*, 1(1):47–53, 1990.
- [8] Wolfgang Ebeling. *Lattices and Codes*. Advanced Lectures in Mathematics. Springer Fachmedien Wiesbaden, 2013.
- [9] Yuichi Futa, Hiroyuki Okazaki, and Yasunari Shidama. \mathbb{Z} -modules. *Formalized Mathematics*, 20(1):47–59, 2012. doi:10.2478/v10037-012-0007-z.

- [10] Yuichi Futa, Hiroyuki Okazaki, and Yasunari Shidama. Quotient module of \mathbb{Z} -module. *Formalized Mathematics*, 20(3):205–214, 2012. doi:10.2478/v10037-012-0024-y.
- [11] Yuichi Futa, Hiroyuki Okazaki, and Yasunari Shidama. Free \mathbb{Z} -module. *Formalized Mathematics*, 20(4):275–280, 2012. doi:10.2478/v10037-012-0033-x.
- [12] Yuichi Futa, Hiroyuki Okazaki, Kazuhisa Nakasho, and Yasunari Shidama. Torsion \mathbb{Z} -module and torsion-free \mathbb{Z} -module. *Formalized Mathematics*, 22(4):277–289, 2014. doi:10.2478/forma-2014-0028.
- [13] Yuichi Futa, Hiroyuki Okazaki, and Yasunari Shidama. Torsion part of \mathbb{Z} -module. *Formalized Mathematics*, 23(4):297–307, 2015. doi:10.1515/forma-2015-0024.
- [14] Eugeniusz Kusak, Wojciech Leończuk, and Michał Muzalewski. Abelian groups, fields and vector spaces. *Formalized Mathematics*, 1(2):335–342, 1990.
- [15] A. K. Lenstra, H. W. Lenstra Jr., and L. Lovász. Factoring polynomials with rational coefficients. *Mathematische Annalen*, 261(4), 1982.
- [16] Daniele Micciancio and Shafi Goldwasser. Complexity of lattice problems: A cryptographic perspective. *The International Series in Engineering and Computer Science*, 2002.
- [17] Jan Popiołek. Some properties of functions modul and signum. *Formalized Mathematics*, 1(2):263–264, 1990.
- [18] Michał J. Trybulec. Integers. *Formalized Mathematics*, 1(3):501–505, 1990.
- [19] Wojciech A. Trybulec. Vectors in real linear space. *Formalized Mathematics*, 1(2):291–296, 1990.
- [20] Edmund Woronowicz. Relations and their basic properties. *Formalized Mathematics*, 1(1):73–83, 1990.

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