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Certain Local Subsemigroups of Semigroups of Linear Transformations

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Abstract: A *local subsemigroup* of a semigroup S is a subsemigroup of S of the form eAe where A is a subsemigroup of S and e is an idempotent of S. It has been shown that for a finite nonempty set X and an idempotent α of $T(X)$, $\alpha G(X)\alpha$ is a local subsemigroup of $T(X)$ if and only if either α is the identity mapping on X or for every $a \in \operatorname{ran}\alpha$, $|a\alpha^{-1}| \geq |\operatorname{ran}\alpha|$ where $T(X)$ and $G(X)$ are the full transformation semigroup and the symmetric group on X, respectively. In this paper, a parallel result is provided on the semigroup $L(V)$, under composition, of all linear transformations of a vector space V. We show that for a finite-dimensional vector space V and an idempotent α of $L(V)$, $\alpha GL(V)\alpha$ is a local subsemigroup of $L(V)$ if and only if either α is the identity mapping on V or $\dim(\ker\alpha) \geq \dim(\operatorname{ran}\alpha)$ where $GL(V)$ is the group of isomorphisms of V.

Keywords: Local subsemigroup, semigroup of linear transformations

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1 Introduction

Denote by $E(S)$ the set of all idempotents of a semigroup S, that is,

$$E(S) = \{x \in S \mid x^2 = x\}.$$

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By a *local subsemigroup* of a semigroup S we mean a subsemigroup of S of the form eAe where $e \in E(S)$ and A is a subsemigroup of S. Then for every $e \in E(S)$, $\{e\}$ and eSe are obviously local subsemigroups of S. This given definition is motivated by [3] and [4].

The cardinality of a set X is denoted by $|X|$. The domain and the range of a mapping α are denoted by $\operatorname{dom}\alpha$ and $\operatorname{ran}\alpha$, respectively, and the value of α at $x \in \operatorname{dom}\alpha$ is written by $x\alpha$. For $A \subseteq \operatorname{dom}\alpha$, $\alpha_{|A}$ denotes the restriction of α to A.

The full transformation semigroup and the symmetric group on a nonempty set X are denoted by $T(X)$ and $G(X)$, respectively. Then $G(X)$ is the group of units of $T(X)$. We also have that

$$E(T(X)) = \{\alpha \in T(X) \mid x\alpha = x \text{ for all } x \in \operatorname{ran}\alpha\}$$

([1], page 12). In [5], the authors provided a neccessary and sufficient condition for $\alpha \in E(T(X))$, where X is finite, so that $\alpha G(X)\alpha$ is a local subsemigroup of $T(X)$ as follows:

Theorem 1.1 ([5]). *Let X be a finite nonempty set and $\alpha \in E(T(X))$. Then $\alpha G(X)\alpha$ is a local subsemigroup of $T(X)$ if and only if either*

(i) $\alpha = 1_X$, *the identity mapping on X, or*

(ii) *for every* $a \in \operatorname{ran}\alpha, |a\alpha^{-1}| \geq |\operatorname{ran}\alpha|$.

In the second case, $\alpha G(X)\alpha = \alpha T(\operatorname{ran}\alpha) \cong T(\operatorname{ran}\alpha)$.

An analogous result of Theorem 1.1 on the semigroup of linear transformations of a vector space is considered in this paper.

Let V be a vector space over a field F, $L(V)$ the semigroup, under composition, of all linear transformations of V. Then

$$E(L(V)) = \{\alpha \in L(V) \mid v\alpha = v \text{ for all } v \in \operatorname{ran}\alpha\}.$$

Let $GL(V)$ be the group of all isomorphisms of V under composition. Then $GL(V)$ is the group of units of $L(V)$. Recall that for $\alpha \in L(V)$, α is a monomorphism if and only if $\ker\alpha = \{0\}$ where $\ker\alpha$ denotes the kernel of α. Also, if V is finite-dimensional, then for $\alpha \in L(V)$, α is an isomorphism of V if and only if α is a monomorphism [an epimorphism]. Hence

$$\dim V < \infty \Rightarrow GL(V) = \{\alpha \in L(V) \mid \ker\alpha = \{0\}\}$$

where $\dim V$ denotes the dimension of V over F. Recall that $\ker\alpha$ and $\operatorname{ran}\alpha$ are subspaces of V and

$$\dim V = \dim(\ker\alpha) + \dim(\operatorname{ran}\alpha).$$

The following facts of linear transformations will be used. The proofs are straightforward.

Proposition 1.2. *If* $\alpha \in L(V)$ *and* B *is a basis of* V *such that* $\alpha_{|_B}$ *is* $1-1$ *and* $B\alpha$ *is a basis of* V, *then* $\alpha \in GL(V)$.

Proposition 1.3. *Let* $\alpha \in L(V)$, B_1 *a basis of* $\ker\alpha$ *and* B_2 *a basis of* $\operatorname{ran}\alpha$. *If for every* $v \in B_2$, *choose* $v' \in v\alpha^{-1}$, *then* $B_1 \dot{\cup} \{v' \mid v \in B_2\}$ *is a basis of* V.

Here, $\dot{\cup}$ stands for a disjoint union.

Proposition 1.4. *If* $\alpha \in E(L(V))$, *then* $V = \ker\alpha \oplus \operatorname{ran}\alpha$.

Proposition 1.4 yields the following result.

Corollary 1.5. *If* $\alpha \in E(L(V))$, B_1 *is a basis of* $\ker\alpha$ *and* B_2 *is a basis of* $\operatorname{ran}\alpha$, *then* $B_1 \cup B_2 = B_1 \dot{\cup} B_2$ *which is a basis of* V.

Hence for every $w \in \ker\alpha \smallsetminus \{0\}$, $\{w\} \cup B_2$ *is a linearly independent subset of* V.

The purpose of this paper is to show that for $\alpha \in E(L(V))$, $\alpha GL(V)\alpha$ is a local subsemigroup of $L(V)$ if and only if either $\alpha = 1_V$ or $\dim(\ker\alpha) \geq \dim(\operatorname{ran}\alpha)$. In the latter case, $\alpha GL(V)\alpha = \alpha L(\operatorname{ran}\alpha) \cong L(\operatorname{ran}\alpha)$.

In the remaining of this paper, V is a vector space over a field F.

2 Main Results

First, we recall that every element $\alpha \in L(V)$ can be defined on a basis B of V. We may write $\alpha \in L(V)$ defined on B by a bracket notation as follows:

$$\alpha = \begin{pmatrix} u \\ u' \end{pmatrix}_{u \in B} \quad \text{if } u\alpha = u' \text{ for all } u \in B.$$

The following series of lemmas is needed to obtain our main result.

Lemma 2.1. *If $\alpha \in E(L(V))$, then $\alpha L(\operatorname{ran}\alpha)$ is a subsemigroup of $L(V)$ and $\alpha L(\operatorname{ran}\alpha) \cong L(\operatorname{ran}\alpha)$.*

Proof. It is evident that $\alpha L(\operatorname{ran}\alpha) \subseteq L(V)$. Since $v\alpha = v$ for all $v \in \operatorname{ran}\alpha$, we have that $\beta\alpha = \beta$ for all $\beta \in L(\operatorname{ran}\alpha)$. Thus

$$\begin{aligned}(\alpha L(\operatorname{ran}\alpha))(\alpha L(\operatorname{ran}\alpha)) &= \alpha(L(\operatorname{ran}\alpha)\alpha)L(\operatorname{ran}\alpha)\\ &= \alpha L(\operatorname{ran}\alpha)L(\operatorname{ran}\alpha)\\ &= \alpha L(\operatorname{ran}\alpha)\end{aligned}$$

and for all $\beta, \gamma \in L(\operatorname{ran}\alpha)$,

$$\alpha(\beta\gamma) = \alpha(\beta\alpha)\gamma = (\alpha\beta)(\alpha\gamma),$$

$$\alpha\beta = \alpha\gamma \text{ implies that for all } v \in \operatorname{ran}\alpha,\ v\beta = v\alpha\beta = v\alpha\gamma = v\gamma.$$

This shows that $\alpha L(\operatorname{ran}\alpha)$ is a subsemigroup of $L(V)$ and the mapping $\beta \mapsto \alpha\beta$ is an isomorphism from $L(\operatorname{ran}\alpha)$ onto $\alpha L(\operatorname{ran}\alpha)$. □

Lemma 2.2. *Assume that V is finite-dimensional and let $\alpha \in E(L(V))$. If $\dim(\ker\alpha) \geq \dim(\operatorname{ran}\alpha)$, then $\alpha GL(V)\alpha = \alpha L(\operatorname{ran}\alpha)$.*

Proof. If $\beta \in GL(V)$, then $\operatorname{ran}(\beta\alpha) \subseteq \operatorname{ran}\alpha$ which implies that $\alpha\beta\alpha = \alpha((\beta\alpha)_{|\operatorname{ran}\alpha}) \in \alpha L(\operatorname{ran}\alpha)$. Thus $\alpha GL(V)\alpha \subseteq \alpha L(\operatorname{ran}\alpha)$.

To show that $\alpha L(\operatorname{ran}\alpha) \subseteq \alpha GL(V)\alpha$, let $\lambda \in L(\operatorname{ran}\alpha)$. Then $\alpha\lambda \in L(V)$ and $\operatorname{ran}(\alpha\lambda) \subseteq \operatorname{ran}\lambda \subseteq \operatorname{ran}\alpha = \operatorname{dom}\lambda$. But since $\dim(\ker\alpha) \geq \dim(\operatorname{ran}\alpha)$, we have

$$\dim(\ker\lambda) \leq \dim(\operatorname{ran}\alpha) \leq \dim(\ker\alpha). \tag{1}$$

Let B_1 be a basis of $\ker\lambda$ and B_2 a basis of $\operatorname{ran}\lambda$. For each $v \in B_2$, let $v' \in v\lambda^{-1}$. By Proposition 1.3, $B_1\dot{\cup}\{v' \mid v \in B_2\}$ is a basis of $\operatorname{ran}\alpha$ $(= \operatorname{dom}\lambda)$. Let B_3 be a basis of $\operatorname{ran}\alpha$ containing B_2. Then

$$\dim(\operatorname{ran}\alpha) = |B_1\dot{\cup}\{v' \mid v \in B_2\}| = |B_3| = |(B_3\smallsetminus B_2)\dot{\cup} B_2|.$$

Since $\dim V < \infty$ and $|\{v' \mid v \in B_2\}| = |B_2|$, it follows that $|B_1| = |B_3\smallsetminus B_2|$. Let B_4 be a basis of $\ker\alpha$. By Corollary 1.5,

$$B_1\dot{\cup}\,\{v' \mid v \in B_2\}\,\dot{\cup}\,B_4 \ \text{ is a basis of } V \tag{2}$$

and

$$B_3\,\dot{\cup}\,B_4 \ \text{ is a basis of } V. \tag{3}$$

From (1), we have $|B_1| \le |B_4|$. Let $\varphi : B_1 \to B_4$ be $1-1$. Then we have

$$|B_3\smallsetminus B_2| = |B_1| = |B_1\varphi|$$

which implies that

$$|B_4| = |(B_4\smallsetminus B_1\varphi)\dot{\cup}\,B_1\varphi| = |(B_4\smallsetminus B_1\varphi)\,\dot{\cup}\,(B_3\smallsetminus B_2)|$$

since $B_3 \cap B_4 = \emptyset$ (see (3)). Let $\psi : B_4 \to (B_4\smallsetminus B_1\varphi)\,\dot{\cup}\,(B_3\smallsetminus B_2)$ be a bijection. Define $\beta \in L(V)$ on the basis $B_1\,\dot{\cup}\,\{v' \mid v \in B_2\}\,\dot{\cup}\,B_4$ of V (see (2)) by

$$\beta = \begin{pmatrix} u & v' & w \\ u\varphi & v & w\psi \end{pmatrix}_{\substack{u\in B_1,\, v\in B_2 \\ w\in B_4}}. \tag{4}$$

Since φ, $v' \mapsto v$ $(v \in B_2)$ and ψ are $1-1$, $B_1\varphi \subseteq B_4$, $B_2 \subseteq B_3$, $B_3 \cap B_4 = \emptyset$ and $B_4\psi = (B_4\smallsetminus B_1\varphi)\,\dot{\cup}\,(B_3\smallsetminus B_2)$, it follows that β restricted to the basis $B_1\,\dot{\cup}\,\{v' \mid v \in B_2\}\,\dot{\cup}\,B_4$ of V is $1-1$. Also,

$$\begin{aligned}(B_1\,\dot{\cup}\,\{v' \mid v \in B_2\}\,\dot{\cup}\,B_4)\beta &= B_1\varphi\,\dot{\cup}\,B_2\,\dot{\cup}\,(B_4\smallsetminus B_1\varphi)\,\dot{\cup}\,(B_3\smallsetminus B_2) \\ &= B_3\,\dot{\cup}\,B_4\end{aligned}$$

which is a basis of V by (3). By Proposition 1.2, we deduce that $\beta \in GL(V)$. We claim that $\alpha\beta\alpha = \alpha\lambda$. Recall that $v\alpha = v$ for all $v \in \operatorname{ran}\alpha$. Since $B_1 \subseteq \ker\lambda \subseteq \operatorname{ran}\alpha$, $B_2 \subseteq \operatorname{ran}\alpha$, $\{v' \mid v \in B_2\} \subseteq \operatorname{ran}\alpha$, $B_1\varphi \subseteq B_4 \subseteq \ker\alpha$ and $v'\lambda = v$, for all

$v \in B_2$, from (4), we have

$$\begin{aligned} \text{for } u \in B_1, \quad u\alpha\beta\alpha &= u\beta\alpha = u\varphi\alpha = 0, \\ u\alpha\lambda &= \ u\lambda \ = 0, \\ \text{for } u \in B_2, \quad u'\alpha\beta\alpha &= u'\beta\alpha = u\alpha = u, \\ u'\alpha\lambda &= \ u'\lambda \ = u, \\ \text{for } u \in B_4, \quad u\alpha\beta\alpha &= \ \ 0 \ \ = u\alpha\lambda. \end{aligned} \tag{5}$$

Hence (2) and (5) yield $\alpha\beta\alpha = \alpha\lambda$.

This proves that $\alpha GL(V)\alpha = \alpha L(\operatorname{ran}\alpha)$, as desired. □

Lemma 2.3. *Assume that V is finite-dimensional, $\alpha \in E(L(V))$ and $\alpha \neq 1_V$. If $\alpha GL(V)\alpha$ is a local subsemigroup of $L(V)$, then* $\dim(\ker\alpha) \geq \dim(\operatorname{ran}\alpha)$.

Proof. Since $\alpha \neq 1_V$, $u\alpha = v$ for some distinct $u, v \in V$. Then $u\alpha = u\alpha^2 = v\alpha$, so α is not a monomorphism. Thus $\ker\alpha \neq \{0\}$. Let $w \in \ker\alpha \setminus \{0\}$.

To show that $\dim(\ker\alpha) \geq \dim(\operatorname{ran}\alpha)$, we are done if $\dim(\operatorname{ran}\alpha) = 0$. Assume that $\dim(\operatorname{ran}\alpha) = k > 0$. Let $\{u_1, \ldots, u_k\}$ be a basis of $\operatorname{ran}\alpha$. By Corollary 1.5, we have that for each $i \in \{1, \ldots, k\}$, $u_1, \ldots, u_{i-1}, w, u_{i+1}, \ldots, u_k$ are linearly independent. Let B_0 be a basis of $\ker\alpha$. By Corollary 1.5, $B_0 \dot{\cup} \{u_1, \ldots, u_k\}$ is a basis of V. For each $i \in \{1, \ldots, k\}$, let B_i be a basis of V containing $\{u_1, \ldots, u_{i-1}, w, u_{i+1}, \ldots, u_k\}$. Since $\dim V < \infty$,

$$|B_0| = \dim V - k = |B_i \setminus \{u_1, \ldots, u_{i-1}, w, u_{i+1}, \ldots, u_k\}| \quad \text{for all } i \in \{1, \ldots, k\}.$$

For each $i \in \{1, \ldots, k\}$, let $\varphi_i : B_0 \to B_i \setminus \{u_1, \ldots, u_{i-1}, w, u_{i+1}, \ldots, u_k\}$ be a bijection and define $\beta_i \in L(V)$ on the basis $B_0 \cup \{u_1, \ldots, u_k\}$ by

$$\beta_i = \begin{pmatrix} u_1 & \cdots & u_{i-1} & u_i & u_{i+1} & \cdots & u_k & v \\ u_1 & \cdots & u_{i-1} & w & u_{i+1} & \cdots & u_k & v\varphi_i \end{pmatrix}_{v \in B_0}.$$

By Proposition 1.2, $\beta_i \in GL(V)$ for all $i \in \{1, \ldots, k\}$. Note that $u_i\alpha = u_i$ for all $i \in \{1, \ldots, k\}$ and $v\alpha = 0$ for all $v \in B_0$. Then

$$\alpha\beta_1\alpha = \begin{pmatrix} u_1 & u_2 & \cdots & u_k & v \\ 0 & u_2 & \cdots & u_k & 0 \end{pmatrix}_{v \in B_0}.$$

In general, for $i \in \{1, \ldots, k\}$,

$$\alpha\beta_i\alpha = \begin{pmatrix} u_1 & \cdots & u_{i-1} & u_i & u_{i+1} & \cdots & u_k & v \\ u_1 & \cdots & u_{i-1} & 0 & u_{i+1} & \cdots & u_k & 0 \end{pmatrix}_{v \in B_0}.$$

Notice that

$$(\alpha\beta_1\alpha)(\alpha\beta_2\alpha) = \begin{pmatrix} u_1 & u_2 & \cdots & u_k & v \\ 0 & u_2 & \cdots & u_k & 0 \end{pmatrix}_{v \in B_0} \begin{pmatrix} u_1 & u_2 & u_3 & \cdots & u_k & v \\ u_1 & 0 & u_3 & \cdots & u_k & 0 \end{pmatrix}_{v \in B_0}$$

$$= \begin{pmatrix} u_1 & u_2 & u_3 & \cdots & u_k & v \\ 0 & 0 & u_3 & \cdots & u_k & 0 \end{pmatrix}_{v \in B_0}.$$

By induction, we have

$$(\alpha\beta_1\alpha)(\alpha\beta_2\alpha)\ldots(\alpha\beta_k\alpha) = \begin{pmatrix} u_1 & \cdots & u_k & v \\ 0 & \cdots & 0 & 0 \end{pmatrix}_{v \in B_0}.$$

Since $\alpha GL(V)\alpha$ is a subsemigroup of $L(V)$, it follows that the zero map 0 on V belongs to $\alpha GL(V)\alpha$. Thus $\alpha\gamma\alpha = 0$ for some $\gamma \in GL(V)$. Consequently,

$$(\operatorname{ran}\alpha)\gamma = (V\alpha)\gamma \subseteq \ker\alpha.$$

Since $\gamma \in GL(V)$, $\dim(\ker\alpha) \geq \dim((\operatorname{ran}\alpha)\gamma) = \dim(\operatorname{ran}\alpha)$.

Hence the lemma is proved. □

The following main result is obtained directly from Lemma 2.1, Lemma 2.2 and Lemma 2.3.

Theorem 2.4. *Let V be finite-dimensional and $\alpha \in E(L(V))$. Then $\alpha GL(V)\alpha$ is a local subsemigroup of $L(V)$ if and only if either*

(i) $\alpha = 1_V$, *or*

(ii) $\dim(\ker \alpha) \geq \dim(\operatorname{ran} \alpha)$.
In the second case, $\alpha GL(V)\alpha = \alpha L(\operatorname{ran} \alpha) \cong L(\operatorname{ran} \alpha)$.

If $\dim V < \infty$, then we have

$$\begin{aligned}\dim(\operatorname{ran} \alpha) \leq \dim(\ker \alpha) &\Leftrightarrow \dim(\operatorname{ran} \alpha) \leq \dim V - \dim(\operatorname{ran} \alpha) \\ &\Leftrightarrow 2\dim(\operatorname{ran} \alpha) \leq \dim V.\end{aligned}$$

Hence Theorem 2.4 can be restated as follows:

Theorem 2.5. *Let* V *be finite-dimensional and* $\alpha \in E(L(V))$. *Then* $\alpha GL(V)\alpha$ *is a local subsemigroup of* $L(V)$ *if and only if either*

(i) $\alpha = 1_V$, *or*

(ii) $2\dim(\operatorname{ran} \alpha) \leq \dim V$.
In the second case, $\alpha GL(V)\alpha = \alpha L(\operatorname{ran} \alpha) \cong L(\operatorname{ran} \alpha)$.

It is clear that for $\alpha \in E(L(V))$,

$\alpha = 0$ or 1_V if $\dim V = 1$,
$\alpha = 0,\ 1_V$ or $\dim(\operatorname{ran} \alpha) = 1$ if $\dim V = 2$.

Hence by Theorem 2.5, we have

Corollary 2.6. *If* $\dim V \leq 2$, *then for every* $\alpha \in E(L(V))$, $\alpha GL(V)\alpha$ *is a local subsemigroup of* $L(V)$.

Let n be a positive integer and $M_n(F)$ the semigroup of $n \times n$ matrices over a field F under the usual matrix multiplication and let $G_n(F)$ be the group of non-singular $n \times n$ matrices over F. Then there is an isomorphism $\theta : L(V) \to M_n(F)$ which preserves ranks, that is, $\dim(\operatorname{ran} \alpha)$ ($= \operatorname{rank} \alpha$) $= \operatorname{rank}(\alpha\theta)$ for all $\alpha \in L(V)$ ([2], page 330, 339). Then $GL(V)\theta = G_n(F)$ and $1_V\theta = I_n$, the identity $n \times n$ matrix over F. Hence from Theorem 2.5 we have

Theorem 2.7. *Let n be a positive integer, F a field and $A \in E(M_n(F))$. Then $AG_n(F)A$ is a local subsemigroup of $M_n(F)$ if and only if either*

(i) $A = I_n$, *or*

(ii) $2\operatorname{rank}(A) \leq n$.

Example. Let F be a field. Consider the vector space F^4 over F with usual addition and scalar multiplication. Define $\alpha : F^4 \to F^4$ by

$$(x, y, z, w) = (x, 0, z, 0) \quad \text{for all } x, y, z, w \in F.$$

Then $\alpha \in E(L(F^4))$ and $\dim(\operatorname{ran}\alpha) = 2$, so $2\dim(\operatorname{ran}\alpha) = 4 = \dim F^4$. By Theorem 2.5, $\alpha GL(F^4)\alpha$ is a local subsemigroup of $L(F^4)$.

Next, let $x, y, z \in F$,

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ x & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & y & 0 \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & z \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Then $A^2 = A$, $B^2 = B$, $\operatorname{rank} A = 2$ and $\operatorname{rank} B = 3$. Thus $2\operatorname{rank} A = 4$ and $2\operatorname{rank} B = 6 > 4$. By Theorem 2.7, $AG_n(F)A$ is a local subsemigroup of $M_4(F)$ but $BG_n(F)B$ is not. Note that x, y, z can be any elements of F.

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