THE STUDY OF COMMUTATIVE SEMIGROUPS WITH GREATEST GROUP-HOMOMORPHISM\(^{(1)}\)

BY

TAKAYUKI TAMURA AND HOWARD B. HAMILTON

ABSTRACT. This paper characterizes commutative semigroups which admit a greatest group-homomorphism in various ways. One of the important theorems is that a commutative semigroup \(S\) has a greatest group-homomorphic image if and only if for every \(a \in S\) there are \(b, c \in S\) such that \(abc = c\). Further the authors study a relationship between \(S\) and a certain cofinal subsemigroup and discuss the structure of commutative separative semigroups which have a greatest group-homomorphic image.

1. Introduction. In the study of semigroups it would be natural to find a relationship between semigroups and groups by some means. This is our intention in studying group-homomorphisms or group-congruences. Many mathematicians have already studied characterizations of group-congruences on a semigroup in terms of certain subsemigroups ([5], [7], [13], [14], [16]). We are mainly interested in the greatest group-homomorphism on a commutative semigroup. However it does not exist in general. Accordingly the following questions are raised: Under what condition on a commutative semigroup \(S\) does there exist a greatest group-homomorphism on \(S\)? What is the structure of \(S\) admitting a greatest group-homomorphism? The "external" characterization of those semigroups, i.e. in terms of their homomorphisms to other semigroups, is easy, but the "internal" characterization, i.e. the determination of the structure and construction, seems difficult. We have not seen any paper treating the last problem except some special case treated by Head [10], and McAlister and O'Caroll [15]. This is probably due to the lack of a foundation from which to start. The purpose of this paper is to contribute to this point in a manner which may be useful in the future.

In §3 we first characterize the existence of a greatest group-homomorphism in terms of a few homomorphisms including the so-called Grothendieck homomorphism.

Received by the editors September 21, 1971.


Key words and phrases. Greatest group-homomorphism, cofinal unitary subsemigroup, group-congruence, \(gr\)-homomorphism, archimedean, greatest cancellative homomorphic image, greatest separative homomorphic image, semilattice of abelian groups, direct limit, local identity, cofinal cluster, archimedean components are \(\mathcal{G}\)-composed, \(H\)-cluster, group-clusters, \(\mathcal{G}\)-semigroup.

\(^{(1)}\) A part of these results were presented by H. B. Hamilton at the meetings of the American Mathematical Society at Davis, April 1970, and at Pasadena, November 1970.
and as a consequence we derive a multiplicative condition which is necessary and sufficient. Theorem 3.5 is most important and fundamental for the future development of this topic. We treat special cases in §§4 and 5: a semilattice of groups in §4 and the separative case in §5. The concept of cofinal cluster in §6, together with Theorem 3.5, gives us a foundation on which to begin the study of the internal structure of semigroups having a greatest group-homomorphism. In §7 we suggest a direction for this study. In particular, we treat the separative case whose greatest semilattice homomorphic image is a chain. §2 gives the basic definitions and concepts.

A part of the results of this paper is reported in [21] without proof.

2. Basic concepts. Let $S$ be a commutative semigroup. If $f$ is a homomorphism of $S$ onto a group $G$, $f$ is called a group-homomorphism and $G$ is called a group-homomorphic image of $S$. A congruence $\rho$ on $S$ is called a group-congruence on $S$ if $\rho$ is induced by a group-homomorphism of $S$, that is, $S/\rho$ is a group.

Assume that $f_0$ is a group-homomorphism of $S$ onto $G_0$ and that if $f$ is any group-homomorphism of $S$ onto $G$ there is a homomorphism $h$ of $G_0$ onto $G$ such that $f(x) = h(f_0(x))$ for all $x \in S$. Then $f_0$ is called a greatest group-homomorphism of $S$ and $G_0$ is called a greatest group-homomorphic image of $S$, while the congruence $\rho_0$ induced by $f_0$ is called the smallest group-congruence on $S$. Not all commutative semigroups have a smallest group-congruence.

Let $f$ be a group-homomorphism, $S \rightarrow G$, and $\rho$ the group-congruence on $S$ induced by $f$. The inverse image of the identity element of $G \cong S/\rho$ under $f$ is called the kernel of $f$ or of $\rho$, and is denoted by $\ker f$ or $\ker \rho$.

A subsemigroup $H$ of a commutative semigroup $S$ is called cofinal in $S$ or a cofinal subsemigroup of $S$ if for every $x \in S$ there is an element $y \in S$ such that $xy \in H$. A subsemigroup $U$ of $S$ is called unitary in $S$ if $x \in S$, $a \in U$ and $ax \in U$ implies $x \in U$. For example the kernel of a group-congruence $\rho$ on $S$ is unitary and cofinal in $S$.

In particular, a cofinal subsemigroup of a semilattice has the following sense. Let $L$ be a semilattice. It is regarded as a join semilattice (or upper semilattice), i.e. $\alpha, \beta \in L$, $\alpha \leq \beta$, if and only if $\alpha \beta = \beta$. A cofinal subsemilattice $M$ of $L$ is a subsemilattice $M$ of $L$ which satisfies: for each $\alpha \in L$ there is $\beta \in M$ such that $\alpha \leq \beta$. A cofinal subsemilattice $M$ is unitary in $L$ if and only if $M = L$.

Dubreil [7] and others ([5], [13], [14], [16]) studied group-congruences and Theorem 2.1 is a consequence of known theorems [4, Chapter 10] but we can obtain them directly because of commutativity.

Let $S$ be a commutative semigroup and $A$ a cofinal subsemigroup of $S$. Define a relation $\rho_A$ on $S$ by

$$x \rho_A y \text{ if and only if } ax = by \text{ for some } a, b \in A.$$ 

**Theorem 2.1.** The following statements hold.
(2.1.1) \( \rho_A \) is a group-congruence on \( S \) and \( A \subseteq \text{Ker} \rho_A \).

(2.1.2) If \( U = \text{Ker} \rho_A \), then \( \rho_A = \rho_U \).

(2.1.3) If \( \sigma \) is any group-congruence on \( S \) and if we let \( V = \text{Ker} \sigma \), then \( \sigma = \rho_V \).

(2.1.4) The kernel \( U \) of the homomorphism \( S \to S/\rho_A \) is equal to \( A \) if and only if \( A \) is unitary.

Let \( X \) be a subsemigroup of \( S \) and let \( \tilde{X} \) be the unitary subsemigroup generated by \( X \), i.e. the smallest unitary subsemigroup of \( S \) containing \( X \).

Proposition 2.2. \( \tilde{X} = \{ x \in S : ax \in X \text{ for some } a \in X \} \) and the following are satisfied.

(2.2.1) \( X \subseteq \tilde{X} \).

(2.2.2) \( \tilde{X} \subseteq Y \) implies \( \tilde{X} \subseteq \tilde{Y} \).

(2.2.3) \( X = \tilde{X} \).

Proposition 2.3. (2.3.1) Let \( h \) be a homomorphism of \( S \) onto \( S' \). If \( A \) is cofinal [unitary] in \( S \) then \( h(A) \) is cofinal [unitary] in \( S' \).

(2.3.2) If \( A \) is cofinal [unitary] in \( B \) and if \( B \) is cofinal [unitary] in \( C \) then \( A \) is cofinal [unitary] in \( C \).

Thus the join semilattice of all unitary cofinal subsemigroups of \( S \) is isomorphic to the join semilattice of all group-congruences on \( S \) under the map \( A \to \rho_A \).

Let \( \bar{P} \) denote an implicational property, i.e. a property expressed by a system of implications. A homomorphism \( b \) of \( S \) onto \( S' \) is called a \( \bar{P} \)-homomorphism of \( S \) if \( S' \) satisfies \( \bar{P} \), and the congruence on \( S \) induced by \( b \) is called a \( \bar{P} \)-congruence on \( S \). It goes without saying that there always exists a smallest \( \bar{P} \)-congruence on \( S \). The terminology "greatest \( \bar{P} \)-homomorphism" and "greatest \( \bar{P} \)-homomorphic image" are defined as usual. The partition of all elements of \( S \) induced by the greatest \( \bar{P} \)-homomorphism of \( S \) is called the greatest \( \bar{P} \)-decomposition of \( S \). In this paper "\( \bar{P} \)" is replaced by one of "semilattice", "cancellative" and "separative".

We define a gr-homomorphism to be a homomorphism \( g_0 \) of \( S \) into an abelian group \( Gr \) having the universal repelling property with respect to homomorphisms of \( S \) into abelian groups (see [1], [4, §12.1], [12, p. 43]). That is, if \( g \) is a homomorphism of \( S \) into an abelian group \( G \) there is a unique homomorphism \( h \) of \( Gr \) into \( G \) such that \( g = hg_0 \). \( Gr \) is called a gr-group (Grothendieck group) or free abelian group on \( S \).

The smallest cancellative congruence \( \sigma \) on a commutative semigroup \( S \) is given by \( x \sigma y \text{ iff } ax = ay \text{ for some } a \in S \). The gr-homomorphism \( g_0 \) is obtained as the natural homomorphism \( S \to S/\sigma \) followed by the embedding of \( S/\sigma \) into its group \( Q \) of quotients. Clearly all commutative semigroups have a gr-homomorphism. We have the following immediately.
Proposition 2.4. Let $C = S/\sigma$ where $\sigma$ is defined as above.

(2.4.1) $g_0$ is both injective and surjective if and only if $S \cong C \cong Q$.
(2.4.2) $g_0$ is injective but not surjective if and only if $S \cong C$ and $C \not\cong Q$.
(2.4.3) $g_0$ is not injective but is surjective if and only if $S \not\cong C$ and $C \cong Q$.
(2.4.4) $g_0$ is neither injective nor surjective if and only if $S \not\cong C$ and $C \not\cong Q$.

One sees the definition of archimedeaness in [3] or [17]. The classification of commutative archimedean semigroups can be characterized in Proposition 2.5 by the behavior of the $gr$-homomorphism. First the following classification is known as an immediate consequence of [3, Theorem 4.12] or [17].

Commutative archimedean semigroups are classified as follows:

I. $S$ has a unique idempotent.

(I.1) Nil-semigroup, i.e. $S$ has a zero and some power of every element is a zero.

(I.2) $S$ has an idempotent which is not a zero, i.e. $S$ is an ideal extension of a nontrivial abelian group by a nil-semigroup.

II. $S$ has no idempotent.

(II.1) $S$ is cancellative, i.e. $\mathbb{N}$-semigroup.

(II.2) $S$ is not cancellative.

Proposition 2.5. Let $S$ be a commutative archimedean semigroup. Then

(2.5.1) $S$ is an abelian group if and only if $g_0$ is both injective and surjective.

(2.5.2) $S$ is not a group but has an idempotent $e$ if and only if $g_0$ is not injective but surjective.

(2.5.3) $S$ is an $\mathbb{N}$-semigroup if and only if $g_0$ is injective but not surjective.

(2.5.4) $S$ is neither cancellative nor does it have an idempotent if and only if $g_0$ is neither injective nor surjective.

Proof. (2.5.1) is obvious.

(2.5.2) If $S$ is not a group but has an idempotent $e$, $S$ is not cancellative. We can see that $Se = \{xe : x \in S\}$ is the $gr$-group and $g_0(x) = xe$. Thus $g_0$ is not injective but surjective.

(2.5.3) If $S$ is an $\mathbb{N}$-semigroup, then $S \cong C$ and $C \not\cong Q$. By Proposition 2.4, $f$ is injective but not surjective.

(2.5.4) If $S$ is not cancellative and does not have an idempotent, then $S \not\cong C$ and $C$ is an $\mathbb{N}$-semigroup by [19, Theorem 4, p. 262]. Hence $f$ is neither injective nor surjective.

We have thus proved the implication of (2.5.1) through (2.5.4) in one direction. The other direction is a logical consequence of the disjointness of the statements. Q. E. D.
3. Characterization by homomorphisms and its consequence. Before entering
the main discussion we need some preparation. Assume that $S$ is not a group.

Proposition 3.1. Let $S$ be a commutative semigroup. $S$ has a greatest group-
homomorphism if and only if a proper ideal $I$ of $S$ has a greatest group-homomor-
phism.

Proof. Let $f: S \rightarrow G$ be a group-homomorphism. Since $I$ is an ideal of $S$,
$f(I)$ is an ideal of the group $G$, and hence $f(I) = f(S) = G$. Thus $f \mid I$ is a group-
homomorphism $I \rightarrow G$.

Let $g: I \rightarrow H$ be a group-homomorphism. Define $\bar{g}: S \rightarrow H$ by $\bar{g}(x) = g(ax)$
where $a \in I$ and $g(a) = e$, $e$ being the identity element of $H$. If $g(a) = g(b) = e$ for
$a, b \in I$, then, for $x \in S$,

$$g(ax) = g(ax)g(b) = g(axb) = g(bxa) = g(bx)g(a) = g(bx).$$

Hence $\bar{g}$ is well defined. Also we have, for $x, y \in S$, that

$$\bar{g}(xy) = g(xya) = g(xya)g(a) = g(xya) = g(xa)g(ya) = \bar{g}(x)\bar{g}(y),$$

therefore $\bar{g}$ is a homomorphism. Clearly $\bar{g} \mid I = g$, thus $\bar{g}$ is surjective. To prove
uniqueness of $\bar{g}$ let $f: S \rightarrow G$ be any group-homomorphism such that
$f \mid I = g$. Choose $a \in \text{Ker} g$. Then for all $x \in S$, $f(x) = f(a)f(x) = f(ax) = g(ax) = \bar{g}(x)$.

We have proved that there is a one-to-one correspondence from all group-
homomorphisms $f$ of $S$ to all group-homomorphisms $g$ of $I$ by the map $f \rightarrow g$, $g = f \mid I$.
In other words the semilattice of all group-congruences on $S$ is isomorphic to the
semilattice of all group-congruences on $I$. Therefore our conclusion is easily de-
erived. (Notice that the statement is true for all proper ideals $I$, equivalently for
some proper ideal.) Q.E.D.

A commutative semigroup is called separative [3] if it satisfies $a^2 = ab = b^2$
implies $a = b$. It is known in [3] that a commutative semigroup is separative if
and only if its archimedean components are cancellative. A smallest separative
congruence $\tau_0$ on a commutative semigroup $S$ is given by

$$ar_0b \text{ if and only if } ab^n = b^{n+1} \text{ and } ba^n = a^{n+1} \text{ for some positive integer } n.$$ Let $S = \bigcup_{a \in T} S_a$ be the greatest semilattice decomposition of a commutative semi-
group $S$. Each $S_a$ is archimedean ([3], [17]).

We define a relation $\tau_1$ on $S$ as follows:

$$ar_1b \text{ if and only if } a \text{ and } b \text{ are in the same archimedean component } S_a \text{ and }$$
$$ax = bx \text{ for some } x \in S_a.$$ Lemma 3.2. $\tau_1 = \tau_0$.

Proof. $\tau_0 \subseteq \tau_1$ is clear. To prove $\tau_1 \subseteq \tau_0$, assume $ar_1b$. Then $a$ and $b$
in $S_a$ and $ax = bx$ for $x \in S_a$. Since $S_a$ is archimedean $b^n = xy$, $a^n = xz$ for some
y, z ∈ S_a and some n > 0. Now \( ax = bx \) implies \( axy = bxy \), hence \( ab^n = b^{n+1} \).
Likewise \( ba^n = a^{n+1} \). Q.E.D.

We have

**Theorem 3.3.** Let \( S \) be a commutative semigroup. Then the following are equivalent:

1. (3.3.1) The \( gr \)-homomorphism \( g_0 \) is surjective.
2. (3.3.2) The greatest cancellative homomorphic image \( C \) of \( S \) is a group.
3. (3.3.3) \( S \) has a greatest group-homomorphism.
4. (3.3.4) The greatest separative homomorphic image of \( S \) has a greatest group-homomorphism.

**Proof.** The equivalence of (3.3.1) and (3.3.2) follows from Proposition 2.4. The equivalence between (3.3.2) and (3.3.3) is obtained by Head [10], and McAlister and O'Caroll [15]. The equivalence of (3.3.3) and (3.3.4) follows from the fact that groups are separative. Q.E.D.

**Corollary 3.4.** Let \( S \) be a commutative archimedean semigroup. The following are equivalent:

1. (3.4.1) The \( gr \)-homomorphism \( g_0 \) is surjective.
2. (3.4.2) \( S \) has an idempotent.
3. (3.4.3) \( S \) has a greatest group-homomorphism.

**Remark.** Head [10] and McAlister and O'Caroll [15] proved that a commutative semigroup \( S \) has a greatest group-homomorphic image if and only if the greatest cancellative homomorphic image of \( S \) is a group. Head did it from a general point of view [4, §11.6]; McAlister and O'Caroll used a group theoretical result. If \( S \) is a commutative cancellative semigroup and if \( S \) is not a group, \( S \) is a semilattice of \( S_0 \) and \( S_1 \) where \( S_0 \) is a nonempty ideal without idempotent and \( S_1 \) is either a group or empty [11]. Hence Head, McAlister and O'Caroll's result is equivalent to the statement that a commutative cancellative semigroup without idempotent has no smallest group-congruence. However, the following is still true. A commutative cancellative semigroup without idempotent has no minimal group-congruence. Note that "minimal" means "having no smaller one", hence "minimal" is weaker than "smallest". To prove the above, a minimal cofinal unitary subsemigroup is used. (See details in [22].)

As a consequence of Theorem 3.3 we have

**Theorem 3.5.** (2) Let \( S \) be a commutative semigroup. The following are equivalent:

1. (3.5.1) \( S \) has a greatest group-homomorphism.

---

(2) This was obtained by T. Tamura.
(3.5.2) For all \( x, y \in S \) there exist \( z, u \in S \) such that \( xu = yzu \).

(3.5.3) For every \( a \in S \) there are \( b, c \in S \) such that \( abc = c \).

**Proof.** We prove \((3.3.2) \Rightarrow (3.5.3) \Rightarrow (3.5.2) \Rightarrow (3.3.2)\) since \((3.5.1)\) is equivalent to \((3.3.2)\) by Theorem 3.3.

\((3.3.2) \Rightarrow (3.5.3)\). Let \( C \) be the greatest cancellative homomorphic image of \( S \) and \( f: S \rightarrow C \) be the homomorphism of \( S \) onto \( C \). Let \( a \in S \). Since \( C \) is a group by \((3.3.2)\), \( C \) contains an identity element denoted by \( f(p) \) and there is \( f(b) \in C \) such that \( f(a)f(b) = f(p) \). Multiplying both sides by \( f(p) \), we have \( f(a)f(b)f(p) = f(p)^2 = f(p) \) and then \( f(abp) = f(p) \). Recall that the smallest cancellative congruence \( \sigma \) on \( S \) is given by \( x \sigma y \) if and only if \( xz = yz \) for some \( z \in S \). Accordingly \( f(abp) = f(p) \) implies \( abpz = pz \) for some \( z \in S \). Let \( c = pz \). Then we have \( abc = c \).

\((3.5.3) \Rightarrow (3.5.2)\). Let \( x, y \in S \). By \((3.5.3)\) there are \( u, v \in S \) such that \( xu = yvu \), hence \( xu = xyvu = yxvu \). Let \( z = xv \). Then we have \( xu = yzu \).

\((3.5.2) \Rightarrow (3.3.2)\). Let \( \sigma \) be the smallest cancellative congruence on \( S \). By the assumption for \( x, y \in S \) there are \( z, u \in S \) such that \( xu = yzu \), which implies \( x \sigma y \). This tells us that \( S/\sigma \) is a group. Thus \((3.3.2)\) is derived. \( \Box \).

**Remark.** The fact that \((3.5.1)\) is equivalent to \((3.5.3)\) is obtained by M. S. Putcha independently of the authors. See Corollary 2.2, p. 52, Semigroup Forum 3 (1971).

Also, we can easily prove that \((3.5.2)\) implies \((3.5.3)\): Let \( a \) be an arbitrary element of \( S \) and take \( x = a^2, y = a \). By \((3.5.2)\) there are \( z, u \in S \) such that \( a^2zu = au \). Take \( b = z, c = au \). Then we have \( abc = c \).

An element \( p \) of a commutative semigroup \( S \) is called a local identity element if \( pa = a \) for some \( a \in S \). Let \( I \) be the set of all local identity elements of \( S \).

**Lemma 3.6.** If \( I \) is not empty, \( I \) is a unitary subsemigroup of \( S \).

**Proof.** Let \( p, q \in I \). By definition \( pa = a \) and \( qb = b \) for some \( a, b \in S \). Then \((pq)(ab) = (pq)(ba) = p(qb)a = pba = (pa)b = ab \). Hence \( pq \in I \), \( x \in S \) and \( px \in I \). There are \( a \) and \( b \) such that \( pa = a \) and \( pxb = b \). Then \( xba = xbp = ba \), whence \( x \in I \). Thus \( I \) is a unitary subsemigroup of \( S \). \( \Box \).

\( I \) is called the local identity subsemigroup of \( S \).

**Theorem 3.5'.** A commutative semigroup \( S \) has a greatest group-homomorphism if and only if the local identity subsemigroup of \( S \) is not empty and it is cofinal in \( S \).

**Proof.** This is the restatement of Theorem 3.5. The element \( ab \) in \((3.5.3)\) is a local identity element of \( S \). Cofinality is obvious. \( \Box \).

The alternate proof of the "if" part of Theorem 3.5'. Let \( p \) be a local identity element of \( S \). If \( \phi \) is any group-homomorphism of \( S \), then \( pa = a \) implies...
(pφ)(aφ) = aφ, whence pφ ∈ Ker φ. On the other hand, by Lemma 3.6 and the assumption, the local identity subsemigroup of S is unitary cofinal and hence l is the smallest unitary cofinal subsemigroup. Accordingly S has a greatest group-homomorphism. Q.E.D.

**Corollary 3.7.** If the subsemigroup of all idempotents of S is not empty and cofinal in S, then S has a greatest group-homomorphism.

Thus the existence of the cofinal local identity subsemigroup completely determines the greatest group-homomorphism. Of course the condition "cofinality" is important. Only the existence of local identities is not sufficient, for example, the infinite cyclic semigroup with identity element adjoined does not have a greatest group-homomorphism.

4. Group-congruences on a semilattice of groups. As an application of Theorem 3.5 we have

**Proposition 4.1.** A semilattice of abelian groups has a greatest group-homomorphism.

**Proof.** Let S = \( \bigcup_{α \in Γ} S_α \) be a semilattice Γ of abelian groups \( S_α \). Let \( x, y \in S \) and \( x \in S_α, y \in S_β \). Let \( u \in S_{αβ} \) be taken arbitrarily. Then \( xu, yu \in S_{αβ} \). Since \( S_{αβ} \) is a group, \( xu = yu \) for some \( z \in S_{αβ} \). By Theorem 3.5, S has a greatest group-homomorphism. Q.E.D.

A semilattice of abelian groups is determined by a semilattice \( Γ \) (assumed to be an upper semilattice here), a system of abelian groups \( \{ S_α : α \in Γ \} \) and a transitive system \( \{ φ^β_α : α \leq β, α, β ∈ Γ \} \) of homomorphisms \( φ^β_α \) of \( S_α \) into \( S_β, α \leq β \). In detail a transitive system \( \{ φ^β_α : α \leq β, α, β ∈ Γ \} \) is a system of homomorphisms satisfying

1. \( φ^α_α \) is the identity mapping of \( S_α \) for all \( α ∈ Γ \).
2. \( φ^γ_β φ^β_α = φ^γ_α \) for all \( α \leq β \leq γ \).

The operation is defined in the disjoint union \( S = \bigcup_{α ∈ Γ} S_α \) as follows: for \( x_α ∈ S_α, y_β ∈ S_β \),

\[ x_α y_β = φ^{αβ}_α(x_α) \cdot φ^{αβ}_β(y_β). \]

S is, of course, commutative. (See details in [3, p. 128].)

Define a relation \( ρ_0 \) on S by

\[ xρ_0 y \text{ iff } φ^{ξ_0}_ξ(x) = φ^{ξ_β}_β(y), \quad x ∈ S_α, \quad y ∈ S_β \text{ for some } ξ ≥ α, β. \]

It is easy to see \( ρ_0 \) is an equivalence. To show compatibility, let \( x ∈ S_α, y ∈ S_β, z ∈ S_γ \) and assume \( φ^{ξ_α}_α(x) = φ^{ξ_β}_β(y) \). Then

\[ φ^{ξ_γ}_γ(xz) = φ^{ξ_γ}_γ(φ^{αγ}_α(z) φ^{αγ}_α(x)) = φ^{ξ_γ}_γ(z φ^{αγ}_α(x)) = φ^{ξ_γ}_γ(φ^{ξ_β}_β(y)) = φ^{ξ_γ}_γ(φ^{αβ}_β(y)) = φ^{ξ_γ}_γ(y). \]

Therefore \( ρ_0 \) is a congruence on S.
Proposition 4.2. \( p_0 = \{(x, y) \in S \times S : zx = zy \text{ for some } z \in S\} \), and \( p_0 \) is the smallest group-congruence on \( S \).

Proof. First we prove \( xp_0y \) implies \( zx = zy \) for some \( z \in S \). Let \( x \in S_\alpha, y \in S_\beta \).

By assumption \( \phi_\xi^\alpha(x) = \phi_\beta^\xi(y) \) for some \( \xi \geq \alpha \beta \). Let \( z \in S_\xi \). From the above proof we have \( \phi_\xi^\alpha(x) = \phi_\xi^\beta(z) \) whence \( zx = zy \). Conversely assume \( zx = zy, x \in S_\alpha, y \in S_\beta, z \in S_\gamma \). Then \( y_\alpha = y_\beta \).

By definition,

\[
\phi_\gamma^\alpha(z) \phi_\gamma^\alpha(x) = \phi_\gamma^\beta(z) \phi_\beta^\gamma(y),
\]

and \( \phi_\gamma^\alpha(x) = \phi_\beta^\gamma(y) \) by cancellation in \( S_\gamma \). Therefore, \( xp_0y \). Thus we have proved that \( p_0 \) is the smallest cancellative congruence on \( S \). By Proposition 4.1 and Theorem 3.3, \( p_0 \) is the smallest group-congruence. Q.E.D.

\( S/p_0 \) coincides with the so-called direct limit \( \lim \| S_\alpha, \phi_\beta^\alpha, \Gamma \| \) of a system \( \{ S_\alpha : \alpha \in \Gamma \} \) with respect to \( \phi_\beta^\alpha \) in case \( \Gamma \) is a semilattice. It is usually defined as a factor group of the direct sum of \( S_\alpha \)'s without considering the semigroup \( S \).

(See, for example, [8], [12].)

Let \( S = \bigcup \{ S_\alpha, \phi_\beta^\alpha, \Gamma \} \) be a semilattice of abelian groups. For each \( \alpha \in \Gamma \), let

\[
K_\alpha = \bigcup \{ \ker \phi_\xi^\alpha : \alpha \leq \xi, \xi \in \Gamma \}
\]

where \( \bigcup \) denotes the set union. \( K_\alpha \) is, however, a subgroup of \( S_\alpha \). Let \( G = S/p_0 \) and \( G_\alpha = S_\alpha/K_\alpha \).

Proposition 4.3. \( \ker p_0 = \bigcup \{ K_\alpha, \tilde{\phi}_\beta^\alpha, \Gamma \} \) and \( G \cong \lim \{ G_\alpha, \phi_\beta^\alpha, \Gamma \} \) where \( \tilde{\phi}_\phi^\alpha \) is the restriction of \( \phi_\beta^\alpha \) to \( K_\alpha \) and \( \phi_\beta^\alpha \) is an injective homomorphism of \( G_\alpha \) into \( G_\beta \).

5. Separative case. By Theorem 3.3 our problem is reduced to that in commutative separative semigroups. Let \( S \) be a commutative separative semigroup and \( S = \bigcup_{\alpha \in \Gamma} S_\alpha \) be the greatest semilattice decomposition of \( S \). Each \( S_\alpha \) is cancellative archimedean and hence either a group or an \( \mathcal{R} \)-semigroup. \( S \) can be embedded into a semigroup \( C(S) \) which is a semilattice of abelian groups, \( C(S) = \bigcup_{\alpha \in \Gamma} C_\alpha \), such that \( C_\alpha \) is the quotient group of \( S_\alpha \), \( C_\alpha = \{ x_\alpha y_\alpha^{-1} : x_\alpha, y_\alpha \in S_\alpha \} \).

(See [3].) The operation in \( C(S) \) is defined by

\[
(x_\alpha y_\alpha^{-1})(z_\beta u_\beta^{-1}) = (x_\alpha z_\beta)(y_\alpha u_\beta)^{-1}.
\]

Let \( p_0 \) be the smallest group-congruence on \( C(S) \). The kernel \( \ker p_0 \) will be denoted by \( K(C(S)) \).

Proposition 5.1. Let \( S \) be a commutative separative semigroup. Then the following are equivalent.

(5.1.1) \( S \) has a greatest group-homomorphism.
(5.1.2) \( S \cap K(C(S)) \neq \emptyset \) and it is cofinal in \( S \).
Proof. (5.1.1) → (5.1.2). Let \( f_0 \) be the greatest group-homomorphism of \( C(S) \) and let \( f_1 = f_0 | S \). Then \( f_1(S) \) is a cancellative homomorphic image of \( S \) but it is a subgroup of \( f_0(S) \) because \( S \) has a greatest group-homomorphism and hence its greatest cancellative homomorphic image is a group by Theorem 3.3. Clearly \( \text{Ker}f_1 = S \cap \text{K}(C(S)) \neq \emptyset \). Its cofinality is obvious.

(5.1.2) → (5.1.1). We are to prove (5.1.2) → (3.5.3). Then we will get (5.1.1) by Theorem 3.5. Let \( \Gamma_1 = \{ \alpha \in \Gamma: S_\alpha \cap \text{K}(C(S)) \neq \emptyset \} \). Since \( \Gamma_1 \) is a homomorphic image of \( S \cap \text{K}(C(S)) \), \( \Gamma_1 \) is cofinal in \( \Gamma \). Let \( a \in S \), say \( a \in S_{\xi} \). There is \( \alpha \in \Gamma_1 \) such that \( \xi \leq \alpha \). Take \( u \in S_\alpha \) arbitrarily. Then \( au \in S_a \). Let \( f_0 \) be the same as defined just above. By assumption there is \( d \in S_a \) such that \( f_0(d) = f_0(e) \) where \( e \) is the identity element of \( C_\alpha \). Since \( S_\alpha \) is archimedean \( auv = dm \) for some \( v \in S_\alpha \) and some \( m > 0 \); and \( f_0(auv) = f_0(dm) = f_0(e) \). Recalling that \( f_0 \) is the greatest cancellative homomorphic image of \( C(S) \) by Proposition 4.2, there is an element \( c'p^{-1} \in S, c', p \in S_y \) for some \( y \).

\[
auv(c'p^{-1}) = e(c'p^{-1}), \text{ hence } auvc' = ec'.
\]

Let \( b = uv, c = ec' \). Then \( abc = auvc' = auvc' = ec' = c \). Q.E.D.

In the proof of (5.1.1) → (5.1.2), we have stated that \( f_1(S) \) is a subgroup of \( f_0(C(S)) \) but in fact \( f_1(S) = f_0(C(S)) \). This is due to the following proposition which describes a relation between group-congruences of \( S \) and \( C(S) \).

**Proposition 5.2.** Let \( S \) be a commutative separative semigroup. A group-homomorphism \( f: S \rightarrow G \) can be uniquely extended to a group-homomorphism \( \overline{f} \) of \( C(S) \) in the following sense:

\[
\overline{f}(S) = f(S) \cap \text{K}(C(S)) \text{ and if } g \text{ is a group-homomorphism of } C(S) \text{ such that } f(S) \subseteq g(C(S)) \text{ and } g | S = f, \text{ then } g = \overline{f} \text{ on } C(S).
\]

**Proof.** Let \( x \in C(S), x = ab^{-1} \) for some \( a, b \in S_a \). Define \( \overline{f} \) by

\[
\overline{f}(x) = f(a)(f(b))^{-1}.
\]

If \( x = a_1b_1^{-1} = a_2b_2^{-1} \), then \( a_1b_2 = a_2b_1 \) and \( f(a_1)f(b_2) = f(a_2)f(b_1) \) whence \( f(a_1)(f(b_1))^{-1} = f(a_2)(f(b_2))^{-1} \). Thus \( \overline{f} \) is well defined. To prove \( \overline{f} \) is a homomorphism,

\[
\overline{f}(ab^{-1}, cd^{-1}) = \overline{f}(ac \cdot (bd)^{-1}) = f(ac)(f((bd))^{-1}
\]

\[
= f(a)(f(b))^{-1} f(c)(f(d))^{-1} = \overline{f}(ab^{-1}) \overline{f}(cd^{-1}).
\]

It is easy to show \( \overline{f}(x) = f(x) \) for \( x \in S \) and \( \overline{f}(C(S)) = G \). Hence \( \overline{f} \) is a group-homomorphism \( C(S) \rightarrow G \). To prove uniqueness let \( g: C(S) \rightarrow G' \) be a group-homomorphism such that \( g(x) = f(x) \) for all \( x \in S \) and \( G \subseteq G' \). Then for \( x = ab^{-1} \in C(S), \)

\[
g(x) = g(ab^{-1}) = g(a)g(b)^{-1} = f(a)(f(b))^{-1} = \overline{f}(ab^{-1}) = \overline{f}(x). \text{ Q.E.D.}
\]

**Remark.** Theorem 3.5 is not used in the proof of Proposition 5.1. As a consequence of Proposition 5.1 and Proposition 5.2, we get an alternate proof of (3.5.3).
First assuming separativity we can prove that (5.1.2) implies (3.5.3), and (3.5.3) implies (5.1.1). Let  be a commutative semigroup and  be the greatest separative homomorphic image of . For , denotes the image of under . By Theorem 3.3 it is sufficient to prove that " holds in if and only if it holds in . Assume that for , there are  in such that . Let  be the greatest semilattice decomposition of . Then  where  is cancellative archimedean. Let , , , , . Since in the sense of Lemma 3.2, there is such that . Setting  and , we have . Conversely, let . By the assumption for there are , such that which implies .

6. Cofinal clusters and group-homomorphisms. Let  be a commutative semigroup and  the greatest semilattice decomposition of . Each , , is archimedean. If  is a subsemilattice of , then  is called a cluster of .  is cofinal in  if and only if  is cofinal in .

Proposition 6.1. Let  be a commutative semigroup and  a cofinal cluster in . A group-homomorphism  of  onto  can be uniquely extended to a homomorphism  of  onto  such that .

Proof. Let . We are to prove first

(1) There are  and  in such that  and  imply .

Since  is cofinal in  and  is a group, there are  and  in such that  and  imply . Let  denote the element in such that . Now let  and . Then

\[
abc = (abc')^2 = abc', \quad bc = a(bc')^2 = abc' \quad \text{and} \quad c \leq abc = abc' \leq c.
\]

It follows that  and  are in the same archimedean component, say . Since  in  we see  in . Therefore  is well defined. It is easy to see that is a group homomorphism.

Define  by  where  and are found by (1). Suppose that  and satisfy (1) and also  and  satisfy (1). Then  and . Let  and  and  are in  and  in , and let . Then  implies  and . Since  and where we notice that since , . Therefore  is well defined. It is easy to see that coincides with , and .

This proposition was obtained by H. B. Hamilton.
Since $abc \in W$, $g(abc) = f(abc) = e^*$ which implies $g(a) = (g(bc))^{-1}$ but $bc \in W$ and so $g(bc) = f(bc)$, therefore $g(a) = (f(bc))^{-1} = f(a)$. Q.E.D.

Let $f: W \to G$ and $g: W \to H$ be group-homomorphisms. Let $\sigma$ and $\rho$ be the congruences on $W$ associated with $f$ and $g$ respectively. Also let $\sigma^*$ and $\rho^*$ be the congruences on $S$ associated with $f^*$ and $g^*$ respectively.

**Proposition 6.2.** $\sigma \subseteq \rho$ if and only if $\sigma^* \subseteq \rho^*$.

**Proof.** Note that $a \sigma b$ if and only if $f(a) = f(b)$; $a \rho b$ if and only if $g(a) = g(b)$; $a \sigma^* b$ if and only if $f^*(a) = f^*(b)$; $a \rho^* b$ if and only if $g^*(a) = g^*(b)$. Also $\sigma \subseteq \rho$ if and only if $f(x) = f(y)$ implies $g(x) = g(y)$ if and only if $\text{Ker} f \subseteq \text{Ker} g$. Using this information and definition of $f^*$ and $g^*$ we can prove in a routine manner that $\sigma \subseteq \rho$ implies $\sigma^* \subseteq \rho^*$. Assume $\sigma^* = \rho^*$. Then $\sigma = \sigma^* \mid W = \rho^* \mid W = \rho$. Thus we have the "only if" part. Conversely, if $\sigma^* \subseteq \rho^*$ it is easy to see $\sigma \subseteq \rho$, but we have $\sigma \subseteq \rho$ by Proposition 6.1. Q.E.D.

Let $\bigodot(D)$ denote the set of all group-congruences on a semigroup $D$. $\bigodot(D)$ is a join semilattice. A cluster $W$ of $S$ is called proper if $W \not\subseteq S$.

**Theorem 6.3.** We assume that $S$ is not archimedean. A commutative semigroup $S$ has a greatest group-homomorphism if and only if there is a proper cofinal cluster $W$ of $S$ such that $W$ has a greatest group-homomorphism. Further $\bigodot(S)$ is isomorphic to $\bigodot(W)$.

**Proof.** Assume that a cofinal cluster $W$ of $S$ has a greatest group-homomorphism. Let $S = \bigcup_{\alpha \in \Gamma} S_{\alpha}$, $W = \bigcup_{\lambda \in \Lambda} S_{\lambda}$ be defined as above. Let $x \in S$, and assume $x \in S_{\alpha}$, $\alpha \in \Gamma$. Since $\Lambda$ is cofinal in $\Gamma$, there is $\gamma \in \Gamma$ such that $\alpha \leq \gamma$. Take $a \in S_{\gamma}$ arbitrarily. Then $xa \in S_{\gamma} \subseteq W$. By Theorem 3.5 there are $b$ and $c$ in $W$ such that

$$(xa)bc = c \quad \text{or} \quad x(ab)c = c.$$ 

This shows that $S$ has a greatest group-homomorphism again by Theorem 3.5.

Conversely assume that $S = \bigcup_{\alpha \in \Gamma} S_{\alpha}$ has a greatest group-homomorphism $f_0$. Let $\Gamma_1 = \{\alpha \in \Gamma: S_{\alpha} \cap \text{Ker} f_0 \neq \emptyset\}$. Then $\Gamma_1$ is cofinal in $\Gamma$. Let $\Lambda$ be a non-empty cofinal proper subset of $\Gamma_1$. Clearly $\Lambda$ is cofinal in $\Gamma$. Let $W = \bigcup_{\lambda \in \Lambda} S_{\lambda}$. $W$ is then a proper cofinal cluster of $S$. Let $f$ be a group-homomorphism of $S$. We are to prove $f(W) = f(S)$. Let $x \in S$, say $x \in S_{\alpha}$ for some $\alpha \in \Gamma$. Since $\Lambda$ is cofinal in $\Gamma$, there is $\lambda \in \Lambda$ such that $\alpha \leq \lambda$. Let $y \in S_{\lambda} \cap \text{Ker} f_0$. Since $\text{Ker} f_0 \subseteq \text{Ker} f$ we have

$$f(x) = f(x)f(y) = f(xy) \in f(S_{\lambda}) \subseteq f(W).$$

This proves $f(W) = f(S)$ and hence $f \mid W$ is a group-homomorphism. The isomorphism of $\bigodot(S)$ and $\bigodot(W)$ follows from Propositions 6.1 and 6.2. Accordingly $W$ has a greatest group-homomorphism. Q.E.D.

A cluster $W = \bigcup_{\lambda \in \Lambda} S_{\lambda}$ in $S = \bigcup_{\alpha \in \Gamma} S_{\alpha}$ is called a group-cluster of $S$ if $S_{\lambda}$ is a group for all $\lambda \in \Lambda$. 

License or copyright restrictions may apply to redistribution; see https://www.ams.org/journal-terms-of-use
Corollary 6.4. If \( S \) contains a cofinal group-cluster then \( S \) has a greatest group-homomorphism.

As a consequence of Theorem 6.3 the problem of group-homomorphism of \( S = \bigcup_{\alpha \in \Gamma} S_{\alpha} \) can be reduced to that of a cofinal cluster \( W = \bigcup_{\lambda \in \Lambda} S_{\lambda} \) if \( \Lambda \) has a special type. For example,

(i) If \( \Gamma \) contains a cofinal chain, \( \Lambda \) can be chosen as a well ordered cofinal chain. (See [2], [20].)

(ii) If \( |\Gamma| \) is countable, \( \Lambda \) can be chosen as a cofinal \( \omega \)-chain, i.e. chain of ordinal \( \omega \). (See [20].)

(iii) If \( \Gamma \) has a greatest element as an upper semilattice, \( \Lambda \) can be chosen as \( |\Lambda| = 1 \).

For case (iii) we have

Corollary 6.5. In case (iii), for example, in case \( \Gamma \) is finite, \( S \) contains an archimedean component \( S_0 \) which is an ideal of \( S \). \( S \) has a greatest group-homomorphism if and only if \( S_0 \) contains an idempotent.

This is a consequence of Proposition 3.1 or Corollary 3.4 or Theorem 3.5.

7. Study of structure of \( \mathcal{G} \)-semigroups. For our convenience a commutative semigroup admitting a greatest group-homomorphism will be called a \( \mathcal{G} \)-semigroup. So far we have obtained various characterizations of \( \mathcal{G} \)-semigroups, but it is far from a complete construction of \( \mathcal{G} \)-semigroups. The problem is related to semilattice compositions of archimedean semigroups. We will not enter deeply into this problem at this moment except for a special case.

Let us return to separative semigroups again. Let \( S = \bigcup_{\alpha \in \Gamma} S_{\alpha} \) be the greatest semilattice decomposition of a commutative separative semigroup \( S \). Again note that each \( S_{\alpha} \) is cancellative archimedean.

Proposition 7.1. Let \( a \in S_{\alpha} \) and \( a < \beta \). If \( ax = x \) for some \( x \in S_{\beta} \), then \( ay = y \) for all \( y \in S_{\xi} \), all \( \xi \geq \beta \).

Proof. Let \( u \in S_{\xi} \). Then since \( \xi \geq \beta \), \( xu \in S_{\xi} \), and \( ax = x \) implies \( axu = xu \).

We are now to prove that if \( az = z \) for some \( z \in S_{\xi} \) then \( ay = y \) for all \( y \in S_{\xi} \).

Since \( S_{\xi} \) is archimedean, \( z^n = yv \) for some \( v \in S_{\xi} \) and \( n > 0 \). Then \( az = z \) implies \( az^n = z^n \) and \( (ay)v = yv \), whence \( ay = y \) since \( ay \in S_{\xi} \) and \( S_{\xi} \) is cancellative.

Q.E.D.

Assume that \( S \) is a \( \mathcal{G} \)-semigroup and \( a < \beta \), \( ab = b \) for some \( a \in S_{\alpha} \), \( b \in S_{\beta} \). Then \( S_{\alpha}S_{\beta} \subseteq S_{\beta} \). For each \( a \in S_{\alpha} \) we define a transformation \( \varphi_{a_{\alpha}}^{\beta} : S_{\beta} \to S_{\beta} \) by

\[ x\varphi_{a_{\alpha}}^{\beta} = xa_{\alpha}, \quad x \in S_{\beta}. \]

\( \varphi_{a_{\alpha}}^{\beta} \) is a translation of \( S_{\beta} \). Let \( \Phi_{a_{\alpha}}^{\beta} = \left\{ \varphi_{a_{\alpha}}^{\beta} : a_{\alpha} \in S_{\alpha} \right\} \). \( \Phi_{a_{\alpha}}^{\beta} \) is a subsemigroup of the translation semigroup of \( S_{\beta} \). Then we have
Proposition 7.2. \( \phi^B_a \) is a permutation group.

Proof. Clearly \( \Phi^B_a \) is a homomorphic image of \( S_a \) under \( a_a \rightarrow \phi^B_a \). Since \( S_a \) is commutative archimedean, \( \Phi^B_a \) is commutative archimedean but it contains the identity element \( \phi^B_a \). (It follows from Proposition 7.1 that \( \phi^B_a \) is the identity mapping.) Hence \( \Phi^B_a \) is a group. For each \( \phi_1 \in \Phi^B_a, \phi_2 \phi_1 = \phi_2 \phi_1 \) for some \( \phi_2 \in \Phi^B_a \). This implies that \( \Phi^B_a \) is injective and surjective. Therefore \( \Phi^B_a \) is a permutation group. Q.E.D.

When \( \alpha < \beta \) and \( \Phi^B_a \) is a permutation group we say that \( S_a \) is \( \Phi \)-composed with \( S\beta \).

A cluster \( W = \bigcup_{\lambda \in \Lambda} S_{\lambda} \) is called an \( \mathcal{N} \)-cluster of \( S \) if all \( S_{\lambda}, \lambda \in \Lambda \), are \( \mathcal{N} \)-semigroups.

Let \( S \) be a commutative separative semigroup, and let \( S = \bigcup_{\alpha \in \Gamma} S_{\alpha} \) as usual. Let \( \Delta = \{ \xi \in \Gamma: S_{\xi} \text{ is a group} \} \). Of course \( \Delta \) is a subsemilattice of \( \Gamma \). Suppose \( \Delta \) is not cofinal and \( \Delta \neq \Gamma \). Then there is \( \alpha \in \Gamma - \Delta \) such that there is no element \( \xi \in \Delta \) satisfying \( \alpha \leq \xi \), in other words, the principal ideal \( \alpha \Gamma \) is contained in \( \Gamma - \Delta \). Therefore \( W = \bigcup_{\lambda \in \Gamma - \Delta} S_{\lambda} \) is an \( \mathcal{N} \)-cluster of \( S \), precisely it is an ideal of \( S \). We call such \( W \) an ideal \( \mathcal{N} \)-cluster.

(7.3) A commutative separative semigroup contains either a cofinal group-cluster or an ideal \( \mathcal{N} \)-cluster.

Thus the study of separative \( \mathcal{G} \)-semigroups has been reduced to that of \( \mathcal{G} \)-semigroups whose archimedean components are all \( \mathcal{N} \)-semigroups. For simplicity \( \mathcal{G} \)-semigroups of the latter type are called \( \mathcal{N} \)-\( \mathcal{G} \)-semigroups.

Let \( S = \bigcup_{\alpha \in \Gamma} S_{\alpha} \) be an \( \mathcal{N} \)-\( \mathcal{G} \)-semigroup. By Proposition 7.2 there is a pair \((\alpha, \beta)\) such that \( S_{\alpha} \) is \( \Phi \)-composed with \( S_{\beta} \). Such a pair is called a \( \Phi \)-pair. Let \( \mathcal{P} \) be the set of all \( \Phi \)-pairs for \( S \). We do not know at the present time how \( \Phi \)-pairs are distributed in \( \Gamma \times \Gamma \) and what part \( \mathcal{P} \) plays in general, except the following property:

Proposition 7.4. (7.4.1) \( \mathcal{P} \) is cofinal in \( \Gamma \times \Gamma \) where the order of elements of \( \Gamma \times \Gamma \) is defined by the component-wise order. In particular the set of \( \alpha \) for which \( (\alpha, \beta) \in \mathcal{P} \) is cofinal in \( \Gamma \).

(7.4.2) If \( (\alpha, \beta) \in \mathcal{P}, \text{ then } (\alpha, \gamma) \in \mathcal{P} \text{ for all } \gamma \geq \beta, \gamma \in \Gamma \).

(7.4.3) If \( (\alpha, \beta) \) and \( (\gamma, \beta) \) are in \( \mathcal{P} \), then \( \beta \neq \alpha \gamma \) in \( \Gamma \).

Proof. (7.4.1), (7.4.2) are obvious.

Proof of (7.4.3). Suppose \( \beta = \alpha \gamma \). Then \( W = S_{\beta} \cup S_{\alpha} \cup S_{\gamma} \) is a cluster of \( S \). Consider a homomorphism \( \phi \) of \( W \) into the translation semigroup of \( S_{\beta} \) in the natural way. Under \( \phi \), the elements \( x_{\alpha} (x_{\gamma}) \) of \( S_{\alpha} (S_{\gamma}) \) are mapped into \( \phi^B_{\alpha} (\Phi^B_{\gamma}) \), and \( \phi(S_{\beta}) \) is the inner translation semigroup of \( S_{\beta} \) being isomorphic to \( S_{\beta} \) since \( S_{\beta} \) is an \( \mathcal{N} \)-semigroup ([6], [9]). Now \( x_{\alpha} x_{\gamma} \) is in \( S_{\beta} \) by assumption but \( \phi(x_{\alpha}) \phi(x_{\gamma}) \) is not in
\( \phi(S_\beta) \) since \( \phi(S_\beta) \) contains no permutation. Q.E.D.

Immediately we have

**Proposition 7.5.** Let \( S = \bigcup_{a \in \Gamma} S_a \) be an \( \mathcal{H} \)-\( \mathcal{G} \)-semigroup. If, for all \( \alpha, \beta \in \Gamma \) such that \( \alpha < \beta \), \( S_\alpha \) is \( \mathcal{B} \)-composed with \( S_\beta \), then \( \Gamma \) has to be a chain.

If, for all \( \alpha, \beta \in \Gamma \) such that \( \alpha < \beta \), \( S_\alpha \) is \( \mathcal{B} \)-composed with \( S_\beta \), we say that \( S \) is \( \mathcal{B} \)-composed.

We mean by an \( \mathcal{H} \)-separative semigroup a commutative semigroup whose archimedean components are all \( \mathcal{H} \)-semigroups and we assume that \( \Gamma \) has no greatest element.

**Theorem 7.6.** Let \( S = \bigcup_{a \in \Gamma} S_a \) be an \( \mathcal{H} \)-separative semigroup with chain \( \Gamma \). \( S \) is a \( \mathcal{G} \)-semigroup if and only if \( S \) contains a cofinal cluster \( W = \bigcup_{a \in \Lambda} S_a \) of \( S \) such that

1. \( \Lambda \) is a well ordered cofinal chain of \( \Gamma \), and
2. \( W \) is a \( \mathcal{B} \)-composed \( \mathcal{H} \)-cluster.

**Proof.** Assume that \( W = \bigcup_{a \in \Lambda} S_a \) be a cofinal \( \mathcal{B} \)-composed \( \mathcal{H} \)-cluster in \( S \) such that \( \Lambda \) is a cofinal chain in \( \Gamma \). Let \( x \in W \) and \( y \in W \), say, \( x \in S_\alpha \) and \( y \in S_\beta \), with \( \alpha \leq \beta \). Let \( u \in S_\gamma \subseteq W \) with \( \alpha \leq \beta < \gamma \). Now \( S_\alpha \) is \( \mathcal{B} \)-composed with \( S_\gamma \).

Hence there exists \( z \in S_\alpha \) such that \( (xz)z = yu \). Therefore by Theorem 3.5, \( W \) is a \( \mathcal{G} \)-semigroup, and hence \( S \) is a \( \mathcal{G} \)-semigroup by Theorem 6.3.

Conversely assume that \( S = \bigcup_{a \in \Gamma} S_a \) is a \( \mathcal{G} \)-semigroup. Let \( \Gamma \) be well ordered by \( \leq \). (Be aware of "\( \leq \)" distinguished from "\( \leq \)" originally given in the chain \( \Gamma \).) Say

\[ \Gamma = \{\alpha_0, \alpha_1, \ldots, \alpha_\omega, \alpha_{\omega + 1}, \ldots, \alpha_\eta\} \]

where \( \leq \) denotes the order for not only elements of \( \Gamma \) but their suffixes: \( \alpha_\xi \leq \alpha_\eta \) if and only if \( \xi \leq \eta \). Since \( S \) is a \( \mathcal{G} \)-semigroup, by Theorem 3.5, for each \( a \in S \) there exists \( b \in S \) and \( c \in S \) such that \( abc = c \). Thus for each \( \alpha \in \Gamma \) there exists \( \beta \in \Gamma \) and \( \gamma \in \Gamma \) such that \( S_{\alpha \beta} \) is \( \mathcal{B} \)-composed with \( S_{\gamma} \). For each \( \alpha \in \Gamma \) consider the set

\[ \Omega_\alpha = \{(a, \beta, \gamma): \text{there is } a \in S_{\alpha \beta}, b \in S_{\beta}, c \in S_{\gamma} \text{ such that } abc = c \} \]

We define a lexicographical order \( \leq \) in \( \Omega_\alpha \), i.e.

\[ (\alpha_\xi, \alpha_\eta) < (\alpha_\xi, \alpha_\eta) \text{ if and only if either } \alpha_\xi < \alpha_\xi \text{, or } \alpha_\xi = \alpha_\xi \text{ and } \alpha_\xi < \alpha_\eta \text{, or } \alpha_\xi = \alpha_\xi \text{ and } \alpha_\eta < \alpha_\eta \text{.} \]

Let \( (\alpha^1, \alpha^2) \) denote the \( \leq \) smallest element of \( \Omega_\alpha \). Now define a partial transformation \( \theta \) of \( \Gamma \) by

\[ \theta(\alpha_0) = \alpha^1_0, \]
\[ \theta(\xi) = \left( \theta(\xi - 1)^2 \right)^1 \text{ if } \xi \text{ is isolated and } \alpha_\xi \leq \left( \theta(\xi - 1)^2 \right)^1, \]

\[ = \alpha_\xi^1 \text{ if } \xi \text{ is isolated and } \alpha_\xi > \left( \theta(\xi - 1)^2 \right)^1, \]

\[ = \min \{ \alpha_\xi \in \Gamma : \alpha_\xi > \theta(\alpha_\eta) \text{ for all } \eta < \xi \} \text{ if } \xi \text{ is a limit ordinal and if this set is not empty and } \alpha_\xi \leq \theta(\alpha_\eta) \text{ for some } \eta < \xi, \]

\[ = \text{undefined if } \xi \text{ is a limit ordinal and if this set is empty, } \]

\[ = \text{undefined if } \xi \text{ is isolated and if } \theta(\alpha_\xi - 1) \text{ is undefined. } \]

Let \( W = \bigcup_{\xi < \eta + 1} S_{\theta(\xi)} \) if \( \theta(\alpha) = \alpha \) whenever it is defined and if \( \theta(\alpha) \) is undefined, there exists \( \beta \) such that \( \theta(\beta) \geq \alpha \). To see that \( W \) is \( \mathcal{B} \)-composed we will induct on \( \xi \) and show that \( S_{\theta(\alpha_\xi)} \) is \( \mathcal{B} \)-composed with \( S_{\theta(\alpha_\eta)} \) for all \( \eta < \xi \). The following can easily be used to show this. For all \( \xi \) and all \( \eta < \xi \),

(3) \( (\alpha_\xi^1)^1 = \alpha_\xi^1 \),

(4) \( \theta(\alpha_\xi) = \theta(\alpha_\xi) \),

(5) \( \alpha_\xi^2 \geq \theta(\alpha_\eta)^2 \),

(6) \( \alpha_\xi^2 \geq \theta(\alpha_\eta)^2 \).

Each of these is an immediate consequence of the definition of \( \theta, \alpha^1 \) and \( \alpha^2 \). Then since \( \theta(\alpha_\xi) \geq \theta(\alpha_\eta)^2 \), \( S_{\theta(\alpha_\xi)} \) is \( \mathcal{B} \)-composed with \( S_{\theta(\alpha_\eta)} \), and hence \( S_{\theta(\alpha_\eta)} \) is \( \mathcal{B} \)-composed with \( S_{\theta(\alpha_\xi)} \), for all \( \eta < \xi \). From the definition of \( \theta \) it follows that

\[ \text{if } \theta(\alpha_\eta) \text{ and } \theta(\alpha_\xi) \text{ are defined and if } \eta < \xi \text{ then } \theta(\alpha_\eta) \leq \theta(\alpha_\xi). \]

Let \( \Lambda \) be the set consisting of elements of \( \Gamma \) on which \( \theta \) is defined. Then \( \theta \) is an order-homomorphism of the well-ordered set \( (\Lambda, \prec) \) into \( (\Gamma, \leq) \). Thus \( \theta(\Lambda) \) has been proved to be \( \Lambda \) in the assertion (1). Q.E.D.

In the following theorem we describe the construction of a chain of \( \mathcal{N} \)-semigroups in order that \( S \) be an \( \mathcal{N}_{\mathcal{G}} \)-semigroup. By the group of translations of an \( \mathcal{N} \)-semigroup \( D \) we mean the group of permutations of \( D \) which are translations of \( D \). Since the translation semigroup \( \mathcal{F} \) is commutative cancellative, the group is a unique maximal subgroup of \( \mathcal{F}(D) \). See the details in [6], [9].

**Theorem 7.7.** Let \( (\Gamma, \leq) \) be a chain without greatest element, \( \{ S_\alpha : \alpha \in \Gamma \} \) a family of \( \mathcal{N} \)-semigroups and \( G_\alpha \) the group of translations of \( S_\alpha \). If \( \alpha < \beta \), a homomorphism of \( S_\alpha \) into \( G_\beta \) is denoted by \( F_\alpha^\beta \), and the image of \( x_\alpha \in S_\alpha \) under \( F_\alpha^\beta \) is denoted by \( x_\alpha F_\alpha^\beta \) and the image of \( x_\beta \in S_\beta \) under the permutation \( x_\alpha F_\alpha^\beta \) is denoted...
by \((x_a F^\beta_a) x_\beta\). Assume that a system of homomorphisms \(\{F^\beta_\alpha\}: \text{for all } \alpha, \beta \text{ with } \alpha < \beta\) is given such that whenever \(\alpha < \beta < \gamma\)

\[(x_a F^\gamma_\alpha)(x_\beta F^\gamma_\beta) = ((x_a F^\beta_\alpha) x_\beta) F^\gamma_\beta \text{ for all } x_\alpha \in S_\alpha, x_\beta \in S_\beta.\]

Let \(S = \bigcup \{S_\alpha: \alpha \in \Gamma\}\). Define an operation on \(S\) by

\[x_\alpha y_\beta = y_\beta x_\alpha = \begin{cases} x_\alpha y_\alpha & \text{the product in } S_\alpha \text{ if } \alpha = \beta, \\ (x_a F^\beta_\alpha)y_\beta & \text{if } \alpha < \beta. \end{cases}\]

Then \(S\) is a \(\mathcal{B}\)-composed \(R-\Omega\)-semigroup. Every \(\mathcal{B}\)-composed \(R-\Omega\)-semigroup with chain \(\Gamma\) can be obtained in this manner. \(S\) is denoted by \(S = \bigcup \{S_\alpha, F^\xi_\eta, \Gamma\}\).

Proof is obvious.

Note that for arbitrary \(\{S_\alpha: \alpha \in \Gamma\}\) with chain \(\Gamma\), there always exists a composition, for example we can define \(x_a F^\beta_\alpha\) by the identity mapping of \(S_\beta\) for all \(x_\alpha \in S_\alpha\).

We can describe the compositions by induction on \(\alpha \in \Gamma\).

Let \(\Gamma\) be a well-ordered chain without greatest element. It is regarded as a set of ordinals \(\Gamma = \{0, 1, \ldots, \omega, \ldots, n, \ldots\}\). Assume a family of \(\mathcal{R}\)-semigroups \(\{S_\alpha: \alpha \in \Gamma\}\) is given. Let \(S_1 = S_0\). A \(\mathcal{B}\)-composed \(S_2 = S_1 \cup S_1\) is constructed by a homomorphism \(S_1\) into the group of translations of \(S_1\) and \(f^1_\alpha\) is defined to be an inclusion map of \(S_1\) into \(S_2\). Thus we have a \((S_2, f^1_\alpha)\). Assume that for all \(\xi < \alpha\), a \(\mathcal{B}\)-composed \(\mathcal{R}-\Omega\)-semigroup \(S_\xi\) and inclusion maps \(f^\xi_1, f^\xi_2\) of \(S_\xi\) into \(S_{\xi_1}\) and \(S_{\xi_2}\) for all \(\xi_1, \xi_2\) with \(\xi_1 \leq \xi_2 \leq \xi\) such that \(f^\xi_1 \circ f^\xi_2 = f^\xi_3\) and \(f^\xi_{\xi_1}\) is the identity map of \(S_\xi\), that is, assume that \((S_\xi, f^\xi_1, f^\xi_2, \xi_1 \leq \xi_2 \leq \xi)\) is obtained for all \(\xi < \alpha\). Now we are to define \((S_\alpha, f^\alpha_1, f^\alpha_2; \xi_1 \leq \xi_2 \leq \alpha)\).

If \(\alpha\) is an isolated ordinal, \(S_\alpha\) is defined by \(S_\alpha = S_{\alpha-1} \cup S_{\alpha-1}\) as a \(\mathcal{B}\)-composed \(\mathcal{R}-\Omega\)-semigroup, and \(f^\alpha_\xi, \xi < \alpha\), is defined by \(f^\alpha_\xi = f^\alpha_{\alpha-1} f^\alpha_{\alpha-1}\) where \(f^\alpha_{\alpha-1}\) is the inclusion map of \(S_{\alpha-1}\) into \(S_\alpha\). If \(\alpha\) is a limit ordinal, \(S_\alpha\) is defined by the direct limit \(S_\alpha = \lim_{\rightarrow} \{S_\xi, f^\xi_1, f^\xi_2, \Gamma\}\) and \(f^\alpha_\xi\) is defined to be the inclusion of \(S_\xi\) into \(S_\alpha\).

We have to add a remark. In a \(\mathcal{B}\)-composed \(\mathcal{R}-\Omega\)-semigroup \(S = \bigcup \{S_\alpha, F^\xi_\eta, \Gamma\}\) with well ordered chain \(\Gamma\), we get a homomorphism \(b^\alpha_\alpha\) of \(S_\alpha\) onto a subgroup \(\Phi^\alpha_\alpha\) of \(G_\alpha\), the group of translations of \(S_\alpha\), for each \(\alpha \in \Gamma\). Note that \(b^\alpha_\alpha| S_\alpha = F^\alpha_\alpha\) and \(\Phi^\alpha_\alpha = \bigcup_{\eta < \alpha} \Phi^\eta_\eta\). For each \(\alpha, \beta \in \Gamma\) with \(\alpha < \beta\), there is a unique homomorphism \(g^\alpha_\beta\) of \(\Phi^\beta_\alpha\) onto \(\Phi^\beta_\beta\) such that \(b^\beta_\beta = g^\beta_\alpha b^\alpha_\beta\). To prove this it is sufficient to show if \(\alpha < \beta < \gamma\),

\[\phi^\beta_\alpha = \phi^\beta_\beta \text{ implies } \phi^\gamma_\alpha = \phi^\gamma_\beta \text{ for all } \gamma \geq \beta,\]

in which the notation \(\phi^\beta_\alpha\) is defined before Proposition 7.2. By assumption \(xa_\alpha = xb_\alpha\) for all \(x \in S_\beta\). Let \(y \in S_\gamma\). Then \(y^2 xa_\alpha = y^2 xb_\alpha\) and \((yx)(ya_\alpha) = (yx)(yb_\alpha),\)
yx ∈ S_γ. Since S_γ is cancellative, we have ya_a = yb_a for all y ∈ S_γ.

From h^β = g^α_b^a it follows that, whenever α < β < γ,

\[ r^γ_a = g^γ b^α, \quad \text{and} \quad r^ξ_a \text{ is the identity for all } ξ. \]

When η < α, recall F^α_η = b^α | S_η, and let K_α = \( \bigcup \{ \ker F^ξ_a : α < ξ \} \). Let

\[ F^ξ_a = F^ξ_a | K_α. \]

We have a similar result to Proposition 4.3.

**Proposition 7.8.** The greatest group-homomorphic image of S = U \( \{ S_a, F^ξ_α, Γ \} \) is isomorphic to \( \lim_{ξ} \{ Φ^α_ξ, K_α, Γ \} \), and the kernel of the homomorphism is \( \bigcup \{ K_α, F^α_ξ, Γ \} \).

Finally we list basic property on the class of \( \mathcal{G} \)-semigroups which are not necessarily separative.

(i) A homomorphic image of a \( \mathcal{G} \)-semigroup is a \( \mathcal{G} \)-semigroup.

(ii) An ideal of a \( \mathcal{G} \)-semigroup is a \( \mathcal{G} \)-semigroup.

(iii) If S is a commutative semigroup and if S is a union of \( \mathcal{G} \)-semigroups, then S is a \( \mathcal{G} \)-semigroup.

(iv) A semilattice of \( \mathcal{G} \)-semigroups is a \( \mathcal{G} \)-semigroup.

(v) If a commutative semigroup S contains a cofinal \( \mathcal{G} \)-subsemigroup, then S is a \( \mathcal{G} \)-semigroup.

(vi) If a commutative semigroup S contains a \( \mathcal{G} \)-semigroup as an ideal of S, then S is a \( \mathcal{G} \)-semigroup.

(vii) If S_ξ, ξ ∈ \( \Xi \), are \( \mathcal{G} \)-semigroups, the direct product of \( \Pi_ξ S_ξ \) is a \( \mathcal{G} \)-semigroup.

Some of the above have been proved in this paper, but we note that we can very easily prove (i) through (vii) by using (3.5.3) of Theorem 3.5.

Restating Theorem 3.5',

(viii) S has a greatest group-homomorphism if and only if

1. there is at least one local identity element e: be = b,
2. for each a ∈ S there is a local identity element e and an element x such that ax = e.

This shows that the concept of \( \mathcal{G} \)-semigroups is really a natural generalization of groups.

REFERENCES


