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Formalization of Integral Linear Space[1]

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Summary. In this article, we formalize integral linear spaces, that is a linear space with integer coefficients. Integral linear spaces are necessary for lattice problems, LLL (Lenstra-Lenstra-Lovász) base reduction algorithm that outputs short lattice base and cryptographic systems with lattice [8].

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The notation and terminology used here have been introduced in the following papers: [1], [10], [3], [9], [11], [2], [4], [6], [16], [14], [13], [12], [5], [7], [15], and [17].

1. Preliminaries

The following propositions are true:

(1) Let X be a real linear space and R_1, R_2 be finite sequences of elements of X. If $\operatorname{len} R_1 = \operatorname{len} R_2$, then $\sum(R_1 + R_2) = \sum R_1 + \sum R_2$.

(2) Let X be a real linear space and R_1, R_2, R_3 be finite sequences of elements of X. If $\operatorname{len} R_1 = \operatorname{len} R_2$ and $R_3 = R_1 - R_2$, then $\sum R_3 = \sum R_1 - \sum R_2$.

(3) Let X be a real linear space, R_1, R_2 be finite sequences of elements of X, and a be an element of $\mathbb{R}$. If $R_2 = a\, R_1$, then $\sum R_2 = a \cdot \sum R_1$.

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2. Integral Linear Space

For simplicity, we use the following convention: x denotes a set, a denotes a real number, i denotes an integer, V denotes a real linear space, v, v_1, v_2, v_3, u, w, w_1, w_2, w_3 denote vectors of V, A, B denote subsets of V, L denotes a linear combination of V, and l, l_1, l_2 denote linear combinations of A.

Let us consider V, i, L. The functor $i \cdot L$ yielding a linear combination of V is defined as follows:

(Def. 1) For every v holds $(i \cdot L)(v) = i \cdot L(v)$.

Let us consider V, A. The functor $\mathrm{Lin}_{\mathbb{Z}}\, A$ yielding a subset of V is defined by:

(Def. 2) $\mathrm{Lin}_{\mathbb{Z}}\, A = \{\sum l : \mathrm{rng}\, l \subseteq \mathbb{Z}\}$.

One can prove the following propositions:

(4) $(i) \cdot l = i \cdot l$.

(5) If $\mathrm{rng}\, l_1 \subseteq \mathbb{Z}$ and $\mathrm{rng}\, l_2 \subseteq \mathbb{Z}$, then $\mathrm{rng}(l_1 + l_2) \subseteq \mathbb{Z}$.

(6) If $\mathrm{rng}\, l \subseteq \mathbb{Z}$, then $\mathrm{rng}(i \cdot l) \subseteq \mathbb{Z}$.

(7) $\mathrm{rng}(\mathbf{0}_{\mathrm{LC}_V}) \subseteq \mathbb{Z}$.

(8) $\mathrm{Lin}_{\mathbb{Z}}\, A \subseteq$ the carrier of $\mathrm{Lin}(A)$.

(9) If v, $u \in \mathrm{Lin}_{\mathbb{Z}}\, A$, then $v + u \in \mathrm{Lin}_{\mathbb{Z}}\, A$.

(10) If $v \in \mathrm{Lin}_{\mathbb{Z}}\, A$, then $i \cdot v \in \mathrm{Lin}_{\mathbb{Z}}\, A$.

(11) $0_V \in \mathrm{Lin}_{\mathbb{Z}}\, A$.

(12) If $x \in A$, then $x \in \mathrm{Lin}_{\mathbb{Z}}\, A$.

(13) If $A \subseteq B$, then $\mathrm{Lin}_{\mathbb{Z}}\, A \subseteq \mathrm{Lin}_{\mathbb{Z}}\, B$.

(14) $\mathrm{Lin}_{\mathbb{Z}}(A \cup B) = (\mathrm{Lin}_{\mathbb{Z}}\, A) + \mathrm{Lin}_{\mathbb{Z}}\, B$.

(15) $\mathrm{Lin}_{\mathbb{Z}}(A \cap B) \subseteq (\mathrm{Lin}_{\mathbb{Z}}\, A) \cap \mathrm{Lin}_{\mathbb{Z}}\, B$.

(16) $x \in \mathrm{Lin}_{\mathbb{Z}}\{v\}$ iff there exists an integer a such that $x = a \cdot v$.

(17) $v \in \mathrm{Lin}_{\mathbb{Z}}\{v\}$.

(18) $x \in v + \mathrm{Lin}_{\mathbb{Z}}\{w\}$ iff there exists an integer a such that $x = v + a \cdot w$.

(19) $x \in \mathrm{Lin}_{\mathbb{Z}}\{w_1, w_2\}$ iff there exist integers a, b such that $x = a \cdot w_1 + b \cdot w_2$.

(20) $w_1 \in \mathrm{Lin}_{\mathbb{Z}}\{w_1, w_2\}$.

(21) $x \in v + \mathrm{Lin}_{\mathbb{Z}}\{w_1, w_2\}$ iff there exist integers a, b such that $x = v + a \cdot w_1 + b \cdot w_2$.

(22) $x \in \mathrm{Lin}_{\mathbb{Z}}\{v_1, v_2, v_3\}$ iff there exist integers a, b, c such that $x = a \cdot v_1 + b \cdot v_2 + c \cdot v_3$.

(23) w_1, w_2, $w_3 \in \mathrm{Lin}_{\mathbb{Z}}\{w_1, w_2, w_3\}$.

(24) $x \in v + \mathrm{Lin}_{\mathbb{Z}}\{w_1, w_2, w_3\}$ iff there exist integers a, b, c such that $x = v + a \cdot w_1 + b \cdot w_2 + c \cdot w_3$.

(25) Let x be a set. Then $x \in \mathrm{Lin}_{\mathbb{Z}} A$ if and only if there exist finite sequences g_1, h_1 of elements of V and there exists an integer-valued finite sequence a_1 such that $x = \sum h_1$ and $\mathrm{rng}\, g_1 \subseteq A$ and $\mathrm{len}\, g_1 = \mathrm{len}\, h_1$ and $\mathrm{len}\, g_1 = \mathrm{len}\, a_1$ and for every natural number i such that $i \in \mathrm{Seg}\, \mathrm{len}\, g_1$ holds $(h_1)_i = a_1(i) \cdot (g_1)_i$.

Let R_4 be a real linear space and let f be a finite sequence of elements of R_4. The functor $\mathrm{Lin}_{\mathbb{Z}} f$ yielding a subset of R_4 is defined by the condition (Def. 3).

(Def. 3) $\mathrm{Lin}_{\mathbb{Z}} f = \{\sum g; g$ ranges over $\mathrm{len}\, f$-element finite sequences of elements of R_4: $\bigvee_{a:\ \mathrm{len}\, f\text{-element integer-valued finite sequence}} \bigwedge_{i:\,\text{natural number}} (i \in \mathrm{Seg}\, \mathrm{len}\, f \Rightarrow g_i = a(i) \cdot f_i)\}$.

One can prove the following propositions:

(26) Let R_4 be a real linear space, f be a finite sequence of elements of R_4, and x be a set. Then $x \in \mathrm{Lin}_{\mathbb{Z}} f$ if and only if there exists a $\mathrm{len}\, f$-element finite sequence g of elements of R_4 and there exists a $\mathrm{len}\, f$-element integer-valued finite sequence a such that $x = \sum g$ and for every natural number i such that $i \in \mathrm{Seg}\, \mathrm{len}\, f$ holds $g_i = a(i) \cdot f_i$.

(27) Let R_4 be a real linear space, f be a finite sequence of elements of R_4, x, y be elements of R_4, and a, b be elements of $\mathbb{Z}$. If $x, y \in \mathrm{Lin}_{\mathbb{Z}} f$, then $a \cdot x + b \cdot y \in \mathrm{Lin}_{\mathbb{Z}} f$.

(28) For every real linear space R_4 and for every finite sequence f of elements of R_4 such that $f = \mathrm{Seg}\, \mathrm{len}\, f \longmapsto 0_{(R_4)}$ holds $\sum f = 0_{(R_4)}$.

(29) Let R_4 be a real linear space, f be a finite sequence of elements of R_4, v be an element of R_4, and i be a natural number. If $i \in \mathrm{Seg}\, \mathrm{len}\, f$ and $f = (\mathrm{Seg}\, \mathrm{len}\, f \longmapsto 0_{(R_4)}) {+\cdot} (\{i\} \longmapsto v)$, then $\sum f = v$.

(30) Let R_4 be a real linear space, f be a finite sequence of elements of R_4, and i be a natural number. If $i \in \mathrm{Seg}\, \mathrm{len}\, f$, then $f_i \in \mathrm{Lin}_{\mathbb{Z}} f$.

(31) For every real linear space R_4 and for every finite sequence f of elements of R_4 holds $\mathrm{rng}\, f \subseteq \mathrm{Lin}_{\mathbb{Z}} f$.

(32) Let R_4 be a real linear space, f be a non empty finite sequence of elements of R_4, g, h be finite sequences of elements of R_4, and s be an integer-valued finite sequence. Suppose $\mathrm{rng}\, g \subseteq \mathrm{Lin}_{\mathbb{Z}} f$ and $\mathrm{len}\, g = \mathrm{len}\, s$ and $\mathrm{len}\, g = \mathrm{len}\, h$ and for every natural number i such that $i \in \mathrm{Seg}\, \mathrm{len}\, g$ holds $h_i = s(i) \cdot g_i$. Then $\sum h \in \mathrm{Lin}_{\mathbb{Z}} f$.

(33) For every real linear space R_4 and for every non empty finite sequence f of elements of R_4 holds $\mathrm{Lin}_{\mathbb{Z}}\, \mathrm{rng}\, f = \mathrm{Lin}_{\mathbb{Z}} f$.

(34) $\mathrm{Lin}(\mathrm{Lin}_{\mathbb{Z}} A) = \mathrm{Lin}(A)$.

(35) Let x be a set, g_1, h_1 be finite sequences of elements of V, and a_1 be an integer-valued finite sequence. Suppose $x = \sum h_1$ and $\mathrm{rng}\, g_1 \subseteq \mathrm{Lin}_{\mathbb{Z}} A$ and $\mathrm{len}\, g_1 = \mathrm{len}\, h_1$ and $\mathrm{len}\, g_1 = \mathrm{len}\, a_1$ and for every natural number i such that $i \in \mathrm{Seg}\, \mathrm{len}\, g_1$ holds $(h_1)_i = a_1(i) \cdot (g_1)_i$. Then $x \in \mathrm{Lin}_{\mathbb{Z}} A$.

(36) $\mathrm{Lin}_{\mathbb{Z}}\,\mathrm{Lin}_{\mathbb{Z}}\,A = \mathrm{Lin}_{\mathbb{Z}}\,A$.

(37) If $\mathrm{Lin}_{\mathbb{Z}}\,A = \mathrm{Lin}_{\mathbb{Z}}\,B$, then $\mathrm{Lin}(A) = \mathrm{Lin}(B)$.

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