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The group $K_1(S_n)$ of the algebra of one-sided inverses of a polynomial algebra

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Abstract
The algebra $S_n$ of one-sided inverses of a polynomial algebra $P_n$ in $n$ variables is obtained from $P_n$ by adding commuting, left (but not two-sided) inverses of the canonical generators of the algebra $P_n$. The algebra $S_n$ is a noncommutative, non-Noetherian algebra of classical Krull dimension $2n$ and of global dimension $n$ and is not a domain. If the ground field $K$ has characteristic zero then the algebra $S_n$ is canonically isomorphic to the algebra $K(\frac{\partial}{\partial x_1}, \ldots, \frac{\partial}{\partial x_n}, f_1, \ldots, f_n)$ of scalar integro-differential operators. It is proved that $K_1(S_n) \simeq K^*$. The main idea is to show that the group $GL_\infty(S_n)$ is generated by $K^*$, the group of elementary matrices $E_\infty(S_n)$ and $(n - 2)2^{n-2} + 1$ explicit (tricky) matrices and then to prove that all the matrices are elementary. For each nonzero idempotent prime ideal $p$ of height $m$ of the algebra $S_n$, it is proved that

$$K_1(S_n, p) \simeq \begin{cases} K^*, & \text{if } m = 1, \\ \mathbb{Z}^{\frac{(m-1)}{2}} \times K^*, & \text{if } m > 1. \end{cases}$$

Key Words: the group $K_1$, the current groups, the group of automorphisms, group generators, the group of units, the semi-direct and the exact products of groups, the minimal primes.


1 Introduction
Throughout, ring means an associative ring with 1; module means a left module; $\mathbb{N} := \{0, 1, \ldots\}$ is the set of natural numbers; $K$ is a field and $K^*$ is its group of units; $P_n := K[x_1, \ldots, x_n]$ is a polynomial algebra over $K$; $\partial_i := \frac{\partial}{\partial x_i}$, $\partial := \frac{\partial}{\partial x_n}$ are the usual partial derivatives ($K$-linear derivations) of $P_n$; $\text{End}_K(P_n)$ is the algebra of all $K$-linear maps from $P_n$ to $P_n$ and $\text{Aut}_K(P_n)$ is its group of units (i.e. the group of all the invertible linear maps from $P_n$ to $P_n$); the subalgebra $A_n := K(x_1, \ldots, x_n, \partial_1, \ldots, \partial_n)$ of $\text{End}_K(P_n)$ is called the $n$’th Weyl algebra.

Definition, [5]. The algebra $S_n = S_n(K)$ of one-sided inverses of $P_n$ is the algebra generated over a field (or a ring) $K$ of by $2n$ elements $x_1, \ldots, x_n, y_1, \ldots, y_n$ that satisfy the defining relations:

$$y_1 x_1 = 1, \ldots, y_n x_n = 1, \quad [x_i, y_j] = [x_i, x_j] = [y_i, y_j] = 0 \quad \text{for all } i \neq j,$$

where $[a, b] := ab - ba$ is the algebra commutator of elements $a$ and $b$.

By the very definition, the algebra $S_n$ is obtained from the polynomial algebra $P_n$ by adding commuting, left (but not two-sided) inverses of its canonical generators. The algebra $S_1 = K(x, y | xy = 1)$ is a well-known primitive algebra [12], p. 35, Example 2. Over the field $\mathbb{C}$ of complex numbers, the completion of the algebra $S_1$ is the Toeplitz algebra which is the $C^*$-algebra generated by a unilateral shift on the Hilbert space $l^2(\mathbb{N})$ (note that $y = x^*$). The Toeplitz algebra is the universal $C^*$-algebra generated by a proper isometry. If $\text{char}(K) = 0$ then the algebra $S_n$ is isomorphic to the algebra $K(\frac{\partial}{\partial x_1}, \ldots, \frac{\partial}{\partial x_n}, f_1, \ldots, f_n)$ of scalar integro-differential operators (via $x_i \mapsto f_i$, $y_i \mapsto \frac{\partial}{\partial x_i}$).
In [7], it is proved that \( K_1(S_1) \simeq K^* \). The first aim of the paper is to prove that

- (Theorem 3.5) \( K_1(S_n) \simeq K^* \) for all \( n \geq 1 \).

The algebra \( S_n \) was studied in detail in [5]: its Gelfand-Kirillov dimension is \( 2n \), its classical Krull dimension \( \text{clKdim}(S_n) = 2n \), and its weak and global dimensions are \( n \). The algebra \( S_n \) is neither left nor right Noetherian as was shown by Jacobson [11] when \( n = 1 \) (see also Baer [1]). Moreover, it contains infinite direct sums of left and right ideals. It is an experimental fact that the algebra \( S_n \simeq S_1^{\otimes n} \) has properties that are a mixture of properties of the Weyl algebra \( A_n \simeq A_1^{\otimes n} \) (in characteristic zero) and the polynomial algebra \( P_{2n} \simeq P_2^{\otimes n} \) which is not surprising when we look at their defining relations:

\[
\begin{align*}
P_2 &= K\langle x, y \rangle : \ yx - xy = 0; \\
A_1 &= K\langle x, y \rangle : \ yx - xy = 1; \\
S_1 &= K\langle x, y \rangle : \ yx = 1.
\end{align*}
\]

The group \( G_n := \text{Aut}_{K-\text{alg}}(S_n) \) of \( K \)-algebra automorphisms of \( S_n \) and the group \( S_n^* \) of units of the algebra \( S_n \) were determined in the series of three papers [6], [7], and [8], and their explicit generators were found (both groups are huge). The group \( G_1 \) was found by Gerritzen [10]).

**Theorem 1.1**

1. [6] \( G_n = S_n \times T^n \times \text{Inn}(S_n) \) where \( S_n \) is the symmetric group, \( T^n \simeq K^{*n} \) is the \( n \)-dimensional algebraic torus and \( \text{Inn}(S_n) \) is the group of inner automorphisms of \( S_n \).

2. [7], [8] \( S_n^* = K^* \times (1 + a_n)^* \) where \( a_n \) is the ideal generated by all the height one prime ideals of \( S_n \).

3. [8] The centre of the group \( S_n^* \) is \( K^* \) and the centre of the group \( (1 + a_n)^* \) is \( \{1\} \).

4. [8] The map \( (1 + a_n)^* \to \text{Inn}(S_n), u \mapsto \omega_u \), is a group isomorphism \( (\omega_u(a) = uau^{-1}) \).

The structure of the proof of Theorem 3.5

The idea of the proof that \( K_1(S_n) \simeq K^* \) (Theorem 3.5) is to use the fact that the group \( \text{GL}_\infty(S_{n-1}) \) is canonically isomorphic to the congruence subgroup \( (1 + p_n)^* \) of \( S_n^* = K^* \times (1 + a_n)^* \), \( (1 + p_n)^* \subseteq (1 + a_n)^* \), where \( p_n \) is an (arbitrary) height one prime ideal of the algebra \( S_n \). The group \( S_n^* \) is huge, e.g.

\[
S_n^* \supset (1 + a_n)^* \supset \underbrace{\text{GL}_\infty(K) \times \cdots \times \text{GL}_\infty(K)}_{2^n-1 \text{ times}}, \tag{1}
\]

the iterated semi-direct product being a small part of the group \( S_n^* \). The key ingredients in finding the groups \( G_n, \text{Inn}(S_n) \) and \( S_n^* \) (and their explicit generators) are the Fredholm operators and their indices, the current subgroups, and the \( K_1 \)-theory. This explains why it is possible to recover the group \( \text{GL}_\infty(S_{n-1}) \) in \( S_n^* \) (this is not straightforward), to find its explicit generators. We prove in Theorem 3.3, Lemma 3.2 and (34)) that

- the group \( \text{GL}_\infty(S_n) \) is generated by \( K^* \), the group of elementary matrices \( E_\infty(S_n) \) and \((n - 2)2^{n-1} + 1 \) matrices \( \big( \begin{smallmatrix} \theta_{ij}(J) & 0 \\ 0 & 1 \end{smallmatrix} \big) \) (Lemma 3.1) where (see (10))

\[
\theta_{ij}(J) := (1 + (y_i - 1) \prod_{k \in J \setminus i} \quad (1 - x_{ij}y_k)(1 + (x_j - 1) \prod_{l \in J \setminus j} (1 - x_{ij}y_l)) \in (1 + a_n)^*.
\]

J is a subset of \( \{1, \ldots, n\} \) with \( |J| \geq 2 \), \( i \) is the largest number in \( J \) and \( j \in J \setminus i \).

The final and the most difficult part of the proof is to show that
• (Theorem 3.4) all the above matrices \((\theta_{ij}(J) \ 0 \ 0)\) are elementary, i.e. the units \(\theta_{ij}(J)\) are elementary when regarded as matrices via the inclusion \(\text{GL}_1(S_n) \subseteq \text{GL}_\infty(S_n)\). □

We spend all of Section 4 to prove this fact.

• (Theorem 5.7) Let \(p\) be a nonzero idempotent prime ideal of the algebra \(S_n\) and \(m = \text{ht}(p)\) be its height. Then

\[
\text{K}_1(S_n, p) \simeq \begin{cases} 
K^*, & \text{if } m = 1, \\
\mathbb{Z}^* \times K^m & \text{if } m > 1.
\end{cases}
\]

Let \(\Theta_{n,s}, \ s = 1, \ldots, n - 1\), denote the finitely generated subgroup of the group \((1 + a_n)^*\), generated by the elements \(\theta_{ij}(J)\) where \(J\) is a subset of \([1, \ldots, n]\) with \(|J| = s + 1 \geq 2\), and \(i\) and \(j\) are two distinct elements of the set \(J\). These, the so-called current subgroups, were introduced in \([7]\) and \([8]\), and they are the core (the non-obvious part) of the groups \(G_n\), \(\text{Inn}(S_n)\), and \(S_n^*\), and the key for determining the groups \(\text{GL}_\infty(S_n)\), \(\text{K}_1(S_n)\), \(\text{GL}_\infty(S_n, p)\) and \(\text{K}_1(S_n, p)\), as this paper demonstrates.

The paper is organized as follows. In Section 2, some necessary results and constructions are collected for the algebra \(S_n\) and the group \((1 + a_n)^*\). In Section 3, the groups \(\text{K}_1(S_n)\), \(\text{GL}_\infty(S_n)\) and their explicit generators are found. In Section 4, Theorem 3.4 is proved. In Section 5, the groups \(\text{GL}_\infty(S_n, p)\), \(\text{K}_1(S_n, p)\) and explicit generators for them are found, and Theorem 5.7 is proved.

The structure of the proof of Theorem 5.7 The line of proof of Theorem 5.7 follows that of Theorem 3.4 (but there are new moments): first, we prove that the group \(\text{GL}_\infty(S_n, p)\) is generated by the group \(E_\infty(S_n, p)\) of \(p\)-elementary matrices, some explicit ‘diagonal’ matrices, and some of the matrices \((\theta_{ij}(J) \ 0 \ 0)\) (Theorem 5.2, Lemma 5.4). Then an ‘obvious’ normal subgroup \(\mathcal{E}(S_n, p)\) of \(\text{GL}_\infty(S_n, p)\) is introduced and we prove that

\[
\text{GL}_\infty(S_n, p)/\mathcal{E}(S_n, p) \simeq \begin{cases} 
K^*, & \text{if } m = 1, \\
\mathbb{Z}^* \times K^m & \text{if } m > 1.
\end{cases}
\]

This gives the inclusion \(E_\infty(S_n, p) \subseteq \mathcal{E}(S_n, p)\). The key moment in proving that the opposite inclusion holds is (surprisingly) the fact that \(\text{K}_1(S_n) \simeq K^*\). The new moment is that not all the ‘diagonal’ matrices and not all the matrices \((\theta_{ij}(J) \ 0 \ 0)\) that form a part of the generating set for the group \(\text{GL}_\infty(S_n, p)\) are \(p\)-elementary. □

A canonical form is found (Theorem 5.7) for each element \(a \in \text{GL}_\infty(S_n, p)\). Using it, an effective criterion (Corollary 5.10) is given for an element \(a \in \text{GL}_\infty(S_n, p)\) to be a product of \(p\)-elementary matrices, i.e. \(a \in E_\infty(S_n, p)\).

2 The groups \(S_n^*\) and \((1 + a_n)^*\) and their subgroups

In this section, we collect some results without proofs on the algebras \(S_n\) from \([5]\) and \([8]\) that will be used in this paper, their proofs can be found in \([5]\) and \([8]\). Several important subgroups of the group \((1 + a_n)^*\) are considered. The most interesting of these are the current subgroups \(\Theta_{n,s}, \ s = 1, \ldots, n - 1\). They encapsulate the most difficult parts of the groups \(S_n^*\) and \(G_n\).

The algebra of one-sided inverses of a polynomial algebra. Clearly, \(S_n = S_1(1) \otimes \cdots \otimes S_1(n) \simeq S_n^m\) where \(S_1(i) := K(x_i, y_i)\), \(y_i x_i = 1\), \(S_1\) and \(S_n = \bigoplus_{\alpha, \beta \in \mathbb{N}^m} K^\alpha y^\beta\) where \(x_\alpha := x_1^\alpha_1 \cdots x_n^\alpha_n, \ \alpha = (\alpha_1, \ldots, \alpha_n)\), \(y_\beta := y_1^{\beta_1} \cdots y_n^{\beta_n}\) and \(\beta = (\beta_1, \ldots, \beta_n)\). In particular, the algebra \(S_n\) contains two polynomial subalgebras \(P_n\) and \(Q_n := K[y_1, \ldots, y_n]\) and is equal, as a vector space, to their tensor product \(P_n \otimes Q_n\).
For all natural numbers \( i \), the ideal \( F_{i,j} := F_{i,j} \) of the algebra of infinite dimensional matrices. The algebra \( \{ E_{i,j} \} \) are the matrix units, and

\[
M_{\infty}(K) := \lim_{\to\infty} M_d(K) = \bigoplus_{i,j \in \mathbb{N}} KE_{i,j}
\]
is the algebra (without 1) of infinite dimensional matrices. The algebra \( S_1 \) contains the ideal \( F := \bigoplus_{i,j \in \mathbb{N}} KE_{i,j} \), where

\[
E_{i,j} := x^i y^j - x^{i+1} y^{j+1}, \quad i, j \geq 0.
\]

For all natural numbers \( i, j, k \), and \( l \), \( E_{i,j} E_{k,l} = \delta_{ik} E_{j,l} \) where \( \delta_{jk} \) is the Kronecker delta function. The ideal \( F \) is an algebra (without 1) isomorphic to the algebra (without 1) \( M_{\infty}(K) \) via \( E_{i,j} \to E_{i,j} \). For all \( i, j \geq 0 \),

\[
x E_{i,j} = E_{i+1,j}, \quad y E_{i,j} = E_{i-1,j} \quad (E_{-1,j} := 0),
\]

\[
E_{i,j} x = E_{i,j-1}, \quad E_{i,j} y = E_{i,j+1} \quad (E_{i,-1} := 0).
\]

The algebra \( S_1 = K \oplus xK[x] \oplus yK[y] \oplus F \) is a direct sum of vector spaces. Then

\[
S_1 / F \simeq K[x, x^{-1}] =: L_1, \quad x \mapsto x, \quad y \mapsto x^{-1},
\]
since \( x y = 1, \ y x = 1 - E_{00} \) and \( E_{00} \in F \).

The algebra \( S_n = \bigotimes_{i=1}^n S_1(i) \) contains the ideal

\[
F_n := F^\otimes n = \bigoplus_{\alpha, \beta \in \mathbb{N}^n} KE_{\alpha,\beta}, \quad \text{where} \quad E_{\alpha,\beta} := \prod_{i=1}^n E_{\alpha_i,\beta_i}(i), \quad E_{\alpha,\beta}(i) := x_1^{\alpha_1} y_1^{\beta_1} - x_1^{\alpha_1+1} y_1^{\beta_1+1}.
\]

Note that \( E_{\alpha,\beta} E_{\gamma,\rho} = \delta_{\beta,\gamma} E_{\alpha,\rho} \) for all elements \( \alpha, \beta, \gamma, \rho \in \mathbb{N}^n \) where \( \delta_{\beta,\gamma} \) is the Kronecker delta function; \( F_n = \bigotimes_{i=1}^n F(i) \) and \( F(i) := \bigoplus_{\alpha, \beta \in \mathbb{N}^n} KE_{\alpha,\beta}(i) \).

- The algebra \( S_n \) is central, prime and catenary. Every nonzero ideal of \( S_n \) is an essential left and right submodule of \( S_n \).
- The ideals of \( S_n \) commute (\( IJ = JI \)); and the set of ideals of \( S_n \) satisfy the a.c.c.
- \( a \cap b = ab \) for all idempotent ideals \( a \) and \( b \) of the algebra \( S_n \);
- The classical Krull dimension \( \text{cl.Kdim}(S_n) \) of \( S_n \) is \( 2n \).
- Let \( I \) be an ideal of \( S_n \). Then the factor algebra \( S_n / I \) is left (or right) Noetherian iff the ideal \( I \) contains all the height one prime ideals of the algebra \( S_n \).

The set of height one prime ideals of \( S_n \). Consider the ideals of the algebra \( S_n \):

\[
p_1 := F \otimes S_{n-1}, \quad p_2 := S_1 \otimes F \otimes S_{n-2}, \ldots, \quad p_n := S_{n-1} \otimes F.
\]

Then \( S_n / p_i \simeq S_{n-1} \otimes (S_1 / F) \simeq S_{n-1} \otimes K[x_i, x_i^{-1}] \) and \( \bigcap_{i=1}^n p_i = \prod_{i=1}^n p_i = F^\otimes n = F_n \). Clearly, \( p_i \not\subseteq p_j \) for all \( i \neq j \).

- The set \( \mathcal{H}_1 \) of height one prime ideals of the algebra \( S_n \) is \( \{ p_1, \ldots, p_n \} \).
Let \( a_n := p_1 + \cdots + p_n \). Then the factor algebra
\[
S_n/a_n \simeq (S_1/F)^{\otimes n} \simeq \bigotimes_{i=1}^{n} K[x_i, x_i^{-1}] = K[x_1, x_1^{-1}, \ldots, x_n, x_n^{-1}] =: L_n
\]
is a skew Laurent polynomial algebra in \( n \) variables, and so \( a_n \) is a prime ideal of height and co-height \( n \) of the algebra \( S_n \).

**Proposition 2.1** \([5]\) The polynomial algebra \( P_n \) is the only (up to isomorphism) faithful simple \( S_n \)-module.

In more detail, \( s_n P_n \simeq S_n / (\sum_{i=0}^{n} S_n y_i) = \bigoplus_{\alpha \in \mathbb{Z}} K x^\alpha \bigotimes \mathbb{T} := 1 + \sum_{i=1}^{n} S_n y_i \); and the action of the canonical generators of the algebra \( S_n \) on the polynomial algebra \( P_n \) is given by the rule:
\[
x_i \ast x^\alpha = x^{\alpha + e_i}, \quad y_i \ast x^\alpha = \begin{cases} x^{\alpha - e_i} & \text{if } \alpha_i > 0, \\ 0 & \text{if } \alpha_i = 0, \end{cases}
\]
and \( E_{\gamma \alpha} \ast x^\alpha = \delta_{\gamma \alpha} x^\beta \),
where the set \( e_1 := (1, 0, \ldots, 0), \ldots, e_n := (0, \ldots, 0, 1) \) is the canonical basis for the free \( \mathbb{Z} \)-module \( \mathbb{Z}^n = \bigoplus_{i=1}^{n} \mathbb{Z} e_i \). We identify the algebra \( S_n \) with its image in the algebra \( \text{End}_K(P_n) \) of all the \( K \)-linear maps from the vector space \( P_n \) to itself, i.e. \( S_n \subset \text{End}_K(P_n) \).

For each non-empty subset \( I \) of the set \( \{1, \ldots, n\} \), let \( S_I := \bigotimes_{i \in I} S_1 \) be its group of units, and let \( [I] \) be the number of elements in the set \( I \). If \( f_I := \bigotimes_{i \in I} F(i) \simeq M_{[I]}(K) \), \( a_I \) is the ideal of the algebra \( S_I \) generated by the vector space \( \bigoplus_{i \in I} F(i) \), i.e. \( a_I := \bigoplus_{i \in I} F(i) \otimes S_{\bar{I}} / a_\bar{I} \). The factor algebra \( L_I := S_I/a_I \simeq K[x_i, x_i^{-1}] \) is a Laurent polynomial algebra. For elements \( \alpha = (\alpha_i)_{i \in I}, \beta = (\beta_i)_{i \in I} \in \mathbb{N}^I \), let \( E_{\alpha \beta}(I) := \bigoplus_{i \in I} E_{\alpha_i \beta_i}(i) \). Then \( E_{\alpha \beta}(I) E_{\rho \gamma}(I) = \delta_{\beta \rho} E_{\alpha \gamma}(I) \) for all \( \alpha, \beta, \xi, \rho \in \mathbb{N}^I \).

**The \( G_n \)-invariant normal subgroups** \((1 + a_{n,s})^* \) of \((1 + a_n)^*\). Let \( G_n := \text{Aut}_{-\text{alg}}(S_n) \). We will use often the following obvious lemma.

**Lemma 2.2** \([5]\) Let \( R \) be a ring and \( I_1, \ldots, I_n \) be ideals of the ring \( R \) such that \( I_i I_j = 0 \) for all \( i \neq j \). Let \( a = 1 + a_1 + \cdots + a_n \in R \) where \( a_1 \in I_1, \ldots, a_n \in I_n \). The element \( a \) is a unit of the ring \( R \) if all the elements \( 1 + a_i \) are units; and, in this case, \( a^{-1} = (1 + a_1)^{-1} (1 + a_2)^{-1} \cdots (1 + a_n)^{-1} \).

Let \( R \) be a ring, \( R^* \) be its group of units, \( I \) be an ideal of \( R \) such that \( I \neq R \), and let \((1 + I)^* \) be the group of units of the multiplicative monoid \( 1 + I \). Then \((R^* \cap (1 + I)) = (1 + I)^* \) and \((1 + I)^* \) is a normal subgroup of \( R^* \).

For each subset \( I \) of the set \( \{1, \ldots, n\} \), let \( p_I := \bigcap_{i \in I} p_i \), and \( p_\emptyset := S_n \). Each \( p_I \) is an ideal of the algebra \( S_n \) and \( p_I = \bigcap_{i \in I} p_i \). The complement to the subset \( I \) is denoted by \( C_i \). For a one-element subset \( \{i\} \), we write \( C_i \) rather than \( C \{i\} \). In particular, \( p_{C_i} := \bigcap_{i \neq i} p_j \).

For each number \( s = 1, \ldots, n \), let \( a_{n,s} := \sum_{|I|=s} p_I \). By the very definition, the ideals \( a_{n,s} \) are \( G_n \)-invariant ideals (since the set \( H_1 \) of all the height one prime ideals of the algebra \( S_n \) is \( \{p_1, \ldots, p_n\} \), \( \mathbb{E} \), and \( H_1 \) is a \( G_n \)-orbit). We have a strictly descending chain of \( G_n \)-invariant ideals of the algebra \( S_n \):
\[
a_n = a_{n,1} \supset a_{n,2} \supset \cdots \supset a_{n,s} \supset \cdots \supset a_{n,n} = F_n \supset a_{n,n+1} := 0.
\]

These are also ideals of the subalgebra \( K + a_n \) of \( S_n \). Each set \( a_{n,s} \) is an ideal of the algebra \( K + a_{n,t} \) for all \( t \leq s \), and the group of units of the algebra \( K + a_{n,s} \) is the direct product of its two subgroups
\[
(K + a_{n,s})^* = K^* \times (1 + a_{n,s})^*, \quad s = 1, \ldots, n.
\]
The groups \((K + a_{n,s})^* \) and \((1 + a_{n,s})^* \) are \( G_n \)-invariant. There is the descending chain of \( G_n \)-invariant (hence normal) subgroups of \((1 + a_n)^*\):
\[
(1 + a_n)^* = (1 + a_{n,1})^* \supset (1 + a_{n,s})^* \supset \cdots \supset (1 + a_{n,n})^* = (1 + F_n)^* \supset (1 + a_{n,n+1})^* = \{1\}.
\]
For each number $s = 1, \ldots, n$, the factor algebra
\[
(K + a_{n,s})/a_{n,s+1} = K \bigoplus_{|I|=s} \mathfrak{p}_I
\]
contains the idempotent ideals $\mathfrak{p}_I := (p_I + a_{n,s+1})/a_{n,s+1}$ such that $\mathfrak{p}_I \mathfrak{p}_J = 0$ for all $I \neq J$ such that $|I| = |J| = s$.

Recall that for a Laurent polynomial algebra $L = K[x_1^{\pm 1}, \ldots, x_n^{\pm 1}]$, $K_1(L) \simeq L^*$, \cite{14}, \cite{2}, \cite{13},
\[
GL_\infty(L) = U(L) \times E_\infty(L)
\]
where $E_\infty(L)$ is the subgroup of $GL_\infty(L)$ generated by all the *elementary matrices* $\{1 + aE_{ij} \mid a \in L, i, j \in \mathbb{N}, i \neq j\}$, and $U(L) := \{\mu(u) := uE_{00} + 1 - E_{00} \mid u \in L^* \} \simeq L^*$, $\mu(u) \leftrightarrow u$. The group $E_\infty(L)$ is a normal subgroup of $GL_\infty(L)$. This is true for an arbitrary coefficient ring.

By Lemma \cite{2} and \cite{3}, the group of units of the algebra $(K + a_{n,s})/a_{n,s+1} =: K + a_{n,s}/a_{n,s+1}$ is the direct product of groups,
\[
(K + a_{n,s}/a_{n,s+1})^* = K^* \times \prod_{|I|=s} (1 + \mathfrak{p}_I)^* \simeq K^* \times \prod_{|I|=s} GL_\infty(L_{CI}) \simeq K^* \times \prod_{|I|=s} U(L_{CI}) \times E_\infty(L_{CI})
\]
since $(1 + \mathfrak{p}_I)^* \simeq (1 + M_\infty(L_{CI}))^* = GL_\infty(L_{CI})$ where $L_{CI} := S_{CI}/a_{CI} = \bigotimes_{i \in CI} K[x_i, x_i^{-1}]$ is the Laurent polynomial algebra. In more detail, for each non-empty subset $I$ of $\{1, \ldots, n\}$, let $\mathbb{Z}^I := \bigoplus_{i \in I} \mathbb{Z} e_i$. It is a subgroup of $\mathbb{Z}^n = \bigoplus_{i=1}^n \mathbb{Z} e_i$. Similarly, $\mathbb{N}^I := \bigoplus_{i \in I} \mathbb{N} e_i$. By \cite{3},
\[
(1 + \mathfrak{p}_I)^* = U(L_{CI}) \times E_\infty(L_{CI}) = (U(I)(K) \times X_{CI}) \times E_\infty(L_{CI})
\]
where
\[
U(L_{CI}) := \{\mu_I(u) := uE_{00}(I) + 1 - E_{00}(I) \mid u \in L_{CI} \} \simeq L_{CI}^*, \mu_I(u) \leftrightarrow u,
\]
\[
L_{CI}^* = \{\lambda \alpha^x \mid \lambda \in K^*, \alpha \in Z_{CI}\},
\]
\[
U_I(K) := \{\mu_I(\lambda) := \lambda E_{00}(I) + 1 - E_{00}(I) \mid \lambda \in K^* \} \simeq K^*, \mu_I(\lambda) \leftrightarrow \lambda,
\]
\[
X_{CI} := \{\mu_I(\alpha^x) := x^\alpha E_{00}(I) + 1 - E_{00}(I) \mid \alpha \in Z_{CI}\} \simeq Z_{CI} \simeq Z_{n-I}, \mu_I(\alpha^x) \leftrightarrow \alpha,
\]
\[
E_\infty(L_{CI}) := (1 + aE_{00}(I) \mid a \in L_{CI}, \alpha, \beta \in \mathbb{N}^I, \alpha \neq \beta).
\]

The algebra epimorphism $\psi_{n,s} : K + a_{n,s} \to (K + a_{n,s})/a_{n,s+1}$, $a \mapsto a + a_{n,s+1}$, yields the group homomorphism of their groups of units $(K + a_{n,s})^* \to (K + a_{n,s}/a_{n,s+1})^*$ and whose kernel is $(1 + a_{n,s+1})^*$. As a result we have an exact sequence of group homomorphisms:
\[
1 \to (1 + a_{n,s+1})^* \to (1 + a_{n,s})^* \psi_{n,s}^* \prod_{|I|=s} (1 + \mathfrak{p}_I)^* \simeq \prod_{|I|=s} GL_\infty(L_{CI}) \to \mathbb{Z}_n \to 1.
\]

For $s = n$, the map $\psi_{n,n}$ is the identity map, and so $\mathbb{Z}_{n,n} = \{1\}$. Intuitively, the group $\mathbb{Z}_{n,s}$ represents *relations* that determine the image $\text{im}(\psi_{n,s})$ as a subgroup of $\prod_{|I|=s} (1 + \mathfrak{p}_I)^*$. The group $\mathbb{Z}_{n,s}$ is a free abelian group of rank $\binom{n}{s+1}$, \cite{8}. So, the image of the map $\psi_{n,s}$ is large. Note that $a_{n,s+1}$ and $p_I$ (where $|I| = s$) are ideals of the algebra $K + a_{n,s}$. The groups $(1 + a_{n,s+1})^*$ and $(1 + p_I)^*$ (where $|I| = s$) are normal subgroups of $(1 + a_{n,s})^*$. Thus the subgroup $\mathbb{Y}_{n,s}$ of $(1 + a_{n,s})^*$ generated by these normal subgroups is a normal subgroup of $(1 + a_{n,s})^*$. As a subset of $(1 + a_{n,s})^*$, the group $\mathbb{Y}_{n,s}$ is equal to the product of the groups $(1 + a_{n,s+1})^*$, $(1 + p_I)^*$, $|I| = s$, in arbitrary order (by their normality), i.e.
\[
\mathbb{Y}_{n,s} = \prod_{|I|=s} (1 + p_I)^* \cdot (1 + a_{n,s+1})^*.
\]

By Theorem \cite{14} the group $\mathbb{Y}_{n,s}$ is a $G_n$-invariant (hence, normal) subgroup of $S_n^*$. The factor group $(1 + a_{n,s})^*/\mathbb{Y}_{n,s}$ is a free abelian group of rank $\binom{n}{s+1}$, \cite{8}. 

6
By (10), the direct product of groups \( \prod_{|I|=s}(1+p_I)^* \) is the semi-direct product of its two subgroups

\[
\mathbb{X}_{n,s} := \prod_{|I|=s} \mathbb{X}_{C|I} \cong \mathbb{Z}^{(n-s)}(n-s) \quad \text{and} \quad \mathbb{T}_{n,s} := \prod_{|I|=s} U_I(K) \ltimes E_{\infty}(L_{C|I}).
\]

(12)

For each subset \( I \) of \( \{1, \ldots, n\} \) such that \( |I| = s \), \( U_I(K) \ltimes E_{\infty}(S_{C|I}) \) is a subgroup of \( (1+p_I)^* \) where

\[
U_I(K) := \{ \mu_I(\lambda) \mid \lambda \in K^* \} \cong K^*, \quad E_{\infty}(S_{C|I}) := \{ 1 + aE_{\alpha\beta}(I) \mid a \in S_{C|I}, \alpha \neq \beta \in \mathbb{N}^I \},
\]

(13)

where \( \mu_I(\lambda) := \lambda E_{00}(I) + 1 - E_{00}(I) \). Clearly,

\[
\psi_{n,s}|_{U_I(K)} : U_I(K) \cong U_I(K), \quad \mu_I(\lambda) \mapsto \mu_I(\lambda),
\]

and \( \psi_{n,s}(U_I(K) \ltimes E_{\infty}(S_{C|I})) = U_I(K) \ltimes E_{\infty}(L_{C|I}) \) for all subsets \( I \) with \( |I| = s \). The subgroup of \( (1+a_{n,s})^* \),

\[
\Gamma_{n,s} := \psi_{n,s}^{-1}(\mathbb{T}_{n,s}) = \text{set} \bigg\{ \prod_{|I|=s} (U_I(K) \ltimes E_{\infty}(S_{C|I}))(1+a_{n,s+1})^* \bigg\},
\]

(14)

is a normal subgroup as it is the pre-image of a normal subgroup. We added the upper script ‘set’ to indicate that this is a product of subgroups but not a direct product, in general. It is obvious that \( \psi_{n,s}(\Gamma_{n,s}) = \mathbb{T}_{n,s} \) and \( \Gamma_{n,s} \subseteq \mathbb{T}_{n,s} \). In fact, \( \Gamma_{n,s} = \mathbb{T}_{n,s} \). Let \( \Delta_{n,s} := (1+a_{n,s})^*/\Gamma_{n,s} \). The group homomorphism \( \psi_{n,s} \) (see [10]) induces the group monomorphism

\[
\overline{\psi}_{n,s} : \Delta_{n,s} \to \prod_{|I|=s} (1+p_I)^*/\Gamma_{n,s} \cong \mathbb{X}_{n,s} \cong \mathbb{Z}^{(n-s)}.
\]

This means that the group \( \Delta_{n,s} \) is a free abelian group of rank \( \leq \binom{n}{s} (n-s) \). In fact, the rank is equal to \( \binom{n}{s} \). [8]

For each subset \( I \) with \( |I| = s \), consider the free abelian group \( \mathcal{X}_{C|I} := \bigoplus_{j \in C|I} \mathbb{Z}(j, I) \cong \mathbb{Z}^{n-s} \) where \( \{(j, I) \mid j \in C|I\} \) is its free basis. Let

\[
\mathcal{X}'_{n,s} := \bigoplus_{|I|=s} \mathcal{X}_{C|I} = \bigoplus_{|I|=s} \bigoplus_{j \in C|I} \mathbb{Z}(j, I) \cong \mathbb{Z}^{(n-s)}.
\]

For each subset \( I \), consider the isomorphism of abelian groups

\[
\mathcal{X}_{C|I} \to \mathcal{X}'_{n,s}, \quad \mu_I(x_j) := x_j E_{00}(I) + 1 - E_{00}(I) \mapsto (j, I).
\]

These isomorphisms yield the group isomorphism

\[
\mathbb{X}_{n,s} \to \mathcal{X}'_{n,s}, \quad \mu_I(x_j) \mapsto (j, I).
\]

(15)

Each element \( a \) of the group \( \mathbb{X}_{n,s} \) is a unique product \( a = \prod_{|I|=s} \prod_{j \in C|I} \mu_I(x_j)^{n(j, I)} \) where \( n(j, I) \in \mathbb{Z} \). Each element \( a' \) of the group \( \mathcal{X}'_{n,s} \) is a unique sum \( a' = \sum_{|I|=s} \sum_{j \in C|I} n(j, I) \cdot (j, I) \) where \( n(j, I) \in \mathbb{Z} \). The map (15) sends \( a \) to \( a' \). To make computations more readable we set \( e_I := E_{00}(I) \). Then \( e_I e_{I,j} = e_{I+j} \).

**The current groups** \( \Theta_{n,s}, s = 1, \ldots, n-1 \). The current groups \( \Theta_{n,s} \) are the most important subgroups of the group \( (1+a_{n,s})^* \). They are finitely generated groups and generators are given explicitly. The generators of the groups \( \Theta_{n,s} \) are units of the algebra \( S_n \), but they are defined as a product of two *non-units*. As a result the groups \( \Theta_{n,s} \) capture the most delicate phenomena regarding the structure and properties of the groups \( S_n \) and \( G_n \).

For each non-empty subset \( I \) of \( \{1, \ldots, n\} \) with \( s := |I| < n \) and an element \( i \in C|I \), let

\[
X(i, I) := \mu_I(x_i) = x_i E_{00}(I) + 1 - E_{00}(I) \quad \text{and} \quad Y(i, I) := \mu_I(y_i) = y_i E_{00}(I) + 1 - E_{00}(I).
\]
Then $Y(i, I)X(i, I) = 1$, ker $Y(i, I) = P_{C(I,J)}$, and $P_n = \text{im} X(i, I) \bigoplus P_{C(I,J)}$ where $P_{C(I,J)} := K[x_j]_{j \in C(I,J)}$. Recall that $S_n \subset \text{End}_K(P_n)$. As an element of the algebra $\text{End}_K(P_n)$, the map $X(i, I)$ is injective (but not bijective), and the map $Y(i, I)$ is surjective (but not bijective).

**Definition.** For each subset $J$ of $\{1, \ldots, n\}$ with $|J| = s + 1 \geq 2$ and for two distinct elements $i$ and $j$ of the set $J$, let

$$\theta_{ij}(J) := Y(i, J \setminus i)X(j, J \setminus j) \in (1 + p_{J \setminus i} + p_{J \setminus j})^* \subseteq (1 + a_{n,s})^*.$$  \hfill (16)

The current group $\Theta_{n,s}$ is the subgroup of $(1 + a_{n,s})^*$ generated by all the elements $\theta_{ij}(J)$ (for all the possible choices of $J, i, j$).

The unit $\theta_{ij}(J)$ is the product in $\text{End}_K(P_n)$ of an injective map and a surjective map, none of which is a bijection.

$$\theta_{ij}(J) = \theta_{ji}(J)^{-1}. \hfill (17)$$

Suppose that $i, j,$ and $k$ are distinct elements of the set $J$ (hence $|J| \geq 3$). Then

$$\theta_{ij}(J)\theta_{jk}(J) = \theta_{ik}(J). \hfill (18)$$

For each number $s = 1, \ldots, n - 1$, the free abelian group $X'_{n,s}$ admits the decomposition $X'_{n,s} = \bigoplus |J|=s+1 \bigoplus j,J=J \mathbb{Z}(j, I)$, and using it we define a character (a homomorphism) $\chi'_J$, for each subset $J$ with $|J| = s + 1$:

$$\chi'_J : X'_{n,s} \to \mathbb{Z}, \quad \sum_{|J|=s+1} \sum_{j,J} n_{j,J}(j, I) \mapsto \sum_{j,J} n_{j,J}.$$

Let max$(J)$ be the largest number in the set $J$. The group $X'_{n,s}$ is the direct sum

$$X'_{n,s} = \mathbb{K}'_{n,s} \bigoplus \mathbb{V}'_{n,s} \hfill (19)$$

of its free abelian subgroups,

$$\mathbb{K}'_{n,s} = \bigcap_{|J|=s+1} \ker(\chi'_J) = \bigoplus_{|J|=s+1} \bigoplus_{j,J \in J} \mathbb{Z}(-\text{max}(J, J \setminus \text{max}(J))) \simeq \mathbb{Z}(n+1)^s,$$

$$\mathbb{V}'_{n,s} = \bigoplus_{|J|=s+1} \mathbb{Z}(\text{max}(J, J \setminus \text{max}(J))) \simeq \mathbb{Z}(n+1).$$

The same decompositions hold if instead of max$(J)$, we choose any element of the set $J$. Consider the group homomorphism $\psi'_{n,s} : (1 + a_{n,s})^* \to X'_{n,s}$ defined as the composition of the following group homomorphisms:

$$\psi'_{n,s} : (1 + a_{n,s})^* \to (1 + a_{n,s})^*/\Gamma_{n,s} \xrightarrow{\bar{\psi}_{n,s}} \prod_{|J|=s} \overline{(1 + p_J)^*}/\overline{\Gamma}_{n,s} \simeq X_{n,s} \simeq X'_{n,s}.$$  \hfill (20)

Then

$$\psi'_{n,s}(\theta_{ij}(J)) = -(i, J \setminus i) + (j, J \setminus j). \hfill (20)$$

It follows that

$$\psi'_{n,s}(\Theta_{n,s}) = \mathbb{K}'_{n,s}, \hfill (21)$$

since, by (20), $\psi'_{n,s}(\Theta_{n,s}) \supseteq \mathbb{K}'_{n,s}$ (as the free basis for $\mathbb{K}'_{n,s}$, introduced above, belongs to the set $\psi'_{n,s}(\Theta_{n,s})$); again, by (20), $\psi'_{n,s}(\Theta_{n,s}) \subseteq \bigcap_{|J|=s+1} \ker(\chi'_J) = \mathbb{K}'_{n,s}$.

Let $H, H_1, \ldots, H_m$ be subsets (usually subgroups) of a group $H$. We say that $H$ is the *product* of $H_1, \ldots, H_m$, and write $H = \bigcup_{i=1}^m H_i = H_1 \cdots H_m$, if each element $h$ of $H$ is a product $h = h_1 \cdots h_m$ where $h_i \in H_i$. We add the subscript `set' (sometime) in order to distinguish it
from the direct product of groups. We say that $H$ is the exact product of $H_1,\ldots,H_m$, and write $H = \text{exact} \prod_{i=1}^m H_i = H_1 \times_{ex} \cdots \times_{ex} H_m$, if each element $h$ of $H$ is a unique product $h = h_1 \cdots h_m$ where $h_i \in H_i$. The order in the definition of the exact product is important. A semi-direct product of groups $H_1,\ldots,H_m$ is denoted by

$$H_1 \ltimes (H_2 \ltimes (\cdots \ltimes H_m)) = H_1 \ltimes H_2 \ltimes \cdots \ltimes H_m = \text{semi-direct} \prod_{i=1}^m H_i.$$  

The subgroup of $(1 + a_{n,s})^*$ generated by the groups $\Theta_{n,s}$ and $\Gamma_{n,s}$ is equal to their product $\Theta_{n,s}\Gamma_{n,s}$, by the normality of $\Gamma_{n,s}$. The subgroup $\Gamma_{n,s}$ of the group $\Theta_{n,s}\Gamma_{n,s}$ is a normal subgroup, hence the intersection $\Theta_{n,s} \cap \Gamma_{n,s}$ is a normal subgroup of $\Theta_{n,s}$.

**Lemma 2.3** [3] For each number $s = 1,\ldots,n-1$, the group $\Theta_{n,s}\Gamma_{n,s}$ is the semi-direct product

$$\Theta_{n,s}\Gamma_{n,s} = \text{semi-direct} \prod_{|J|=s+1} \prod_{j \in J \setminus \max(J)} (\theta_{\max(J),j}(J)) \ltimes \Gamma_{n,s},$$

where the order in the double product is arbitrary. Each element $a \in \Theta_{n,s}\Gamma_{n,s}$ is a unique product $a = \prod_{|J|=s+1} \prod_{j \in J \setminus \max(J)} \theta_{\max(J),j}(J)^{n(j,J)} \cdot \gamma$ where $n(j,J) \in \mathbb{Z}$ and $\gamma \in \Gamma_{n,s}$.

For each number $s = 1,\ldots,n-1$, consider the subset of $(1 + a_{n,s})^*$,

$$\Theta_{n,s}' := \text{exact} \prod_{|J|=s+1} \prod_{j \in J \setminus \max(J)} (\theta_{\max(J),j}(J)),$$

which is the exact product of cyclic groups (each of them is isomorphic to $\mathbb{Z}$), since each element $u$ of $\Theta_{n,s}'$ is a unique product $u = \prod_{|J|=s+1} \prod_{j \in J \setminus \max(J)} \theta_{\max(J),j}(J)^{n(j,J)}$ where $n(j,J) \in \mathbb{Z}$ (Lemma 2.3).

By Lemma 2.3, $\Theta_{n,s}/\Theta_{n,s} \cap \Gamma_{n,s} \simeq \Theta_{n,s}\Gamma_{n,s}/\Gamma_{n,s} \simeq \mathbb{S}^s_{n,s} \simeq \mathbb{Z}^{s+1}$, and so the commutant of the current group $\Theta_{n,s}$ belongs to the group $\Gamma_{n,s}$, i.e.

$$[\Theta_{n,s},\Theta_{n,s}] \subseteq \Gamma_{n,s}. \quad (23)$$

Recall that the commutant $[G,G]$ of a group $G$ is the subgroup of $G$ generated by all group commutators $[a,b] := aba^{-1}b^{-1}$ where $a,b \in G$. The commutant is a normal subgroup. The next theorem is the key point in finding explicit generators for the groups $\mathbb{S}^n_{s}$ and $G_{n,s}$.

**Theorem 2.4** [3] $\psi'_{n,s}(1 + a_{n,s})^* = \psi'_{n,s}(\Theta_{n,s})$ for $s = 1,\ldots,n-1$.  

For each number $s = 1,\ldots,n-1$, consider the following subsets of the group $(1 + a_{n,s})^*$,

$$E_{n,s} := \prod_{|I|=s} U_1(K) \ltimes E_{\infty}(S_{CI}) \text{ and } P_{n,s} := \prod_{|I|=s} (1 + p_i)^*.$$  

These are products of subgroups $(1 + a_{n,s})^*$ in arbitrary order, but which is fixed for each $s$.

**Theorem 2.5** [3]  

1. $(1 + a_{n,s})^* = \Theta_{n,1}\Gamma_{n,1} = \Theta_{n,2}\Gamma_{n,2}E_{n,2}\cdots \Theta_{n,n-1}E_{n,n-1}$. Moreover, for $s = 1,\ldots,n-1$,  

2. $(1 + a_{n,s})^* = \Theta_{n,1}\Gamma_{n,1} = \Theta_{n,2}\Gamma_{n,2}P_{n,2}\cdots \Theta_{n,n-1}P_{n,n-1}$. Moreover, for $s = 1,\ldots,n-1$,  

**Theorem 2.6** [3]  

1. $(1 + a_{n,s})^* = \Theta_{n,1}\Gamma_{n,1} = \Theta_{n,2}\Gamma_{n,2}E_{n,2}\cdots \Theta_{n,n-1}E_{n,n-1}$. Moreover, for $s = 1,\ldots,n-1$,  

2. $(1 + a_{n,s})^* = \Theta_{n,1}\Gamma_{n,1} = \Theta_{n,2}\Gamma_{n,2}P_{n,2}\cdots \Theta_{n,n-1}P_{n,n-1}$. Moreover, for $s = 1,\ldots,n-1$,  


3 The groups $K_1(S_n)$ and $GL_\infty(S_n)$ and their generators

In this section, explicit generators are found for the group $GL_\infty(S_n)$ (Theorem 3.3 Theorem 3.3 (1)) and it is proved that $K_1(S_n) \simeq K^*$ (Theorem 3.3 (2)) modulo Theorem 3.4 which is proved in Section 4.

The subgroup $(1 + p_n)^*$ of the group $S_n^*$ is canonically isomorphic to the group $GL_\infty(S_{n-1})$ via the isomorphism $1 + \sum a_{ij}E_{ij}(u) \mapsto 1 + \sum a_{ij}E_{ij}$ where $a_{ij} \in S_{n-1} = \bigotimes_{i=1}^{n-1} S_1(i)$. It is convenient to identify the groups $(1 + p_n)^*$ and $GL_\infty(S_{n-1})$ and to identify the matrix units $E_{ij}(n)$ and $E_{ij}$, i.e. $(1 + p_n)^* = GL_\infty(S_{n-1})$ and $E_{ij}(n) = E_{ij}$. The group $(1 + p_n)^*$ contains the descending chain of normal subgroups

$$(1 + p_n)^* = (1 + p_n)_1^* \supset \cdots \supset (1 + p_n)^* \supset \cdots \supset (1 + p_n)_n^* = (1 + F_n)^* \supset (1 + p_n)_{n+1}^* = \{1\}$$

where $(1 + p_n)^*_s := (1 + p_n)^* \cap (1 + a_{n,s})^*$. The following lemma describes the normal subgroups $(1 + p_n)_s^*$.

Lemma 3.1

$$(1 + p_n)_s^* = \begin{cases} (1 + \sum_{|I|=s, n \in I} p_I)^* & \text{if } s = 1, \ldots, n-1, \\ (1 + F_n)^* & \text{if } s = n. \end{cases}$$

Proof. As the case $s = n$ is obvious, we assume that $s \neq n$. The ideal $a_{n,s} = \sum_{|I|=s} p_I$ of the algebra $S_n$ is the sum of idempotent ideals $p_I$. Therefore, $a_{n,s}^2 = a_{n,s}$. By Corollary 7.4.3, $a \cap b = ab$ for all idempotent ideals $a$ and $b$ of the algebra $S_n$. Since the ideals $p_n$ and $a_{n,s}$ of the algebra $S_n$ are idempotent,

$$p_n \cap a_{n,s} = p_n a_{n,s} = \sum_{|I|=s} p_n p_I = \sum_{|I|=s, n \in I} p_I.$$

Thus $(1 + p_n)_s^* = (1 + p_n)^* \cap (1 + a_{n,s})^* = (1 + p_n \cap a_{n,s})^* = (1 + \sum_{|I|=s, n \in I} p_I)^*$. □

For each number $s = 1, \ldots, n-1$, consider the following subset of $E_{n,s}$,

$$\tilde{E}_{n,s} = \prod_{|I|=s, n \in I} U_I(K) \times E_\infty(S_CI),$$

where the groups $U_I = U_I(K)$ and $E_\infty(S_CI)$ are defined in [13]. This is the product of the subgroups $U_I(K) \times E_\infty(S_CI)$ of $(1 + p_n)_s^*$ in arbitrary order but which is assumed to be fixed.

Notice that $\tilde{E}_{n,1} = U_n(K) \times E_\infty(S_{n-1})$ where $U_n(K) = \{ \mu_n(\lambda) = \lambda e_n + 1 - e_n = \begin{pmatrix} \lambda & 0 \\ 0 & 1 \end{pmatrix} | \lambda \in K^* \}$ and $E_\infty(S_{n-1})$ is the subgroup of $GL_\infty(S_{n-1})$ generated by all the elementary matrices.

Consider the element $\mu_I(\lambda) = \lambda e_I + 1 - e_I \in U_I(K)$ where $|I| = s$ and $n \in I$. Then

$$\mu_I(\lambda) = e_n(1 + (\lambda - 1)e_{I \setminus n}) + 1 - e_n = \begin{pmatrix} 1 + (\lambda - 1)e_{I \setminus n} & 0 \\ 0 & 1 \end{pmatrix} \in GL_\infty(S_{n-1}).$$

Lemma 3.2 $E_\infty(S_{n-1}) \supset \tilde{E}_{n,s}$ for all $s = 2, \ldots, n-1$.

Proof. It is sufficient to show that the group $E_\infty(S_{n-1})$ of elementary matrices contains the groups $E_\infty(S_CI)$ and $U_I(K)$ when $|I| = s$ and $n \in I$. The group $E_\infty(S_CI)$ is generated by the elementary matrices $u = 1 + aE_{a,\beta}(I)$ where $a \in S_CI$, $\alpha = (\alpha_i)_{i \in I}$, $\beta = (\beta_i)_{i \in I} \in N^I$ and $\alpha \neq \beta$. If $\alpha_n \neq \beta_n$ then $u = 1 + (a \prod_{i \in I, i \neq n} E_{\alpha_i,\beta_i}(i)E_{\alpha_n,\beta_n}(n) \in E_\infty(S_{n-1})$. If $\alpha_n = \beta_n$ then choose an element $\gamma \in N^I$ such that $\gamma_n \neq \alpha_n$, and so $\gamma \neq \alpha$ and $\gamma \neq \beta$. Since the elements $1 + E_{\alpha \gamma}$ and $1 + aE_{\gamma \beta}$ belong to the group $E_\infty(S_{n-1})$ (by the previous case), so does their group commutator

$$E_\infty(S_{n-1}) \supset [1 + E_{\alpha \gamma}, 1 + aE_{\gamma \beta}] = 1 + aE_{\alpha \beta} = u.$$
Therefore, \( E_\infty(S_{CI}) \subseteq E_\infty(S_{n-1}) \).

It remains to show that \( U_I(K) \subseteq E_\infty(S_{n-1}) \), i.e. \( \mu_I(\lambda) = 1 + \lambda E_{00}(I) \in E_\infty(S_{n-1}) \) for all scalars \( \lambda \in K \setminus \{ -1 \} \). Notice that \( n \in I \) and \(|I| = s \geq 2 \). Choose an element, say \( m \in I \), distinct from \( n \). In the subgroup \( GL_\infty(S_1(m)) \) of \( GL_\infty(S_{n-1}) \), we have for all scalars \( \lambda \in K \setminus \{ -1 \} \) the equality:

\[
\left( \begin{array}{ccc}
\frac{1}{\lambda + \lambda} & 0 & \frac{1}{\lambda} x_m \\
0 & \frac{1}{\lambda} & \frac{1}{\lambda} y_m \\
\frac{1}{\lambda} & 0 & 1
\end{array} \right) \left( \begin{array}{ccc}
\frac{1}{\lambda + \lambda} & 0 & \frac{1}{\lambda} x_m \\
0 & \frac{1}{\lambda} & \frac{1}{\lambda} y_m \\
\frac{1}{\lambda} & 0 & 1
\end{array} \right) = \left( \begin{array}{ccc}
1 + \lambda & 0 & \frac{1}{\lambda - \lambda E_{00}(m) \lambda + \lambda} \\
0 & 1 & 0
\end{array} \right). \tag{27}
\]

This can be checked by direct multiplication using the equalities \( y_m x_m = 1 \) and \( x_m y_m = 1 - E_{00}(m) \) that hold in the algebra \( S_1(m) \). The first five matrices in the equality belong to the group \( E_\infty(S_1(m)) \). Therefore, the last matrix \( c = \left( \begin{array}{ccc}
1 - \frac{\lambda E_{00}(m)}{\lambda + \lambda} & 0 \\
0 & 1
\end{array} \right) \) belongs to the group \( E_\infty(S_1(m)) \).

The idempotent \( e := \left\{ \prod_{i \in I \setminus \{ n, m \}} E_{00}(i) \right\} \) if \(|I| > 2\),
\[
e = \left\{ \begin{array}{ll}
\prod_{i \in I \setminus \{ n, m \}} E_{00}(i) & \text{if } |I| > 2, \\
1 & \text{if } |I| = 2,
\end{array} \right.
\]
determines the group monomorphism

\[
\tau_e : GL_\infty(S_1(m)) = (1 + \sum_{i,j \in N} S_1(m) E_{ij}(m))^* \rightarrow GL_\infty(S_{n-1}) = (1 + p_\ast)^*, \ u \mapsto eu + 1 - e, \tag{28}
\]
that maps the group \( E_\infty(S_1(m)) \) into the group \( E_\infty(S_{n-1}) \). Therefore,

\[
\tau_e(c) = e(E_{00}(n)(1 - \frac{\lambda}{1 + \lambda} E_{00}(m)) + 1 - e E_{00}(n)) + 1 - e
\]

\[
= 1 - \frac{\lambda}{1 + \lambda} E_{00}(I) = \mu_I(- \frac{\lambda}{1 + \lambda}) \in E_\infty(S_{n-1}) \cap U_K(I).
\]

Since the map \( \varphi : K \setminus \{ -1 \} \rightarrow K \setminus \{ -1 \} \), \( \lambda \mapsto - \frac{\lambda}{1 + \lambda} \), is a bijection \( (\varphi^{-1} = \varphi) \), all the elements \( \mu_I(\lambda) \) belong to the group \( E_\infty(S_{n-1}) \). The proof of the lemma is complete. \( \square \)

By \( (\text{III}) \), there is the group monomorphism

\[
\varphi_{n,s} : \frac{(1 + p_n)_s^*}{(1 + p_n)_s^*} \rightarrow \frac{(1 + a_{n,s})^*}{(1 + a_{n,s})^*} \rightarrow \prod_{|I| = s} (1 + \overline{p}_I)^* = \prod_{|I| = s, n \in I} (1 + \overline{p}_I)^* \times \prod_{|I'| = s, n \not\in I'} (1 + \overline{p}_{I'})^*
\]
which is the composition of two group monomorphisms. By Lemma \( 3.1 \)

\[
\text{im} (\varphi_{n,s}) \subseteq \prod_{|I| = s, n \in I} (1 + \overline{p}_I)^*. \tag{29}
\]

Recall that \( (1 + \overline{p}_I)^* = (X_{CI} \times U_I) \times E_\infty(LCI) \). Since \( \varphi_{n,s}(\overline{X}_{n,s}(1 + p_n)_s^*) = \prod_{|I| = s, n \in I} U_I \times E_\infty(LCI) \), we see that

\[
\varphi_{n,s}^{-1}(\Gamma_{n,s}) = \varphi_{n,s}^{-1}(\text{im}(\varphi_{n,s}) \cap \Gamma_{n,s}) = \varphi_{n,s}^{-1}(\prod_{|I| = s, n \in I} U_I \times E_\infty(LCI)) = \overline{X}_{n,s}(1 + p_n)_s^*,
\]
and so there is the group monomorphism

\[
\overline{\varphi}_{n,s} : (1 + p_n)_s^*/\overline{X}_{n,s}(1 + p_n)_s^* \rightarrow (1 + a_{n,s})^*/\Gamma_{n,s} \simeq X_{n,s} \simeq X'_{n,s} = \prod_{|I| = s, n \in I} X_{CI} \times \prod_{|I'| = s, n \not\in I'} X'_{CI'}.
\]

Notice that the group \( \overline{X}_{n,s}(1 + p_n)_s^* \) is a normal subgroup of \( (1 + p_n)_s^* \). For each number \( s = 2, \ldots, n - 1 \), in the set \( \Theta'_{n,s} \) consider the exact product of cyclic groups (the order is arbitrary)

\[
\overline{\Theta}_{n,s} := \prod_{|J| = s + 1, n \in J, j \in J \setminus \{ n, m(J) \}} \langle \theta_{m(J), j}(J) \rangle \tag{30}
\]
where \( m(J) \) is the largest element of the set \( J \setminus n \). Instead of the element \( m(J) \) we can choose an arbitrary element of the set \( J \setminus n \). By (29), \( \det(\varphi_{n,s}) \subseteq \prod_{|I| = s, n \in I} \mathcal{X}_{CI} \). Recall that \( \det(\varphi_{n,s}) = \psi'_{n,s}(\Theta_{n,s}) = \mathcal{X}_{n,s} = \prod_{|J| = s + 1} \ker(\chi_{J}) \), by Theorem 2.3 and (21). The following argument is the key moment in the proof of Theorem 3.3

\[
\text{im}(\varphi_{n,s}) \subseteq \bigcap_{|I| = s, n \in I} \mathcal{X}_{CI} = \bigcap_{|J| = s + 1} \ker(\chi_{J}) \bigcap_{|I| = s, n \in I} \mathcal{X}_{CI}
\]

\[
= \begin{cases}
0 & \text{if } s = 1, \\
\prod_{|J| = s + 1, n \in J} \prod_{j \in J \setminus \{n, m(J)\}} \mathcal{Z}(-(m(J), J \setminus m(J)) + (j, J \setminus j)) & \text{if } s = 2, \ldots, n - 1,
\end{cases}
\]

\[
= \begin{cases}
0 & \text{if } s = 1, \\
\psi'_{n,s}(\Theta_{n,s}) & \text{if } s = 2, \ldots, n - 1,
\end{cases}
\]

\[
= \begin{cases}
0 & \text{if } s = 1, \\
(1 + p_n)_{s+1} & \text{if } s = 2, \ldots, n - 1.
\end{cases}
\]

It follows that

\[
(1 + p_n)^* = \begin{cases}
\bar{E}_{n,1}(1 + p_n)^* & \text{if } s = 1, \\
\bar{\Theta}_{n,s} \times_{ex} \bar{E}_{n,s}(1 + p_n)^*_{s+1} & \text{if } s = 2, \ldots, n - 1.
\end{cases}
\]

Theorem 3.3 The group \( GL_\infty(S_{n-1}) = (1 + p_n)^* \) is equal to \( \bar{E}_{n,1}\bar{\Theta}_{n,2}\bar{E}_{n,2} \cdots \bar{\Theta}_{n,n-1}\bar{E}_{n,n-1} \).

Moreover,

\[
(1 + p_n)^* = \begin{cases}
\bar{E}_{n,1}\bar{\Theta}_{n,2}\bar{E}_{n,2} \cdots \bar{\Theta}_{n,n-1}\bar{E}_{n,n-1} & \text{if } s = 1, \\
\bar{\Theta}_{n,s}\bar{E}_{n,s} \cdots \bar{\Theta}_{n,n-1}\bar{E}_{n,n-1} & \text{if } s = 2, \ldots, n - 1, \\
(1 + F_n)^* & \text{if } s = n.
\end{cases}
\]

Proof. By Proposition 3.10, \( \mathcal{S} \), we have the inclusion \( (1 + p_n)^* \subseteq \bar{E}_{n,n-1} \). Now, the theorem follows from (31). \( \square \)

For each subset \( J \) of the set \( \{1, \ldots, n\} \) such that \( n \in J \) and \( |J| \geq 3 \), and for each pair of distinct elements \( i \) and \( j \) of the set \( J \setminus n \), the unit \( \theta_{ij}(J) \in S_{n-1}^\ast \) can be written as follows

\[
\theta_{ij}(J) = (y_{i,j}e_n + 1 - e_n + e_n(1 - e_{j,i}))(x_{i,j}e_n + 1 - e_n + e_n(1 - e_{j,i})) = e_n(y_{i,j}e_n + 1 - e_{j,i})(x_{i,j}e_n + 1 - e_{j,i}) + 1 - e_n = e_n\theta_{ij}(J \setminus n) + 1 - e_n
\]

where \( e_n := E_{00}(n) \), \( e_{j,i} := \prod_{k \in J \setminus i} E_{00}(k) \) and \( e_{j,i} := \prod_{k \in J \setminus i} E_{00}(k) \).

Therefore, the unit \( \theta_{ij}(J) \), as an element of the group \( GL_\infty(S_{n-1}) \), is the matrix

\[
\theta_{ij}(J) = \begin{pmatrix}
\theta_{ij}(J \setminus n) & 0 \\
0 & 1
\end{pmatrix} \in GL_\infty(S_{n-1})
\]

where \( \theta_{ij}(J \setminus n) \in S_{n-1}^\ast \).

The determinant \( \overline{\det} \) on \( GL_\infty(S_{n-1}) \). The algebra epimorphism \( S_{n-1} \to S_{n-1}/a_{n-1} = L_{n-1}, a \mapsto \overline{a} := a + a_{n-1} \), yields the group homomorphisms \( GL_\infty(S_{n-1}) \to GL_\infty(L_{n-1}), u \mapsto \overline{u} \), and \( \det : GL_\infty(S_{n-1}) \to GL_\infty(L_{n-1}) \). Clearly, \( \det(E_{00}(n)) = 1 \), \( \det(\Theta_{n,s}) = 1 \) for all \( s = 2, \ldots, n - 1 \), and \( \det(U_n(K)) = K^* \) since \( \det(\mu_n(\lambda)) = \lambda \) for all \( \lambda \in K^* \). By Theorem 3.3 and Lemma 3.2, \( GL_\infty(S_{n-1}) = U_n(K)\bar{\Theta}_{n,2} \cdots \bar{\Theta}_{n,n-1}\bar{E}_{n,n-1} \) is a normal subgroup of \( GL_\infty(S_{n-1}) \).

It follows that the image of the map \( \det \) is \( K^* \), i.e. we have the group epimorphism

\[
\overline{\det} : GL_\infty(S_{n-1}) \to K^*, \ u \mapsto \det(\overline{u}),
\]

(33)
and
\[ \text{GL}_\infty(S_{n-1}) = U_n(K) \times \ker(\det), \quad \text{SL}_\infty(S_{n-1}) := \ker(\det) = \tilde{\Theta}_{n,2} \cdots \tilde{\Theta}_{n,n-1} E_\infty(S_{n-1}). \quad (34) \]

**Theorem 3.4** \( \tilde{\Theta}_{n,s} \subseteq E_\infty(S_{n-1}) \) for all \( s = 2, \ldots, n - 1 \).

The proof of Theorem 3.4 is not easy and is given in Section 4.

**Theorem 3.5**
1. \( \text{GL}_\infty(S_{n-1}) = U_n(K) \times E_\infty(S_{n-1}) \) and \( \text{SL}_\infty(S_{n-1}) = E_\infty(S_{n-1}) \) where \( U_n(K) = \{ \mu_n(\lambda) \in GL_n(k) \mid \lambda \in K^* \} \). So, each element \( a \in \text{GL}_\infty(S_{n-1}) \) is the unique product \( a = \mu_n(\lambda)e \) where \( \lambda = \det(a) \) and \( e = \mu_n(\det(a))^{-1}a \in E_\infty(S_{n-1}) \).

2. \( K_1(S_n) \cong K^* \) for all \( n \geq 1 \).

**Proof.** The theorem follows from Theorem 3.4 and (34). \( \Box \)

The number of generators \( \theta_{\text{max}(J),J}(J) \) in the block \( \tilde{\Theta}_{n+1,2} \cdots \tilde{\Theta}_{n+1,n} \) for the group \( \text{GL}_\infty(S_n) = U_{n+1}(K) \times \tilde{\Theta}_{n+1,2} \cdots \tilde{\Theta}_{n+1,n} E_\infty(S_n) \) is \( \sum_{s=2}^n (s-1) = (n-2)2^{n-1}+1 \) as the next lemma shows.

**Lemma 3.6** For each natural number \( n \geq 2 \), \( \sum_{s=2}^n (s-1) = (n-2)2^{n-1}+1 \).

**Proof.** Taking the derivative of the polynomial \( (1+x)^n = \sum_{s=0}^n \binom{n}{s}x^s \), we have the equality \( n(1+x)^{n-1} = \sum_{s=1}^n \binom{n}{s}sx^{s-1} \). Then taking the difference of both equalities at \( x = 1 \), we obtain the result: \( \sum_{s=2}^n \binom{n}{s}(s-1) = 2n^2 - 2n = (n-2)2^{n-1} \). \( \Box \)

## 4 Proof of Theorem 3.4

The whole section is a proof of Theorem 3.4. The proof is constructive (but slightly technical) and split into a series of lemmas that produce more and more sophisticated elementary matrices in \( E_\infty(S_{n-1}) \). These elementary matrices are used to show that the elements of the sets \( \Theta_{n,s} \) are elementary matrices (Propositions 1.6 and 1.8).

**Lemma 4.1** Let \( D \) be a division ring and let \( \Lambda = D \oplus De \) be a ring over \( D \) such that \( e^2 = e \) and \( de = ed \) for all \( d \in D \). Then

1. the group of units \( \Lambda^* \) of the ring \( \Lambda \) is the semi-direct product \( D^* \rtimes \Gamma \) of the group of units \( D^* \) of the ring \( D \) and the subgroup \( \Gamma := \{ 1 + \lambda e \mid \lambda \in D \setminus \{-1\} \} \) of \( \Lambda^* \).

2. \( (1 + \lambda e)^{-1} = 1 - \frac{\lambda e}{1 + \lambda e} \) for all elements \( \lambda \in D \setminus \{-1\} \).

3. The map \( \phi : D \setminus \{-1\} \to D \setminus \{-1\}, \lambda \mapsto -\frac{1}{1 + \lambda e} \), is a bijection with \( \phi^{-1} = \phi \).

4. \( (1 - 2e)^{-1} = 1 - 2e \).

**Proof.** Straightforward. \( \Box \)

We are interested in the rings \( \Lambda \) and their groups of units, since the algebra \( K + M_\infty(S_{n-1}) \) of infinite dimensional matrices over the algebra \( S_{n-1} \) contains plenty of them and as a result the group \( \text{GL}_\infty(S_{n-1}) \) contains their groups of units.

**Lemma 4.2** Let \( S_1(\Lambda) = \Lambda(x, y \mid yx = 1) \) be the algebra \( S_1 \) over the ring \( \Lambda \) from Lemma 4.1. Then, for each element \( \lambda \in D \setminus \{-1\} \),

\[
\begin{pmatrix}
1 & y \\
-\frac{y}{1 + \lambda e} & 1 + \lambda e
\end{pmatrix}
\begin{pmatrix}
0 & 1 - \frac{\lambda e}{1 + \lambda e} \\
1 & 0
\end{pmatrix}
= \begin{pmatrix}
1 + \lambda e & 0 \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
-\frac{y}{1 + \lambda e} & 1
\end{pmatrix}
\begin{pmatrix}
0 & 0 \\
1 & 0
\end{pmatrix}.
\]

(35)

where \( E_{00} := 1 - xy \) (the element \( 1 + \lambda e \) is a unit of the algebra \( S_1(\Lambda) \), by Lemma 4.1).
Lemma 4.3  
1. \((\begin{smallmatrix} y & 0 \\ E_{00} & x \end{smallmatrix}) \in E_2(S_1)\) where \(E_{00} := 1 - xy\).

2. \((\begin{smallmatrix} x & 0 \\ E_{00} & y \end{smallmatrix}) = (\begin{smallmatrix} y & 0 \\ E_{00} & x \end{smallmatrix})^{-1} \in E_2(S_1)\).

Proof. 1. Using the equalities \(yx = 1\) and \(E_{00}x = 0\), we can easily check that

\[
\begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & y \\ x & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 - 2E_{00} & 0 \\ 0 & 1 \end{pmatrix}.
\]

By (27), the RHS is an element of the group \(E_2(S_1)\) since \(-\frac{2}{1+2} = 2\), and so statement 1 holds.

2. It is obvious. □

Let \(R\) be a ring and \(u\) be its unit. The \(2 \times 2\) matrix \((\begin{smallmatrix} y & 0 \\ uE_{00} & x \end{smallmatrix}) \in M_2(S_1(R))\) is invertible where \(E_{00} := 1 - xy\). Moreover,

\[
(\begin{smallmatrix} y & 0 \\ uE_{00} & x \end{smallmatrix})^{-1} = (\begin{smallmatrix} x & 0 \\ 0 & u^{-1}E_{00} \end{smallmatrix}).
\]

Lemma 4.4  
Let the ring \(\Lambda\) be as in Lemma 4.1. Then, for each element \(\lambda \in D\setminus\{-1\},

\((\begin{smallmatrix} y & 0 \\ (1 + \lambda e)E_{00} & x \end{smallmatrix}) \in E_2(S_1(\Lambda))\) and

\((\begin{smallmatrix} x & 0 \\ 0 & y \end{smallmatrix}) \in E_2(S_1(\Lambda))\)

where \((1 + \lambda e)^{-1} = 1 - \frac{\lambda}{1+\lambda}e\) (by Lemma 4.1(2)).

Proof. It suffices to prove the first inclusion since then the equality and the second inclusion follow from (35). Using the equalities \(yx = 1\) and \(E_{00}x = 0\) we can check that

\[
\begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 & y \\ (1 + \lambda e)E_{00} & x \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -y & 1 \end{pmatrix} = \begin{pmatrix} 1 - (2 + \lambda e)E_{00} & 0 \\ 0 & 1 \end{pmatrix},
\]

\[
\begin{pmatrix} 1 - (2 + \lambda e)E_{00} & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 - 2E_{00} & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 + \lambda eE_{00} & 0 \\ 0 & 1 \end{pmatrix}.
\]

By (37), \((1 - 2E_{00} 0) \in E_2(S_1)\), and then by (35), \((1 + \lambda eE_{00} 0) \in E_2(S_1(\Lambda))\) since \(\lambda \in D\setminus\{-1\}\). Therefore, \((\begin{smallmatrix} y & 0 \\ (1 + \lambda e)E_{00} & x \end{smallmatrix}) \in E_2(S_1(\Lambda))\), by (35). □

Lemma 4.5  
\((\begin{smallmatrix} 1 + y(2 - 1)x_1y_1 & 0 \\ e_2y_1 & x_2 \end{smallmatrix}) \in E_2(S_2)\) where \(e_2 := E_{00}(2) = 1 - x_2y_2\).
Proof. The statement follows from the equality
\[
\begin{pmatrix}
1 & 0 \\
-x_2 y_1 & 1
\end{pmatrix}
\begin{pmatrix}
1 & (y_2 - 1)x_1 \\
y_1 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
-(y_2 - 1)x_1 & 1
\end{pmatrix}
\begin{pmatrix}
1 & (y_2 - 1)(1 - x_2)x_1 \\
e_2 y_1 & 1
\end{pmatrix}
= \begin{pmatrix}
1 + (y_2 - 1)x_1 y_1 & 0 \\
e_2 y_1 & x_2
\end{pmatrix}
\]
(40)
which can be checked directly using the equalities \(y_i x_i = 1\), \(x_i y_i = 1 - e_i\), \(y_i e_i = 0\) and \(e_i x_i = 0\) where \(e_i := E_{00}(i)\). The RHS of the equality (40) is the product of five matrices \(A_1 \cdots A_5\).

\[
A_1 A_2 A_3 = \begin{pmatrix}
1 & (y_2 - 1)x_1 \\
-x_2 y_1 & 1 - x_2(y_2 - 1)
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
y_1 & 1
\end{pmatrix}
\begin{pmatrix}
1 & (y_2 - 1)x_1 \\
e_2 y_1 & 1 - x_2(y_2 - 1)
\end{pmatrix}
= \begin{pmatrix}
1 + (y_2 - 1)x_1 y_1 & (y_2 - 1)x_1 \\
e_2 y_1 & 1 - x_2(y_2 - 1)
\end{pmatrix}
\]

since \(-x_2 y_1 + (1 - x_2) y_1 + x_2 y_1 = e_2 y_1\). Now,

\[
A_1 \cdots A_4 = \begin{pmatrix}
1 + (y_2 - 1)x_1 y_1 & -(y_2 - 1)^2 x_1 \\
e_2 y_1 & 1 - (x_2 + e_2)(y_2 - 1)
\end{pmatrix}
\]

since \(-y_1 x_1 e_2 (y_2 - 1) + 1 - x_2(y_2 - 1) = 1 - (x_2 + e_2)(y_2 - 1)\). Finally, \(A_1 \cdots A_5 = \begin{pmatrix}
1 + (y_2 - 1)x_1 y_1 & a \\
e_2 y_1 & b
\end{pmatrix}\)

where
\[
a = (1 + (y_2 - 1)x_1 y_1)(y_2 - 1)(1 - x_2)x_1 - (y_2 - 1)^2 x_1,
\]
\[
b = 1 - (x_2 + e_2)(y_2 - 1) + e_2 y_1(y_2 - 1)(1 - x_2)x_1.
\]

Proposition 4.6 \((\theta_{12} \ 0 \ 0) \in E_2(S_2)\) where \(\theta_{12} = \theta_{12}([1, 2]) = (1 + (y_1 - 1)e_2)(1 + (x_2 - 1)e_1),\)
\(e_1 = E_{00}(1)\) and \(e_2 = E_{00}(2)\).

Proof. By Lemma 4.5 \(\begin{pmatrix} x_2 & e_2 \\ 0 & y_2 \end{pmatrix} \in E_2(S_2) \subseteq E_2(S_2)\). Then, by Lemma 4.5,

\[
E_2(S_2) \ni \begin{pmatrix} x_2 & e_2 \\ 0 & y_2 \end{pmatrix} \begin{pmatrix} 1 + (y_2 - 1)x_1 y_1 & 0 \\ e_2 y_1 & x_2 \end{pmatrix} = \begin{pmatrix} \theta_{12} & 0 \\ 0 & 1 \end{pmatrix}.
\]

(41)

Indeed, let \(a\) be the \((1, 1)\)-entry of the product, then
\[
a = x_2(1 + (y_2 - 1)x_1 y_1) + e_2 y_1 = x_2 + (x_2 y_2 - x_2)x_1 y_1 + e_2 y_1
\]
\[
= x_2 e_1 + (1 - e_2)(1 - e_1) + e_2 y_1 = 1 + (x_2 - 1)e_1 + (y_1 - 1)e_2 + e_1 e_2
\]
\[
= (1 + (y_1 - 1)e_2)(1 + (x_2 - 1)e_1) = \theta_{12}
\]
since \((y_1 - 1)e_2 \cdot (x_2 - 1)e_1 = (y_1 - 1)e_1 \cdot e_2(x_2 - 1) = (e_1 \cdot (e_2) = e_1 e_2\).

Lemma 4.7 Let \(J = \{1, \ldots, m\}\) where \(m \geq 3\), and let \(I = J \setminus \{1, 2\}\). Then

\[
\begin{pmatrix}
1 + (y_2 - 1)x_1 y_1 e_I \\
e_2 y_1 e_I & 1 + x_2 e_I
\end{pmatrix} \in E_2(S_2(K \oplus K e_I))
\]

where \(e_2 := E_{00}(2)\) and \(e_I := \prod_{k \in I} E_{00}(k)\).

Proof. The statement follows from the equality
\[
\begin{pmatrix}
1 & 0 \\
-x_2 y_2 e_I & 1
\end{pmatrix}
\begin{pmatrix}
1 & (y_2 - 1)x_1 \\
y_1 e_I & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
-(y_2 - 1)x_1 & 1
\end{pmatrix}
\begin{pmatrix}
1 & (y_2 - 1)(1 - x_2)x_1 e_I \\
e_2 y_1 e_I & 1 + (x_2 - 1)e_I
\end{pmatrix}
= \begin{pmatrix}
1 + (y_2 - 1)x_1 y_1 e_I & 0 \\
e_2 y_1 e_I & 1 + (x_2 - 1)e_I
\end{pmatrix}
\]

(42)
The equality can be written shortly as $A_1 \cdots A_5 = A$.

$$A_2A_3A_4 = \begin{pmatrix} 1 + (y_2 - 1)x_1y_1e_I & (y_2 - 1)x_1 \\ y_1e_I & 1 \end{pmatrix} \begin{pmatrix} 1 & -(y_2 - 1)x_1 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 + (y_2 - 1)x_1y_1e_I & -(y_2 - 1)^2x_1e_I \\ y_1e_I & 1 - (y_2 - 1)e_I \end{pmatrix}$$

where we have used the fact that $y_1x_1 = 1$.

$$A_1 \cdots A_4 = \begin{pmatrix} 1 + (y_2 - 1)x_1y_1e_I & -(y_2 - 1)^2x_1e_I \\ e_2y_1e_I & 1 - (x_2 + e_2)(y_2 - 1)e_I \end{pmatrix}.$$  

In more detail, let $(\alpha, \beta)$ be the second row of the product. Using the fact that $y_1x_1 = 1$ and $e_I^2 = e_I$, we see that

$$\alpha = -x_2y_1e_I(1 + (y_2 - 1)x_1y_1e_I) + y_1e_I = (-x_2(y_1 + (y_2 - 1)y_1) + y_1)e_I = (1 - x_2y_2)y_1e_I = e_2y_1e_I,$$

$$\beta = x_2y_1e_I(y_2 - 1)^2x_1e_I + 1 - (y_2 - 1)e_I = 1 + (x_2y_2 - x_2 - 1)(y_2 - 1)e_I = 1 - (x_2 + e_2)(y_2 - 1)e_I.$$

Finally, $A_1 \cdots A_5 = \begin{pmatrix} 1 + (y_2 - 1)x_1y_1e_I & a' \\ e_2y_1e_I & b' \end{pmatrix}$ where (below, we use the fact that $a = 0$ and $b = x_2$,

see the proof of Lemma 4.3).

Let $J = \{1, 2, \ldots, m\}$ and $m \geq 3$. By multiplying out, the element $\theta_{12}(J) = (1 + (y_2 - 1)e_{J\setminus 1})(1 + (x_2 - 1)e_{J\setminus 2}) \in S_m^*$ can be written as the sum

$$\theta_{12}(J) = x_2e_1e_I + (1 - e_1e_I)(1 - e_2e_I) + y_1e_2e_I \tag{43}$$

where $I := J \setminus \{1, 2\}$.

**Proposition 4.8** Let $J = \{1, 2, \ldots, m\}$ and $m \geq 3$. Then $\begin{pmatrix} \theta_{12}(J) & 0 \\ 0 & 1 \end{pmatrix} \in E_2(S_m)$.

**Proof.** We keep the notation of Lemma 4.7. By Lemma 4.3(2) and Lemma 4.7, the product of the following two elementary matrices is also an elementary matrix,

$$E_2(S_2) \ni \begin{pmatrix} x_2 & e_2 \\ 0 & y_2 \end{pmatrix} \begin{pmatrix} 1 + (y_2 - 1)x_1y_1e_I & 0 \\ e_2y_1e_I & 1 + (x_2 - 1)e_I \end{pmatrix} = \begin{pmatrix} \theta_{12}(J) + (x_2 - 1)(1 - e_I) & e_2(1 - e_I) \\ e_2y_1e_I & e_I + (1 - e_I)y_2 \end{pmatrix} \tag{44}$$

Indeed, the LHS is a matrix of type $\begin{pmatrix} \alpha & \gamma \\ 0 & \beta \end{pmatrix}$ (since $y_2e_2 = 0$) where

$$\alpha = x_2(1 + (y_2 - 1)x_1y_1e_I) + e_2y_1e_I = x_2 + (1 - e_2 - x_2)(1 - e_1)e_I + e_2y_1e_I$$

$$= x_2 - x_2(1 - e_1)e_I + (1 - e_1)(1 - e_2)e_I + y_1e_2e_I$$

$$= x_2(1 - e_I) + (x_2e_1e_I + (1 - e_2e_I)(1 - e_1e_I) + y_1e_2e_I) + (1 - e_1)(1 - e_2)e_I - (1 - e_1e_I)(1 - e_2e_I)$$

by (43)

$$\begin{array}{l}
\alpha = x_2 (1 - e_I) + \theta_{12}(J) + e_I - e_1e_I - e_2e_I + e_I - 1 + e_1e_I + e_2e_I - e_I \\
\beta = y_2(1 + (x_2 - 1)e_I) = y_2 + (1 - y_2)e_I = e_I + (1 - e_I)y_2, \\
\gamma = e_2(1 + (x_2 - 1)e_I) = e_2(1 - e_I),
\end{array}$$
since \( e_2x_2 = 0 \). By \((43)\),
\[
\theta_{12}(J)(1 - e_I) = 1 - e_I. \tag{45}
\]

Using \((44)\), the RHS of \((44)\) is equal to the product of two matrices
\[
\begin{pmatrix} \theta_{12}(J) + (x_2 - 1)(1 - e_I) & e_2(1 - e_I) \\ 0 & e_1 + (1 - e_I)y_2 \end{pmatrix} = \begin{pmatrix} \theta_{12}(J) & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 + (x_2 - 1)(1 - e_I) & e_2(1 - e_I) \\ 0 & e_1 + (1 - e_I)y_2 \end{pmatrix}.
\]

In order to finish the proof of the proposition, it suffices to show that the last matrix is elementary. This follows from the next two equalities, as the last two matrices in the equality \((47)\) belong to the group \(E_2(S_m)\), by Lemma \[3.2\]
\[
\begin{pmatrix} (1 - (x_2 - 1 + 2e_2)(1 - e_I)) & (1 + (x_2 - 1)(1 - e_I)) \\ 0 & e_1 + (1 - e_I)y_2 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \begin{pmatrix} (1 - (x_2 - 1 + 2e_2)(1 - e_I)) \\ (1 + (x_2 - 1)(1 - e_I)) \end{pmatrix} = \begin{pmatrix} 1 - 2e_2(1 - e_I) \\ 0 \end{pmatrix},
\]
\[
\begin{pmatrix} 0 & 1 - 2e_2(1 - e_I) \\ 1 & 0 \end{pmatrix} = \begin{pmatrix} 1 - 2e_2(1 - e_I) \\ 0 \end{pmatrix}.
\]

The equality \((47)\) is obvious, and the equality \((46)\) can be written in the form \(A_1 \cdots A_5 = A\). Using the identities \(e_2x_2 = 0, y_2x_2 = 1, e_1^2 = e_1\) and \((1 - e_I)^2 = 1 - e_I\), we see that
\[
A_2A_3A_4 = \begin{pmatrix} (1 + (x_2 - 1)(1 - e_I)) \\ 0 \end{pmatrix} \begin{pmatrix} (1 + (x_2 - 1)(1 - e_I)) \\ (1 + (x_2 - 1)(1 - e_I)) \end{pmatrix} = \begin{pmatrix} 1 + (x_2 - 1)(1 - e_I) \\ 1 \end{pmatrix}.
\]

In more detail, let \((u, v)^t\) be the second column of the product of the two matrices in the middle. Then
\[
u = \begin{pmatrix} 1 + (x_2 - 1)(1 - e_I) \\ 1 - e_I \end{pmatrix} = (x_2 - 1 + 2e_2)(1 - e_I),
\]
\[
u = \begin{pmatrix} 1 + (x_2 - 1)(1 - e_I) \\ 1 - e_I \end{pmatrix} = (x_2 - 1 + 2e_2)(1 - e_I),
\]

Finally,
\[
A_2 \cdots A_5 = \begin{pmatrix} 1 - 2e_2(1 - e_I) \\ 0 \end{pmatrix} \begin{pmatrix} x_2 - 1 + 2e_2(1 - e_I) \\ 1 \end{pmatrix}
\]

since \(1 + (x_2 - 1)(1 - e_I) - (x_2 - 1 + 2e_2)(1 - e_I) + (x_2 - 1)(1 - e_I) = 1 + (x_2 - 1 - x_2 + 1 - 2e_2)(1 - e_I) = 1 - 2e_2(1 - e_I)\). Now, \((43)\) is obvious. The proof of the proposition is complete. \(\square\)

**Proof of Theorem \[3.4\]** Notice that \(S_{n-1} \simeq S_1^{\otimes (n-1)}\) and the symmetric group \(S_{n-1}\) is a subgroup of the group of automorphisms of the algebra \(S_{n-1}\) (it acts by permuting the tensor components). Then, the matrix \(\begin{pmatrix} \theta_{ij}(J) \\ 0 \end{pmatrix} \) (where \(J \subseteq \{1, \ldots, n-1\}\) with \(|J| \geq 2\)) is elementary by Proposition \[1.6\] (when \(|J| = 2\)) and Proposition \[4.8\] (when \(|J| > 2\)). Now, Theorem \[3.4\] is obvious. \(\square\)

### 5 The groups \(K_1(S_n, p)\) and \(GL_\infty(S_n, p)\) and their generators

In this section, explicit generators are found for the group \(GL_\infty(S_{n-1}, p)\) where \(p\) is an arbitrary nonzero idempotent prime ideal of the algebra \(S_{n-1}\) and it is proved that \(K_1(S_{n-1}, p) \simeq \mathbb{Z}_2^{(m)} \times K^{sm}\) (Theorem \[5.7\]) where \(m\) is the height of the ideal \(p\).

For a ring \(A\) and an ideal \(\mathfrak{a}\) of \(A\), the normal subgroup of \(GL_\infty(A)\),
\[
GL_\infty(A, \mathfrak{a}) := \ker(GL_\infty(A) \to GL_\infty(A/\mathfrak{a})),
\]
is called the congruence group of level \(\mathfrak{a}\). The normal subgroup \(E_\infty(A, \mathfrak{a})\) of \(E_\infty(A)\) which is generated by all the \(\mathfrak{a}\)-elementary matrices \((1 + aE_{ij}, a \in \mathfrak{a}, i \neq j)\) is a normal subgroup of \(GL_\infty(A)\). Moreover, \([GL_\infty(A), GL_\infty(A, \mathfrak{a})] = E_\infty(A, \mathfrak{a})\) \([2]\), and so the \(K_1\)-group
\[
K_1(A, \mathfrak{a}) := GL_\infty(A, \mathfrak{a})/E_\infty(A, \mathfrak{a})
\]

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is abelian. Let \( E'_\infty(A, a) \) be the subgroup of \( E_\infty(A) \) generated by all the \( a \)-elementary matrices. Then \( E'_\infty(A, a) \subseteq E'_\infty(A, a) \subseteq E_\infty(A) \).

We keep the notation of the previous sections. Recall that we identified the groups \((1 + pp_n)^*\) and \(GL_\infty(S_{n-1})\). Each nonzero idempotent prime ideal \( p \) of the algebra \( S_{n-1} \) is a unique sum (up to order) of distinct height one prime ideals \( p = p_1 + \cdots + p_m \) and \( ht(p) = m \) where \( ht \) stands for the height of an ideal, Corollary 4.8, [5]. The set \( supp(p) := \{i_1, \ldots, i_m\} \) is called the support of the idempotent prime ideal \( p \). The group \( GL_\infty(S_{n-1}, p) \) can be identified with the subgroup \((1 + pp_n)^*\) of the group \((1 + a_n)^*\). The group \((1 + pp_n)^*\) contains the descending chain of normal subgroups

\[(1 + pp_n)^* = (1 + pp_n)_{s+1}^* \supset (1 + pp_n)_{s+2}^* \supset \cdots \supset (1 + pp_n)_{n-1}^* \supset (1 + pp_n)_{n}^* = (1 + F_n)^* \supset (1 + pp_n)_{1} = \{1\}\]

where \((1 + pp_n)^* = (1 + pp_n)_{s}^* \cap (1 + a_{n,s})^*\). Moreover, the groups \((1 + pp_n)^*\) are normal subgroups of the group \((1 + a_n)^*\). The following lemma describes the normal subgroups \((1 + pp_n)^*\).

**Lemma 5.1** Let \( p = p_{i_1} + \cdots + p_{i_m} \) where \( i_1, \ldots, i_m \) are distinct elements of the set \( \{1, \ldots, n\} \). Then

\[(1 + pp_n)^*_s = \begin{cases} (1 + \sum_{|I| = s, I \in J(p)} p_I)^* & \text{if } s = 2, \ldots, n-1, \\ (1 + F_n)^* & \text{if } s = n, \end{cases}\]

where \( J(p) := \{J \subseteq \{1, \ldots, n\} | n \notin J, J \cap supp(p) \neq \emptyset\}. In particular \((1 + pp_n)^*_1 = (1 + pp_n)_2^* = (1 + pp_n)^*\).

**Proof.** The case \( s = n \) is obvious. So, we assume that \( s \neq n \). Since the ideals \( pp_n \) and \( a_{n,s} \) of the algebra \( S_n \) are idempotent ideals,

\[pp_n \cap a_{n,s} = pp_n a_{n,s} = \sum_{\nu = 1}^m p_{i_{\nu}} p_n a_{n,s} = \sum_{|I| = s, I \in J(p)} p_I.\]

Therefore, \((1 + pp_n)^* = (1 + pp_n)^* \cap (1 + a_{n,s})^* = (1 + pp_n \cap a_{n,s})^* = (1 + \sum_{|I| = s, I \in J(p)} p_I)^*\). \(\square\)

By **(1)**, there is a group monomorphism

\[
\varphi_{n,s} : \frac{(1 + pp_n)^*_{s+1}}{(1 + pp_n)^*_s} \rightarrow \frac{(1 + a_{n,s})^*}{(1 + a_{n,s})^*} \rightarrow \prod_{|I| = s} (1 + \overline{p}_I)^* = \prod_{|I| = s, I \in J(p)} (1 + \overline{p}_I)^* \times \prod_{|I| = s, I \notin J(p)} (1 + \overline{p}_I)^*
\]

which is the composition of two group monomorphisms. By Lemma **(1)**

\[
\text{im}(\varphi_{n,s}) \subseteq \prod_{|I| = s, I \in J(p)} (1 + \overline{p}_I)^*. \quad (48)
\]

For each number \( s = 2, \ldots, n-1 \), consider the following subset of the group \((1 + pp_n)^*\),

\[
\overline{E}_{n,s}(p) := \prod_{|I| = s, I \in J(p)} U_I \ltimes E_\infty(S_{CI}).
\]

It is a product of subgroups of \((1 + pp_n)^*_{s+1}\) in arbitrary order, but which is assumed to be fixed for each \( s \).

Recall that \((1 + \overline{p}_I)^* = (\mathcal{X}_{CI} \times U_I) \ltimes E_\infty(L_{CI})\). Since \(\varphi_{n,s}(\overline{E}_{n,s}(p)) = \prod_{|I| = s, I \in J(p)} U_I \ltimes E_\infty(L_{CI})\), we see that there is the group monomorphism

\[
\varphi_{n,s} : \frac{(1 + pp_n)^*_{s+1}}{\overline{E}_{n,s}(p)} \rightarrow \frac{(1 + a_{n,s})^*}{\Gamma_{n,s}} \simeq \mathcal{X}_{n,s} \simeq \mathcal{X}_{n,s} = \prod_{|I| = s, I \in J(p)} \mathcal{X}_{CI} \times \prod_{|I| = s, I \notin J(p)} \mathcal{X}_{CI}. \quad (49)
\]
Notice that the group $\mathbb{E}_{n,s}(p)(1 + pp_n)^s_{*+1}$ is a normal subgroup of $(1 + pp_n)^s_{*}$. For each number \( s = 2, \ldots, n - 1 \), in the set $\Theta^\prime_{n,s}$ consider the exact product of cyclic groups (the order is arbitrary)

$$
\Theta_{n,s}(p) = \Theta^\prime_{n,s}(p) \times_{ex} \Theta^\prime_{n,s}(p),
$$

(49)

$$
\Theta^\prime_{n,s}(p) := \text{exact} \prod_{i \in \text{supp}(p)} \prod_{|J'| = s + 1, n \in J', J' \cap \text{supp}(p) = \{i\}} \prod_{j' \in J'(n,i,m'(J'))} \langle \theta_{m'(J'), j'}(J') \rangle,
$$

$$
\Theta^\prime_{n,s}(p) := \text{exact} \prod_{|J| = s + 1, n \in J, J \cap \text{supp}(p) \geq 2} \prod_{j \in J \setminus \{n,m(J)\}} \langle \theta_{m(j), j}(J) \rangle,
$$

where $m'(J')$ is the largest element of the set $J \setminus \{n, i\}$ and $m(J)$ is the largest element of the set $J \setminus n$. Notice that $\Theta_{n,2}(p) = \Theta^\prime_{n,2}(p)$ as the set $\Theta^\prime_{n,2}(p)$ is an empty set.

By (15), $\text{im}(\mathcal{P}_{n,s}) \subseteq \prod_{|I| = s, I \in J(p)} \mathcal{X}_{CI}$ and

$$
\prod_{|I| = s, I \in J(p)} \mathcal{X}_{CI} = \prod_{|I| = s, I \in J(p)} \prod_{i \in CI} \mathcal{Z}(i, I) = \prod_{|I| = s + 1, n \in J, J \cap \text{supp}(p) \neq \emptyset} \prod_{j \in J \setminus \{n, m(J)\}} \prod_{\text{supp}(p) \geq 2} \prod_{j \in J \setminus \{n, m(J)\}} \mathcal{Z}(j, J \setminus j) \times \mathcal{Z}(j, J \setminus j).
$$

Recall that $\text{im}(\psi^\prime_{n,s}) = \psi^\prime_{n,s}(\Theta_{n,s}) = \mathbb{E}_{n,s} = \bigcap_{|I| = s + 1} \text{ker}(\chi^\prime_J)$, by Theorem 24 and (21). The following argument is the key point in the proof of Theorem 5.2 For each number $s = 2, \ldots, n - 1$,

$$
\text{im}(\mathcal{P}_{n,s}) \subseteq \text{im}(\psi^\prime_{n,s}) \bigcap \prod_{|I| = s, I \in J(p)} \mathcal{X}_{CI} = \bigcap_{|I| = s + 1} \text{ker}(\chi^\prime_J) \bigcap \prod_{|I| = s, I \in J(p)} \mathcal{X}_{CI}
$$

$$
= \prod_{i \in \text{supp}(p)} \prod_{J'^s = 1, n \in J', J' \cap \text{supp}(p) = \{i\}} \prod_{j' \in J'(n,i,m'(J'))} \mathcal{Z}(-m'(J'), J' \setminus m'(J')) + \langle j', J' \setminus j' \rangle
$$

$$
\times \prod_{|J| = s + 1, n \in J, J \cap \text{supp}(p) \geq 2} \prod_{j \in J \setminus \{n, m(J)\}} \mathcal{Z}(-m(j), J \setminus m(J)) + \langle j, J \setminus j \rangle
$$

by (20)

$$
\psi^\prime_{n,s}(\Theta_{n,s}(p)) = \mathcal{P}_{n,s}(\Theta_{n,s}(p)) \mathbb{E}_{n,s}(p)(1 + pp_n)^s_{*+1}.
$$

The first equality above follows from the decomposition of the abelian product $\prod_{|I| = s, I \in J(p)} \mathcal{X}_{CI}$ above and the definition of the homomorphisms $\chi^\prime_J$. It follows that

$$
(1 + pp_n)^s_+ = \Theta_{n,s}(p) \times_{ex} \mathbb{E}_{n,s}(p)(1 + pp_n)^s_{*+1}, \ s = 2, \ldots, n - 1.
$$

(50)

**Theorem 5.2** Let $p$ be a nonzero idempotent prime ideal of the algebra $\mathbb{S}_{n-1}$. Then the group $\text{GL}_{\infty}(\mathbb{S}_{n-1}, p) = (1 + pp_n)^s_*$ is equal to $\Theta_{n,2}(p) \mathbb{E}_{n,2}(p) \cdots \Theta_{n,n-1}(p) \mathbb{E}_{n,n-1}(p)$. Moreover, $\text{im}(\mathcal{P}_{n,1})$ is equal to $\Theta_{n,2}(p) \mathbb{E}_{n,2}(p) \cdots \Theta_{n,n-1}(p) \mathbb{E}_{n,n-1}(p)$ if $s = 1$,

$$
(1 + pp_n)^s_+ = \begin{cases} 
\Theta_{n,2}(p) \mathbb{E}_{n,2}(p) & \text{if } s = 1, \\
\Theta_{n,s}(p) \mathbb{E}_{n,s}(p) \cdots \Theta_{n,n-1}(p) \mathbb{E}_{n,n-1}(p) & \text{if } s = 2, \ldots, n - 1,
\end{cases}
$$

$$
(1 + F_n)^s_+ = \begin{cases} 
\Theta_{n,2}(p) \mathbb{E}_{n,2}(p) \cdots \Theta_{n,n-1}(p) \mathbb{E}_{n,n-1}(p) & \text{if } s = 2, \ldots, n - 1,
\end{cases}
$$

$$
(1 + F_n)^s_+ = \begin{cases} 
\Theta_{n,s}(p) \mathbb{E}_{n,s}(p) \cdots \Theta_{n,n-1}(p) \mathbb{E}_{n,n-1}(p) & \text{if } s = n.
\end{cases}
$$

**Proof.** By Proposition 3.10, (8), we have the inclusion $(1 + pp_n)^s_* = (1 + F_n)^s_* \subseteq \mathbb{E}_{n,1}(p)$. Now, the theorem follows from (39). 

**Lemma 5.3** Let $\mathbb{S}_1(\Lambda)$ be the algebra $\mathbb{S}_1$ over the ring $\Lambda$ from Lemma 4.4. Then, for each element $\lambda \in D \setminus \{-1\},$

$$
\left( \begin{array}{cccc} 
\frac{1}{1 + \lambda c} & 0 & 1 & \lambda e_x \\
0 & 1 & 0 & 1 \\
\lambda e_y & 0 & 1 & 0 \\
1 & 0 & 1 & 0 \\
\end{array} \right) = \left( \begin{array}{cccc} 
1 + \lambda e & 0 & 0 & -\frac{\lambda e}{1 + \lambda} \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\end{array} \right) \left( \begin{array}{cccc} 
\frac{1}{1 + \lambda c} & 0 & 1 & \lambda e_x \\
0 & 1 & 0 & 1 \\
\lambda e_y & 0 & 1 & 0 \\
1 & 0 & 1 & 0 \\
\end{array} \right),
$$

(51)

where $E_{00} := 1 - xy$ and $\frac{1}{1 + \lambda c} = 1 - \frac{\lambda e}{1 + \lambda c}$, by Lemma 4.4 (2).
Proof. The RHS of the equality (11) is the product of four matrices, say $A_1 \cdots A_4$.

$$A_1 A_2 A_3 = \left( \begin{array}{cc} 1 & \frac{\lambda ex}{1 + \lambda e} \\ \frac{1}{1 + \lambda e} & 1 \end{array} \right) \left( \begin{array}{cc} 1 & 0 \\ \frac{\lambda ex}{1 + \lambda e} & 1 \end{array} \right), \quad A_4 = \left( \begin{array}{cc} 1 + \lambda ex & 0 \\ 0 & 1 + \lambda e \end{array} \right),$$

since $(1 + \lambda ex)(-\frac{\lambda ex}{1 + \lambda e}) + \lambda ex = -\frac{\lambda ex}{1 + \lambda e}(1 + \lambda e)x + \lambda ex = 0$. The product $A_1 \cdots A_4$ coincides with the product $A_1 \cdots A_4$ in the proof of Lemma 4.2 and so the equality (11) follows from (10).

□

Lemma 5.4 $E'_\infty(S_{n-1}, p) \supseteq E_{n,s}^s$ for all $s = 3, \ldots, n - 1$ and $E'_\infty(S_{n-1}, p) \supseteq E_\infty(S_{CI})$ for all sets $I \in J(p)$ such that $|I| = 2$.

Proof. We have to show that the group $E'_\infty(S_{n-1}, p)$ contains the groups $E_\infty(S_{CI})$ for all subsets $I \in J(p)$ such that $|I| = 2, 3, \ldots, n - 1$, and the groups $U_I$ for all subsets $I \in J(p)$ such that $|I| = 3, \ldots, n - 1$. By Lemma 5.3, the groups $U_I$ belong to the group $E'_\infty(S_{n-1}, p)$. Indeed, by (10), each element of the group $U_I$ is a matrix $u = (1 + \mu_\{i \in I \} \in \mathbb{C}^{n} \setminus \{1\}$.

Since $I \in J(p)$ and $|I| \geq 3$, we can choose a number $j \in I \setminus n$ such that $(I \setminus \{j, n\}) \cap \text{supp}(p) \neq \emptyset$. Then $e_{I \setminus \{j\}} e_{\{j\}} e_{\{i \}} e_{\{n \}} = e_{\{i \}} e_{\{j\}} e_{\{n \}} e_{\{i \}} e_{\{n \}} = e_{\{i \}} e_{\{j\}} e_{\{n \}} e_{\{i \}} e_{\{n \}}$.

The group $E_\infty(S_{CI})$ is generated by the elementary matrices $u = 1 + a E_{\alpha \beta}(I)$ where $a \in \mathbb{R}^\times$, $\alpha = (\alpha_i)_{i \in I}$, $\beta = (\beta_i)_{i \in I} \in \mathbb{N}^I$ and $\alpha \neq \beta$. If $\alpha_i \neq \beta_i$, then $u = 1 + (\alpha_i \neq \beta_i) E_{\alpha_i, \beta_i}$. Since $I \in J(p)$, we have $E_{\alpha_i, \beta_i} E_{\alpha_i, \beta_i} = E_{\alpha_i, \beta_i} E_{\alpha_i, \beta_i}$ by (10).

Then $E_{\alpha_i, \beta_i} E_{\alpha_i, \beta_i} = E_{\alpha_i, \beta_i} E_{\alpha_i, \beta_i}$, and so $E_{\alpha_i, \beta_i} E_{\alpha_i, \beta_i} = E_{\alpha_i, \beta_i} E_{\alpha_i, \beta_i}$.

Therefore, $E_\infty(S_{n-1}, p) \supseteq [1 + E_{\alpha \beta}, 1 + a E_{\alpha \beta}] = 1 + a E_{\alpha \beta} = u$.

Lemma 5.5 Let $J = \{i, j, n\}$ where the numbers $i$, $j$ and $n$ are distinct. Let $I = \{k, l\}$ where $k \neq n$, and $\lambda \in K^\times$. Then

$$[\theta_{ij}(J), \mu_I(\lambda)] = \begin{cases} 1 & \text{if } k \neq i, k \neq j, \\ 1 + (\lambda^{-1} - 1)e_{I} \mu_{I}(\lambda)^{-1} & \text{if } k = i, \\ 1 + (\lambda^{-1} - 1)e_{I} \mu_{I}(\lambda)^{-1} & \text{if } k = j. \end{cases}$$

Proof. Let $c$ be the group commutator, $J' = \{i, j\}$, $\theta_{ij} = \theta_{ij}(J)$ and $\theta'_{ij} = \theta_{ij}(J')$. Since $\theta_{ij} e_n = e_n \theta_{ij} = \theta_{ij} e_n$ and $\theta_{ij} = \theta_{ij}$, we have that

$$\theta_{ij} e_n = e_n \theta_{ij} = \theta_{ij} e_n = e_n \theta_{ij} = e_n \theta_{ij},$$

$$\theta_{ij}^{-1} = \theta_{ij}^{-1} \quad \text{and} \quad \theta_{ij}^{-1} = \theta_{ij}^{-1}.$$
By Lemma 5.4, the inclusion of the group \( k \) element. In both cases, we can choose an element, say \( \theta \) in the first case, and \( \gamma \) in the second case of the group \((1 + pp) \) of the group (1 + \( pp \)). Hence all the images commute.

**Theorem 5.6** \( \mathcal{E}(S_{n-1}, p) = E_\infty(S_{n-1}, p) = E'_{\infty}(S_{n-1}, p) \).

**Proof.** Recall that \( GL_\infty(R, a)/E_\infty(R, a) \) is an abelian group for any ring \( R \) and ideal \( a \) of \( R \), \([2]\).

By (63), Lemma 5.3 and (64), the factor group \((1 + pp)^*/E(S_{n-1}, p) \) is abelian.

Let us show that \( E'_{\infty}(S_{n-1}, p) \subseteq \mathcal{E} := E(S_{n-1}, p) \). We have to show that \( 1 + pE_{ij}(n) \subseteq \mathcal{S} \) for all \( i \neq j \). Since

\[
1 + pE_{ij}(n) = 1 + (p_{i_1} + \cdots + p_{i_m})E_{ij}(n) = \prod_{\nu=1}^{m} (1 + p_{i_\nu}E_{ij}(n)),
\]

it suffices to show that \( 1 + p_{i_\nu}E_{ij}(n) \subseteq \mathcal{E} \) for all \( \nu = 1, \ldots, m \) and \( i \neq j \), but this is obvious since

\[
1 + p_{i_\nu}E_{ij}(n) \subseteq E_\infty(S_{CT}) \subseteq \mathcal{E}
\]

where \( I = \{i_\nu, n\} \) (and so \( |I| = 2 \) and \( I \in \mathcal{J}(p) \)), see the definition of \( \mathcal{E} \).

To finish the proof of the theorem it suffices to show that \( \mathcal{E}(S_{n-1}, p) \subseteq E'_{\infty}(S_{n-1}, p) \) (since then the group \( E'_{\infty}(S_{n-1}, p) \) is a normal subgroup of \( GL_\infty(S_{n-1}, p) \) as \( GL_\infty(S_{n-1}, p)/\mathcal{E} \) is an abelian group and \( \mathcal{E} \subseteq E'_{\infty}(S_{n-1}, p) \); hence \( E_\infty(S_{n-1}, p) = E'_{\infty}(S_{n-1}, p) \) and \( E'_{\infty}(S_{n-1}, p) = \mathcal{E} \)). By Theorem 5.2,

\[
\mathcal{E}(S_{n-1}, p) = \prod_{|I|=2, I \in \mathcal{J}(p)} E_\infty(S_{CT}) \cdot \Theta_{n,3}(p)\overline{E}_{n,3}(p) \cdots \Theta_{n-1,1}(p)\overline{E}_{n-1,1}(p).
\]

By Lemma 5.4, the inclusion \( \mathcal{E}(S_{n-1}, p) \subseteq E'_{\infty}(S_{n-1}, p) \) holds iff \( \Theta_{n,s}(p) \subseteq E'_{\infty}(S_{n-1}, p) \) for all \( s = 3, \ldots, n-1 \) iff \( \Theta_{n,s}(p) \subseteq E'_{\infty}(S_{n-1}, p) \) for all \( s = 3, \ldots, n-1 \).

Fix an element \( \theta \) such that either \( \theta \in \Theta_{n,s}(p) \) or \( \theta \in \Theta_{n,s}(p) \), i.e. either \( \theta = \theta_{m(J), j} \) or \( \theta = \theta_{m(J), j} \), see (19). In the second case, without loss of generality we may assume that \( m(J) \notin J \cap \mathbb{suppp}(p) \), by changing, if necessary, the order in the set \( J \) (or simply by taking a suitable element). In both cases, we can choose an element, say \( k \in J \cup \mathbb{suppp}(p) \), such that \( k \notin \{m'(J'), j\}' \), in the first case, and \( k \notin \{m(J), j\} \), in the second case. In both cases, we can write \( \theta = \theta_{ij}(J) \) where \( k \in J \cup \mathbb{suppp}(p) \) and \( k \notin \{i, j\} \). As we have seen in Section 3,

\[
\theta_{ij}(J) = e_k \theta_{ij}(J \setminus k) + 1 - e_k.
\]
By Theorem \ref{thm:5.3} \( \theta_{ij}(J \setminus k) \in E_\infty(\bigotimes_{l=1,l \neq k}^{n-1} S_l(l)) \subseteq \GL_\infty(\bigotimes_{l=1,l \neq k}^{n-1} S_l(l)) \). Under the algebra homomorphism
\[
\GL_\infty(\bigotimes_{l=1,l \neq k}^{n-1} S_l(l)) \to \GL_\infty(S_{n-1}, p), \quad a \mapsto e_k a + 1 - e_k,
\]
the group of elementary matrices \( E_\infty(S_{n-1}, p) \) is mapped into the group of \( p \)-elementary matrices \( E_{n-1}(S_{n-1}, p) \) since \( e_k \in p \). Therefore, \( \theta \in E_\infty(S_{n-1}, p) \). The proof of the theorem is complete. \( \Box \)

**Theorem 5.7** Let \( p \) be a nonzero idempotent prime ideal of the algebra \( \mathbb{S}_{n-1} \) and \( m = \text{ht}(p) \) be its height. Then (below is the direct product of groups)
\[
\mathbb{K}_1(\mathbb{S}_{n-1}, p) \isom \prod_{\{i > j \mid i,j \in \text{supp}(p)\}} \langle \theta_{ij}\{i,j,n\} \rangle \times \prod_{k \in \text{supp}(p)} U\{k,n\} \isom \begin{cases} \mathbb{K}^* \times \mathbb{Z}^{(n-2)} & \text{if } m = 1, \\ \mathbb{K}^* & \text{if } m > 1. \end{cases}
\]
The group \( \GL_\infty(\mathbb{S}_{n-1}, p) \) is generated by the elements \( \theta_{ij} := \theta_{ij}\{i,j,n\} \) (where \( i > j \) and \( i,j \in \text{supp}(p) \)) and the groups \( E_\infty(\mathbb{S}_{n-1}, p), U\{k,n\} \) where \( k \in \text{supp}(p) \). Moreover, each element \( a \) of the group \( \GL_\infty(\mathbb{S}_{n-1}, p) \) is the unique product (the order is arbitrary)
\[
a = \prod_{\{i > j \mid i,j \in \text{supp}(p)\}} \theta_{ij}^{n_{ij}}, \prod_{k \in \text{supp}(p)} \mu_{\{k,n\}}(\lambda_k) \cdot c \tag{55}
\]
where \( n_{ij} \in \mathbb{Z}, \lambda_k \in \mathbb{K}^* \) and \( c \in E_\infty(\mathbb{S}_{n-1}, p) \).

**Proof.** The theorem follows from the equality \((53)\) and Theorem \ref{thm:5.6} \( \Box \)

We can find effectively (in finitely many steps) the decomposition \((55)\) (Corollary \ref{cor:5.9}). For, we introduce several explicit group homomorphisms.

**Definition.** For each nonempty subset \( I \) of \( \{1, \ldots, n\} \) with \( |I| < n \) and for each element \( j \in CI \), define the group homomorphism \( \det_I : (1 + a_{n,s})^* \to L^*_C \) as the composition of the group homomorphisms (see \((10)\))
\[
(1 + a_{n,s})^* \xrightarrow{\psi_{ni}} \prod_{|J|=s} (1 + \overline{p}_j)^* \xrightarrow{\text{pr}_I} (1 + \overline{p}_I)^* \isom \GL_\infty(L_{CI}) \xrightarrow{\det} L^*_C
\]
where \( \text{pr}_I \) is the projection map. Define the group homomorphism \( \deg_{n,I,j} : (1 + a_{n,s})^* \to \mathbb{Z} \) as the composition of the group homomorphisms \( (1 + a_{n,s})^* \xrightarrow{\det_I} L^*_C \xrightarrow{\deg_{x_j}} \mathbb{Z} \) where \( \deg_{x_j} \) is the degree in \( x_j \) of monomial \( \deg_{x_j}(\lambda \prod_{i \in CI} x_i^{\alpha_i}) = \alpha_j \) where \( \lambda \in \mathbb{K}^* \) and \( \alpha_i \in \mathbb{Z} \).

**Lemma 5.8** Let \( n \geq 3 \) and \( s = 1, \ldots, n - 1 \). Then for all subsets \( I \) and \( J \) of the set \( \{1, \ldots, n\} \) such that \( |I| = s, \ |J| = s + 1 \) and \( n \in J \),
\[
\deg_{n,I,j}(\theta_{m(J),j}(J)) = \begin{cases} -1 & \text{if } I = J \setminus m(J), i = m(J), \\ 1 & \text{if } I = J \setminus j, i = j, \\ 0 & \text{otherwise}. \end{cases}
\]
where \( i \in CI \) and \( j \in J \setminus m(J) \).

**Proof.** The result follows at once from the equality \( \theta_{m(J),j} = (1 + (y_{m(J)} - 1)e_{J \setminus m(J)})(1 + (x_j - 1)e_{J \setminus j}) \). \( \Box \)
Corollary 5.9  Given a product decomposition \((55)\) for an element \(a \in \text{GL}_{\infty}(S_{n-1}, p)\), we have

\[
\begin{align*}
n_{ij} &= \deg_{n,(i,n)_{j}}(a), \\
\lambda_k &= \det_{(k,n)}(a \cdot \prod_{\{i>j \mid i,j \in \text{supp}(p)\}} \theta_{ij}^{-n_{ij}}), \\
e &= (\prod_{\{i>j \mid i,j \in \text{supp}(p)\}} \theta_{ij}^{n_{ij}} \cdot \prod_{k \in \text{supp}(p)} \mu_{(k,n)}(\lambda_k))^{-1} a.
\end{align*}
\]

**Proof.** By Lemma 5.8, \(\deg_{n,(i,n)_{j}}(a) = n_{ij} \deg_{n,\{i,n\}_{j}}(\theta_{ij}) = n_{ij}\). Similarly,

\[
\det_{(k,n)}(a \cdot \prod_{\{i>j \mid i,j \in \text{supp}(p)\}} \theta_{ij}^{-n_{ij}}) = \det_{(k,n)}(\mu_{(k,n)}(\lambda_k)) = \lambda_k.
\]

The rest is obvious. \(\square\)

Corollary 5.9 gives an effective criterion of whether an element \(a \in \text{GL}_{\infty}(S_{n-1}, p)\) is a product of \(p\)-elementary matrices.

**Corollary 5.10**  Let \(a \in \text{GL}_{\infty}(S_{n-1}, p)\). Then \(a \in \text{E}_{\infty}(S_{n-1}, p)\) iff all \(n_{ij} = 1\) iff \(\deg_{n,(i,n)_{j}}(a) = 1\) for all \(i > j\) such that \(i,j \in \text{supp}(p)\), and \(\det_{(k,n)}(a) = 1\) for all \(k \in \text{supp}(p)\).

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**References**


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