SUBDIRECTLY IRREDUCIBLE SEMIGROUPS

THESIS

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TABLE OF CONTENTS

CHAPTER I

GENERAL PROPERTIES OF SEMIGROUPS

Definition 1.1. The ordered pair $(S,*)$ is a semigroup iff S is a set and $*$ is an associative binary operation (multiplication) on S.

Notation. A semigroup $(S,*)$ will ordinarily be referred to by the set S, with the multiplication understood. In other words, if $(a,b) \in S \times S$, then $*[(a,b)] = a*b = ab$.

The proof of the following proposition is found on p. 4 of Introduction to Semigroups, by Mario Petrich.

Proposition 1.2. Every semigroup S satisfies the general associative law.

Proof. If $\{a_i\}_{i=1}^{n} \subseteq S$, then define $a_1a_2\cdots a_n \equiv a_1(a_2(\cdots(a_{n-1}a_n)\cdots))$. If $a \in S$ and a is the product of one element $a_1 \in S$, then $a = a_1$, and the product does not depend on the positioning of parentheses. Now suppose the general associative law holds for all products of r elements, where $r < n$. If a is the product of n elements of S, then there exists $r \in Z^+$, $1 \leq r \leq n$, such that

$$\begin{aligned} a &= (a_1a_2\cdots a_r)(a_{r+1}a_{r+2}\cdots a_n) \\ &= [a_1(a_2\cdots a_r)](a_{r+1}\cdots a_n) \\ &= a_1[(a_2\cdots a_r)(a_{r+1}\cdots a_n)] \end{aligned}$$

$$= a_1(a_2 \cdots a_r \cdot a_{r+1} \cdots a_n)$$
$$= a_1 a_2 \cdots a_n.$$

Thus by induction, S satisfies the general associative law, and so all parentheses may be omitted from products of elements of a semigroup.

Definition 1.3. A nonempty subset T of a semigroup S is a subsemigroup of S iff T is closed under the operation on S (if $a,b \in T$, then $ab \in T$).

Thus a subsemigroup T of a semigroup S, along with the multiplication of S, is itself a semigroup since associativity is inherited from S.

Definition 1.4. A semigroup S is generated by a subset G of S iff every element of S can be expressed as the product of elements of G.

Definition 1.5. A semigroup S is cyclic iff there exists $a \in S$ such that S is generated by $\{a\}$.

Definition 1.6. If A is a nonempty subset of a semigroup S, then the subsemigroup of S generated by A is $\{a_1 a_2 \cdots a_n \mid a_i \in A,\ 1 \leq i \leq n;\ n \in Z^+\}$, where Z^+ is the set of all positive integers.

Lemma 1.7. If A is a nonempty subset of a semigroup S, then the subsemigroup of S generated by A is the intersection of all subsemigroups of S containing A.

Proof. Let $T \equiv \{\prod_{i=1}^{n} a_i \mid n \in Z^+;\ a_i \in A,\ 1 \leq i \leq n\}$, and let $\{G_\alpha\}_{\alpha \in \Gamma} \equiv \{G \text{ subsemigroup of } S \mid A \subseteq G\}$.

If $\prod_{i=1}^{n} a_i \in T$, then $a_i \in A$ for each i, $1 \leq i \leq n$. Therefore, since $A \subseteq G_\alpha$ for all $\alpha \in \Gamma$, then for each i, $1 \leq i \leq n$, $a_i \in G_\alpha$ for all $\alpha \in \Gamma$.

Therefore, $\prod_{i=1}^{n} a_i \in G_\alpha$ for all $\alpha \in \Gamma$, so that $\prod_{i=1}^{n} a_i \in \bigcap_{\alpha \in \Gamma} G_\alpha$. Thus $T \subseteq \bigcap_{\alpha \in \Gamma} G_\alpha$. However, T itself is a subsemigroup of S and obviously contains A. Therefore, $T \in \{G_\alpha\}_{\alpha \in \Gamma}$, so that $\bigcap_{\alpha \in \Gamma} G_\alpha \subseteq T$, and hence $T = \bigcap_{\alpha \in \Gamma} G_\alpha$.

Definition 1.8. A nonempty subset T of a semigroup S is a left ideal of S iff $a \in S$, $b \in T$ imply $ab \in T$. T is a right ideal of S iff $a \in S$, $b \in T$ imply $ba \in T$. T is a two-sided ideal (or simply an ideal) of S iff T is both a left and right ideal of S. T is a proper ideal of S iff T is an ideal of S and $T \neq S$.

Notation. If $\{A_i\}_{i=1}^{n}$ is a collection of nonempty subsets of a semigroup S, then

$$A_1 A_2 \cdots A_n = \{a_1 \cdot a_2 \cdots a_n \mid a_i \in A_i,\ 1 \leq i \leq n\}.$$

If $A_i = \{a\}$, then $A_1 A_2 \cdots A_{i-1}\, a\, A_{i+1} \cdots A_n = A_1 A_2 \cdots A_n$. If $A_1 = A_2 = \cdots = A_n = A$, then $A^n = A_1 A_2 \cdots A_n$. In general, no distinction will be made between an element a of a semigroup S and the singleton set {a}.

In view of this notation, a nonempty subset T of a semigroup S is: (i) a subsemigroup of S iff $T^2 \subseteq T$, (ii) a left ideal of S iff $ST \subseteq T$, (iii) a right ideal of S iff $TS \subseteq T$, (iv) an ideal of S iff $ST \cup TS \subseteq T$. Also, if A is a nonempty subset of S, then the subsemigroup of S generated by A is $\bigcup_{i=1}^{\infty} A^n$.

Lemma 1.9. Each of the collections (a) of all left ideals, (b) all right ideals, (c) all ideals of a semigroup S is closed under (i) arbitrary intersection, if nonempty, (ii) arbitrary union. Also, the collection of all ideals is closed under finite intersection.

Proof. Part I: Let $\{G_\alpha\}_{\alpha\varepsilon A}$ be a collection of left ideals of a semigroup S such that $\bigcap_{\alpha\varepsilon A} G_\alpha \neq \phi$. If $x\varepsilon S$, $y\varepsilon \bigcap_{\alpha\varepsilon A} G_\alpha$, then $y\varepsilon G_\alpha$ for each $\alpha\varepsilon A$. Since G_α is a left ideal of S, then $xy\,\varepsilon\, G_\alpha$ for each $\alpha\varepsilon A$, so that $xy\,\varepsilon \bigcap_{\alpha\varepsilon A} G_\alpha$. Therefore $\bigcap_{\alpha\varepsilon A} G_\alpha$ is a left ideal of S. Similarly, if $\{G_\alpha\}_{\alpha\varepsilon A}$ is a collection of right ideals (or ideals) of S such that $\bigcap_{\alpha\varepsilon A} G_\alpha \neq \phi$, then $\bigcap_{\alpha\varepsilon A} G_\alpha$ is a right ideal (or ideal) of S.

Part II: If $\{G_\alpha\}_{\alpha\varepsilon A}$ is a collection of left ideals of S, then for each $\alpha\varepsilon A$, $G_\alpha \neq \phi$, so that $\bigcup_{\alpha\varepsilon A} G_\alpha \neq \phi$. Furthermore, if $x\varepsilon S$ and $y\varepsilon \bigcup_{\alpha\varepsilon A} G_\alpha$, then there exists $\beta\varepsilon A$ such that $y\varepsilon G_\beta$. Therefore $xy\,\varepsilon\, G_\beta \subseteq \bigcup_{\alpha\varepsilon A} G_\alpha$, and so $\bigcup_{\alpha\varepsilon A} G_\alpha$ is a left ideal of S. Similarly, if $\{G_\alpha\}_{\alpha\varepsilon A}$ is a collection of right ideals (or ideals) of S, then $\bigcup_{\alpha\varepsilon A} G_\alpha$ is a right ideal (or ideal) of S.

Part III: If A and B are ideals of a semigroup S, then $A \neq \phi$ and $B \neq \phi$, so there exist $x\varepsilon A$, $y\varepsilon B$. Therefore $xy\,\varepsilon\, A$ and $xy\,\varepsilon\, B$, so that $xy\,\varepsilon\, A\cap B$ and thus $A\cap B \neq \phi$. Furthermore, if $p\varepsilon A\cap B$ and $q\varepsilon S$, then $p\varepsilon A$ and $p\varepsilon B$. Therefore $pq, qp\,\varepsilon\, A$ and $pq, qp\,\varepsilon\, B$, so that $pq, qp\,\varepsilon\, A\cap B$. Thus $A\cap B$ is is an ideal of S. Now suppose that if $\{A_i\}_{i=1}^{k}$ is a collection of ideals in S, then $\bigcap_{i=1}^{k} A_i$ is an ideal in S. Therefore, if $\{A_i\}_{i=1}^{k+1}$ is a collection of ideals of S, then $\bigcap_{i=1}^{k} A_i$ is an ideal of S. But then $\bigcap_{i=1}^{k+1} A_i = \bigcap_{i=1}^{k} A_i \cap A_{k+1}$ is an ideal of S since the case for two ideals was already proven. Therefore, by induction, for each $n \varepsilon Z^+$, if $\{A_i\}_{i=1}^{n}$ is a collection of ideals of S, then $\bigcap_{i=1}^{n} A_i$ is an ideal of S.

Definition 1.10. If S is a semigroup, $A \subseteq S$, and $A \neq \phi$, then the left ideal generated by A is $L_A = \bigcap\{T \text{ left ideal of } S \mid A \subseteq T\}$. A left ideal of S generated by a singleton subset $\{a\}$ of S is the principal left ideal of S generated by a, and will be denoted by L(a). Corresponding definitions are valid for right ideals with notation R_A, R(a), and ideals with notation J_A, J(a).

Lemma 1.11. If S is a semigroup and $a \varepsilon S$, then
(1) $L(a) = \{a\} \cup Sa$, (2) $R(a) = \{a\} \cup aS$, and
(3) $J(a) = \{a\} \cup aS \cup Sa \cup SaS$.

Proof. Part I: Let $\{G\alpha\}_{\alpha \varepsilon A}$ be the collection of all left ideals of S containing a, so that $L(a) = \bigcap_{\alpha \varepsilon A} G\alpha$.
(i) Since $a \varepsilon G\alpha$ for each $\alpha \varepsilon A$, then $a \varepsilon \bigcap_{\alpha \varepsilon A} G\alpha = L(a)$, so that $\{a\} \subseteq L(a)$. (ii) Since L(a) is a left ideal of S and $a \varepsilon L(a)$, then for each $x \varepsilon S$, $xa \varepsilon L(a)$ so that $Sa \subseteq L(a)$. Therefore, by (i), (ii), $\{a\} \cup Sa \subseteq L(a)$.

Let $x \varepsilon S$, $y \varepsilon \{a\} \cup Sa$, so that either $y = a$ or $y = ka$ for some $k \varepsilon S$.

(i) If $y = a$, then $xy = xa \in Sa \subseteq \{a\} \cup Sa$.

(ii) If $y = ka$, then $xy = x(ka) = (xk)a \in Sa \subseteq \{a\} \cup Sa$, since $xk \in S$.

Therefore $\{a\} \cup Sa$ is a left ideal of S and contains a, so that $\{a\} \cup Sa \in \{G_\alpha\}_{\alpha \in A}$, and so $L(a) = \bigcap_{\alpha \in A} G_\alpha \subseteq \{a\} \cup Sa$.

Part II: Similarly, $R(a) = \{a\} \cup aS$.

Part III: Let $\{H_\alpha\}_{\alpha \in A}$ be the collection of all ideals of S containing a, so that $J(a) = \bigcap_{\alpha \in A} H_\alpha$.

(i) Since $a \in H_\alpha$ for each $\alpha \in A$, then $a \in \bigcap_{\alpha \in A} H_\alpha = J(a)$, so that $\{a\} \subseteq J(a)$.

(ii) Since $J(a)$ is an ideal of S and $a \in J(a)$, then for each $x \in S$, $ax \in J(a)$ and $xa \in J(a)$, so that $aS \subseteq J(a)$ and $Sa \subseteq J(a)$.

(iii) Also, if $x, y \in S$, then $xa \in J(a)$ since $J(a)$ is a left ideal, and so $xay = (xa)y \in J(a)$ since $J(a)$ is a right ideal. Therefore, $SaS \subseteq J(a)$. Thus by (i)-(iii), $\{a\} \cup Sa \cup aS \cup SaS \subseteq J(a)$.

If $x \in S$, $y \in \{a\} \cup Sa \cup aS \cup SaS$, then either $y = a$, $y \in Sa$, $y \in aS$, or $y \in SaS$.

(i) If $y = a$, then $xy = xa \in Sa$ and $yx = ax \in aS$, so that $xy, yx \in \{a\} \cup Sa \cup aS \cup SaS$.

(ii) If $y \in Sa$, then $y = ka$ for some $k \in S$. Therefore, $xy = x(ka) = (xk)a \in Sa$, since $xk \in S$, and $yx = kax \in SaS$, so that $xy, yx \in \{a\} \cup Sa \cup aS \cup SaS$.

(iii) If $y \in aS$, then $y = ak$ for some $k \in S$. Therefore, $xy = xak \in SaS$ and $yx = (ak)x = a(kx) \in aS$, since $kx \in S$, so that $xy, yx \in \{a\} \cup Sa \cup aS \cup SaS$.

(iv) If $y \varepsilon SaS$, then $y = paq$ for some $p,q \varepsilon S$. Therefore, $xy = x(paq) = (xp)aq \varepsilon SaS$ since $xp \varepsilon S$, and $yx = (paq)x = pa(qx) \varepsilon SaS$ since $qx \varepsilon S$, so that $xy, yx \varepsilon \{a\} \cup Sa \cup aS \cup SaS$.

Thus, by (i)-(iv), $\{a\} \cup Sa \cup aS \cup SaS$ is an ideal of S and contains a, so that $\{a\} \cup Sa \cup aS \cup SaS \varepsilon \{H_\alpha\}_{\alpha \varepsilon A}$, and so $J(a) = \bigcap_{\alpha \varepsilon A} H_\alpha \subseteq \{a\} \cup Sa \cup aS \cup SaS$.

<u>Definition 1.12</u>. A semigroup S is left (right) simple iff S is the only left (right) ideal of S. S is simple iff S is the only ideal of S.

<u>Lemma 1.13</u>. A semigroup S is left simple iff $Sa = S$ for all $a \varepsilon S$. A semigroup S is right simple iff $aS = S$ for all $a \varepsilon S$. A semigroup S is simple iff $SaS = S$ for all $a \varepsilon S$.

<u>Proof</u>. Part I: Suppose S is left simple and $a \varepsilon S$. If $p \varepsilon S$ and $q \varepsilon Sa$, then $q = ka$ for some $k \varepsilon S$, and so $pq = p(ka) = (pk)a \varepsilon Sa$ since $pk \varepsilon S$. Therefore, Sa is a left ideal of S so that $Sa = S$ since S is left simple. Thus $Sa = S$ for all $a \varepsilon S$.

Suppose $Sa = S$ for all $a \varepsilon S$. If G is a left ideal of S, then $G \neq \phi$ so that there exists $a \varepsilon G$. Therefore, $S = Sa \subseteq SG \subseteq G$ (since G is a left ideal) $\subseteq S$, so that $G = S$. Thus S is left simple.

Part II: Similarly, S is right simple iff $aS = S$ for all $a \varepsilon S$.

Part III: Suppose S is simple and $a \varepsilon S$. If $p \varepsilon S$, $q \varepsilon SaS$, then $q = kat$ for some $k,t \varepsilon S$. Therefore

$pq = p(kat) = (pk)at \in SaS$ since $pk \in S$, and
$qp = (kat)p = ka(tp) \in SaS$ since $tp \in S$. Thus SaS is an ideal of S, and so $SaS = S$ since S is simple.

Suppose $SaS = S$ for all $a \in S$. If G is an ideal of S, then $G \neq \phi$ so there exists $a \in G$. Therefore if $x, y \in S$, then $xa \in G$ and so $xay = (xa)y \in G$. Thus $S = SaS \subseteq G \subseteq S$ so that $G = S$, and so S is simple.

<u>Definition 1.14</u>. The intersection of all ideals of a semigroup S, if nonempty, is the kernel of S.

<u>Lemma 1.15</u>. If K is a simple ideal of a semigroup S, then K is the kernel of S.

<u>Proof</u>. Suppose K is a simple ideal of a semigroup S. If G is any ideal of S, then $K \cap G$ is an ideal of S by lemma 1.9. Since $K \cap G \subseteq K$, then $K \cap G = K$ since K is simple. Therefore $K = K \cap G \subseteq G$ for each ideal G of S, so that $K \subseteq \bigcap\{G | G \text{ is an ideal of } S\}$. But $K \in \{G | G \text{ is an ideal of } S\}$, and so $\bigcap\{G | G \text{ is an ideal in } S\} \subseteq K$. Thus $K = \bigcap\{G | G \text{ is an ideal of } S\}$ = kernel of S, since $K \neq \phi$.

<u>Definition 1.16</u>. Let S be a semigroup and let $d \in S$. An element e of S is: (i) a left identity of d iff $ed = d$, (ii) a right identity of d iff $de = d$, (iii) a two-sided identity (or simply an identity) of d iff e is both a left and a right identity of d. Furthermore, e is a left (right) identity of S iff e is a left (right) identity of every element of S; and e is a two-sided identity (or simply an identity) of S iff e is both a left and a right identity of S.

Definition 1.17. An element z of a semigroup S is a left zero of S iff zx = z for all $x \varepsilon S$; z is a right zero of S iff xz = z for all $x \varepsilon S$; z is a two-sided zero (or simply a zero) of S iff z is both a left and a right zero of S.

Definition 1.18. If S is a semigroup with zero z, then an element p of S is a zero divisor of S iff $p \neq z$ and there exists $q \varepsilon S$ such that $q \neq z$ and either pq = z or qp = z.

Notation: If S is a semigroup, an identity 1 may be adjoined to S by defining x1 = 1x = x for all $x \varepsilon S$. Similarly, a zero 0 may be adjoined to S by defining x0 = 0x = 0 for all $x \varepsilon S$. Let S^1 be the semigroup S with 1 adjoined, and let S^0 be S with 0 adjoined. Thus, according to this notation, if S is a semigroup and $a \varepsilon S$, then $L(a) = S^1 a$, $R(a) = aS^1$, and $J(a) = S^1 a S^1$.

Lemma 1.19. If a semigroup S has an identity, then the identity is unique.

Proof. Suppose e and u are identities for a semigroup S. Then e = eu since u is a right identity, and eu = u since e is a left identity. Thus e = u and the identity is unique.

Lemma 1.20. If a semigroup S has a zero, then the zero is unique.

Proof. Suppose z and w are zeros of a semigroup S. Then z = zw since z is a left zero, and zw = w since w is a right zero. Thus z = w and the zero element is unique.

Notation. If A and B are sets, then (i) $A\setminus B = \{x\varepsilon A | x\notin B\}$, (ii) $|A|$ = cardinality of A, and (iii) if S is a semigroup with 0, then $S^* = S\setminus\{0\}$. Notice that S^* is a semigroup iff S has no zero divisors.

Definition 1.21. A semigroup S in which every element is a left (right) zero is a left (right) zero semigroup. A semigroup S with zero 0 is a zero semigroup iff $ab = 0$ for all $a,b\varepsilon S$. A semigroup S with zero 0 is 0-simple iff $S^2 \neq \{0\}$ and S has no nonzero proper ideals. Thus S is 0-simple iff S is not a zero semigroup, and the only ideals in S are $\{0\}$ and S.

Definition 1.22. Elements p and q of a semigroup S commute iff $pq = qp$.

Definition 1.23. The center of a semigroup S is $C(S) \equiv \{a\varepsilon S | ax = xa \text{ for all } x\varepsilon S\}$.

Definition 1.24. A semigroup S is commutative iff $C(S) = S$.

Definition 1.25. An element x of a semigroup S is idempotent iff $x^2 = x$.

Definition 1.26. A semigroup S is idempotent iff every element of S is idempotent.

Definition 1.27. A semilattice is a commutative idempotent semigroup.

Definition 1.28. A subgroup G of a semigroup S is a subsemigroup of S which is also a group.

The proof of the following proposition is found on p. 10 of Introduction to Semigroups, by Mario Petrich.

Proposition 1.29. If e is an idempotent element of a semigroup S, then

$$G_e \equiv \{a \in S \mid a = ea = ae,\ e = ab = ba \text{ for some } b \in S\}$$
$$= \{a \in S \mid a \in eS \cap Se,\ e \in aS \cap Sa\}$$

is the greatest subgroup of S having e as its identity.

Proof. Let e be an idempotent element of a semigroup S, and let $G_e \equiv \{a \in S \mid a = ea = ae,\ e = ab = ba \text{ for some } b \in S\}$.

Part I: If $p \in G_e$, then $p = ep \in eS$ and $p = pe \in Se$, so that $p \in eS \cap Se$. Similarly $e = pq \in pS$ and $e = qp \in Sp$ for some $q \in S$, so that $e \in pS \cap Sp$. Therefore, $p \in \{a \in S \mid a \in eS \cap Se,\ e \in aS \cap Sa\}$, and so $G_e \subseteq \{a \in S \mid a \in eS \cap Se,\ e \in aS \cap Sa\}$. Now if $p \in \{a \in S \mid a \in eS \cap Se,\ e \in aS \cap Sa\}$, then there exist $x, y, z, w \in S$ such that $p = ex = ye$ and $e = pz = wp$. Since $p = ex$, then $ep = e(ex) = (ee)x = ex = p$, and since $p = ye$ then $pe = (ye)e = y(ee) = ye = p$. Therefore $p = ep = pe$. Furthermore, $eze = (wp)ze = w(pz)e = wee = we$, so that $eze = (ee)ze = e(eze) = e(we) = ewe$, and so $eze = ewe$. Define $q = eze = ewe \in S$. Therefore,
$e = ee = (pz)e = p(ze) = (pe)(ze) = p(eze) = pq$ and
$e = ee = e(wp) = (ew)p = (ew)(ep) = (ewe)p = qp$, so that $e = pq = qp$ for $q \in S$. Thus $p \in G_e$, and so $\{a \in S \mid a \in eS \cap Se,\ e \in aS \cap Sa\} \subseteq G_e$. Therefore
$G_e \equiv \{a \in S \mid a = ea = ae,\ e = ab = ba \text{ for some } b \in S\} = \{a \in S \mid a \in eS \cap Se,\ e \in aS \cap Sa\}$.

Part II: (i) If $a, b \in G_e$, then $a = ae = ea$, $b = be = eb$, and there exist $p, q \in S$ such that $e = ap = pa = bq = qb$.

Therefore $ab = (ea)b = e(ab)$ and $ab = a(be) = (ab)e$, so that $ab = e(ab) = (ab)e$. Also, since $p,q \in S$, then $qp \in S$. Therefore $(ab)(qp) = [a(bp)]p = (ae)p = ap = e$ and $(qp)(ab) = q[(pa)b] = q(eb) = qb = e$, so that $e = (ab)(qp) = (qp)(ab)$ and $ab \in G_e$. Thus G_e is closed under the multiplication of S.

(ii) G_e inherits associativity from S.

(iii) Since e is idempotent, then $e = ee = ee$ satisfies both equations in the definition of G_e, and so $e \in G_e$. Furthermore, e is identity for G_e by the definition of G_e.

(iv) If $a \in G_e$, then $ae = ea = a$ and $e = ab = ba$ for some $b \in S$, and so $ebe \in S$. Since $ebe = e(ebe) = (ebe)e$ and $e = (ebe)a = a(ebe)$ for $a \in S$, then $ebe \in G_e$ and is inverse for a. Thus G_e is a group with e as its identity.

Part III: Let G be any subgroup of S containing e as its identity. If $p \in G$, then $p = pe = ep$ and there exists $q \in G \subseteq S$ such that $e = pq = qp$, and so $p \in G_e$. Therefore $G \subseteq G_e$ and so G_e is the largest subgroup of S having e as its identity.

<u>Definition 1.30</u>. If S is a semigroup with identity e, then G_e is the group of units of S, and the elements of G_e are the invertible elements of S.

<u>Lemma 1.31</u>. An element x of a semigroup S with identity is invertible iff $xS = Sx = S$.

<u>Proof</u>. Let S be a semigroup with identity e. If $x \in S$ is invertible, then $x = xe = ex$ and $e = xy = yx$ for some $y \in S$.

Therefore, for each $p\varepsilon S$, $p = pe = p(yx) = (py)x\varepsilon Sx$ and $p = ep = (xy)p = x(yp)\varepsilon xS$, so that $S \subseteq Sx$ and $S \subseteq xS$. However, for each $a\varepsilon S$, $ax\varepsilon S$ and $xa\varepsilon S$, so that $Sx \subseteq S$ and $xS \subseteq S$. Therefore $xS = Sx = S$. Conversely, suppose $xS = Sx = S$. Since e is the identity for S, then $S = eS = Se$, so that $x\varepsilon S = S \cap S = eS \cap Se$. Also, $e\varepsilon S = S \cap S = xS \cap Sx$, so that $x\varepsilon\{a\varepsilon S \mid a\varepsilon eS \cap Se,\ e\varepsilon aS \cap Sa\} = G_e$, and thus x is invertible.

Definition 1.32. An element p of a semigroup S is regular iff there exists $x\varepsilon S$ such that $p = pxp$.

Definition 1.33. A semigroup S is regular iff each element of S is regular.

Definition 1.34. Let S be a semigroup and let $p,x\varepsilon S$. Then x is an inverse of p iff $p = pxp$ and $x = xpx$.

Theorem 1.35. In a semigroup S, each regular element p has an inverse which is also regular. Conversely, if an element p of S has an inverse, then both p and its inverse are regular.

Proof. If $p\varepsilon S$ is regular, then there exists $x\varepsilon S$ such that $p = pxp$. Therefore $xpx\varepsilon S$, $p(xpx)p = (pxp)xp = pxp = p$, and $(xpx)p(xpx) = x(pxp)(xpx) = xp(xpx) = x(pxp)x = xpx$. Thus xpx is inverse for p, and since $(xpx)p(xpx) = xpx$ for $p\varepsilon S$, then xpx is regular. Conversely, if $p,x\varepsilon S$ and x is an inverse of p, then $p = pxp$ and $x = xpx$, so that p and x are regular.

Definition 1.36. The order of a finite semigroup S is the number of its elements. If S is not finite, then S is of infinite order. A semigroup of order one is a trivial semigroup.

Definition 1.37. The order of an element x of a semigroup S is the order of the cyclic subsemigroup of S generated by x.

Definition 1.38. A semigroup S is periodic iff each element of S is of finite order.

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CHAPTER II

RELATIONS AND FUNCTIONS ON A SEMIGROUP

Definition 2.1. A binary relation ρ on a set S is a subset of $S \times S$. An alternate notation for $(x,y)\varepsilon\rho$ will be $x\rho y$, in which case x is said to be ρ-related to y. A binary relation ρ on a set S will ordinarily be referred to simply as a relation on S.

Definition 2.2. A relation ρ on a set S is:

(i) reflexive iff $(x,x)\varepsilon\rho$,

(ii) symmetric iff $(x,y)\varepsilon\rho$ implies $(y,x)\varepsilon\rho$,

(iii) antisymmetric iff $(x,y),(y,x)\varepsilon\rho$ implies $x = y$, and

(iv) transitive iff $(x,y),(y,z)\varepsilon\rho$ implies $(x,z)\varepsilon\rho$ for all $x,y,z\varepsilon S$.

Definition 2.3. A relation ρ on a set S is an equivalence relation on S iff ρ is reflexive, symmetric, and transitive.

Definition 2.4. If ρ is an equivalence relation on a set S, then the disjoint equivalence classes formed by ρ on S are ρ-classes, and the ρ-class containing an element x of S will be denoted by x_ρ.

Definition 2.5. The equivalence relation ρ on a set S defined by $(x,y)\varepsilon\rho$ iff $x = y$ for each $x,y\varepsilon S$ is the equality relation on S and will be denoted by ε_S.

Definition 2.6. The equivalence relation ρ on a set S defined by $(x,y)\varepsilon\ \rho$ for each $x,y\varepsilon S$ is the universal relation on S and will be denoted by w_S. Notice that $w_S = S \times S$.

Definition 2.7. An equivalence relation ρ on a set S is proper iff $\rho \neq \varepsilon_S$.

Definition 2.8. A relation ρ on a set S is a partial ordering of S iff ρ is reflexive, antisymmetric, and transitive.

Notation. A partial ordering for a set S will normally be denoted by $\leq$; $(x,y)\varepsilon\leq$ will be denoted by $x \leq y$; $(S,\leq)$, or simply S, will be called a partially ordered set.

Definition 2.9. If $(S,\leq)$ is a partially ordered set and $B \subseteq S$, then $p\varepsilon S$ is an upper bound of B iff $b \leq p$ for each $b\varepsilon B$. Similarly, p is a lower bound of B iff $p \leq b$ for each $b\varepsilon B$.

Definition 2.10. If $(S,\leq)$ is a partially ordered set and $B \subseteq S$, then $p\varepsilon S$ is a least upper bound of B iff (i) p is an upper bound of B, and (ii) if $q\varepsilon S$ is an upper bound of B, then $p \leq q$. Similarly, p is a greatest lower bound of B iff (i) p is a lower bound of B, and (ii) if q is a lower bound of B, then $q \leq p$.

Notation. The least upper bound and greatest lower bound of a subset B of a partially ordered set $(S,\leq)$ will be denoted by lub B and glb B, respectively.

Definition 2.11. A partially ordered set $(S,\leq)$ is a lower semilattice iff for each $x,y\varepsilon S$ there exists $q\varepsilon S$ such that

$q = \text{glb}\{x,y\}$. $(S,\leq)$ is an upper semilattice iff for each $x,y \in S$ there exists $p \in S$ such that $p = \text{lub}\{x,y\}$.

Definition 2.12. A partial ordering $\leq$ on a set S is a linear ordering on S iff either $x \leq y$ or $y \leq x$ for each $x,y \in S$. In such a case, $(S,\leq)$ is called a linearly ordered set, or simply a chain.

Definition 2.13. If $(S,\leq)$ is a partially ordered set and $p \in S$, then: (i) p is the least element of S iff $p \leq x$ for each $x \in S$, (ii) p is the greatest element of S iff $x \leq p$ for each $x \in S$, (iii) p is a minimal element of S iff $x \leq p$ implies $x = p$ for each $x \in S$, and (iv) p is a maximal element of S iff $p \leq x$ implies $x = p$ for each $x \in S$.

Notation. If S is a semigroup then E_S will denote the set of all idempotent elements of S together with the binary relation $\leq$ defined by $e \leq f$ iff $e = ef = fe$.

Lemma 2.14. If S is a semigroup, then E_S is a partially ordered set.

Proof. If $e \in E_S$, then $e = ee = ee$ so that $e \leq e$ and $(E_S,\leq)$ is reflexive. If $e,f \in E_S$ such that $e \leq f$ and $f \leq e$, then $e = ef = fe$ and $f = fe = ef$ so that $e = ef = f$ and $(E_S,\leq)$ is antisymmetric. If $e,f,g \in E_S$ such that $e \leq f$ and $f \leq g$, then $e = ef = fe$ and $f = fg = gf$ so that $e = ef = e(fg) = (ef)g = eg$ and $e = fe = (gf)e = g(fe) = ge$. Therefore $e = eg = ge$ so that $e \leq g$ and $(E_S,\leq)$ is transitive.

The following proposition will give some insight into the relationship between the concepts of lower (and upper) semilattice (a partially ordered set) and a semilattice (a commutative, idempotent semigroup).

Proposition 2.15. If S is a semilattice, then $E_s = S$ is a lower semilattice with $glb\{x,y\} = xy$. Conversely, if T is a lower semilattice, then $(T,*)$ is a semilattice, where $x*y = glb\{x,y\}$ for all $x,y \varepsilon T$.

Proof. If S is a semilattice then $E_s = S$. Therefore, if $x,y \varepsilon E_s$ then $xy = xxy$ (since S is idempotent) $= xyx$ (since S is commutative), and so $xy \leq x$. Similarly, $xy = xyy = yxy$ so that $xy \leq y$ and thus xy is a lower bound for $\{x,y\}$. Now if p is a lower bound for $\{x,y\}$ then $p \leq x$ and $p \leq y$ so that $p = px = xp$ and $p = py = yp$. Therefore $p = pp = (px)(py) = (pp)(xy) = p(xy) = (xy)p$, so that $p \leq xy$ and $xy = glb\{x,y\}$. Conversely, if T is a lower semilattice, then define the multiplication $*$ on T by $x*y = glb\{x,y\}$ for all $x,y \varepsilon T$. If $x,y \varepsilon T$, then since T is a semilattice, there exists $p \varepsilon T$ such that $p = glb\{x,y\} = x*y$. Therefore $x*y \varepsilon T$ and so $*$ is a binary relation on T. If $x,y,z \varepsilon T$ then $(x*y)*z = glb\{glb\{x,y\},z\}$ so that $(x*y)*z \leq glb\{x,y\}$ and $(x*y)*z \leq z$. Therefore $(x*y)*z \leq x$, $(x*y)*z \leq y$, and $(x*y)*z \leq z$, so that $(x*y)*z$ is a lower bound for $\{x,y,z\}$. Now if p is a lower bound for $\{x,y,z\}$, then p is a lower bound for $\{x,y\}$ and for $\{z\}$, so that $p \leq glb\{x,y\}$ and $p \leq z$. Therefore p is a lower bound for $\{glb\{x,y\},z\}$, and so $p \leq glb\{glb\{x,y\},z\} = (x*y)*z$. Thus $(x*y)*z = glb\{x,y,z\}$. Similarly, $x*(y*z) = glb\{x,y,z\}$, so that $(x*y)*z = x*(y*z)$ and T is associative under $*$. Since T is a lower semilattice, then T is partially ordered, so that $x \leq x$ for each $x \in T$ and thus x is a lower bound for $\{x,x\}$. Also, if b is a lower bound for $\{x,x\}$, then $b \leq x$, so that $x = \text{glb}\{x,x\} = x*x$ and $(T,*)$ is idempotent. Finally, if $x,y \in T$, then $x*y = \text{glb}\{x,y\} = \text{glb}\{y,x\} = y*x$, and so $(T,*)$ is commutative. Thus $(T,*)$ is a semilattice.

<u>Definition 2.16</u>. An equivalence relation ρ on a semigroup S is a left congruence on S iff $(a,b) \in \rho$ implies $(ca,cb) \in \rho$ for all $a,b,c \in S$; ρ is a right congruence on S iff $(a,b) \in \rho$ implies $(ac,bc) \in \rho$ for all $a,b,c \in S$; ρ is a congruence on S iff ρ is both a left and a right congruence on S. A (left or right) congruence ρ on a semigroup S is proper iff ρ is proper as an equivalence relation.

<u>Lemma 2.17</u>. An equivalence relation ρ on a semigroup S is a congruence iff $(w,x) \in \rho$ and $(y,z) \in \rho$ imply $(wy,xz) \in \rho$.

<u>Proof</u>. If ρ is a congruence on S and $w,x,y,z \in S$ such that $(w,x) \in \rho$ and $(y,z) \in \rho$, then $(wy,xy) \in \rho$ since ρ is a right congruence and $(xy,xz) \in \rho$ since ρ is a left congruence. Therefore $(wy,xz) \in \rho$ since ρ is transitive. Conversely, if $(w,x) \in \rho$ and $(y,z) \in \rho$ imply $(wy,xz) \in \rho$, then let $(a,b) \in \rho$. For each $c \in S$, $(c,c) \in \rho$ since ρ is reflexive. Therefore $(ca,cb) \in \rho$ and $(ac,bc) \in \rho$, and so ρ is a congruence on S.

This lemma leads to the following concept of a quotient semigroup.

<u>Definition 2.18</u>. Let ρ be a congruence on a semigroup S, and let S/ρ be the collection of disjoint ρ-classes. Let *

be the binary relation on S/ρ defined by $(x_\rho)*(y_\rho) = (xy)_\rho$ for all $x_\rho, y_\rho \in S/\rho$. Then $(S/\rho, *)$ is the quotient semigroup of S relative to the congruence ρ.

Observe that if $x_\rho, y_\rho \in S/\rho$ then $(x_\rho)(y_\rho) = (xy)_\rho \in S/\rho$ since $xy \in S$, so that multiplication in S/ρ is closed. Furthermore, if $x_\rho, y_\rho, z_\rho \in S/\rho$, then $[(x_\rho)(y_\rho)](z_\rho) = (xy)_\rho(z_\rho) = [(xy)z]_\rho = [x(yz)]_\rho = (x_\rho)(yz)_\rho = (x_\rho)[(y_\rho)(z_\rho)]$, so that multiplication in S/ρ is associative. Thus S/ρ with the operation defined above is indeed a semigroup. In fact, the concept of quotient semigroup with respect to a congruence is a generalization of the notion of quotient group with respect to a normal subgroup. The following theorem expresses this fact.

Theorem 2.19. If N is a normal subgroup of a group G, then there exists a congruence ρ on G such that $G/\rho = G/N$. Conversely, if ρ is a congruence on a group G, then there exists a normal subgroup N of G such that $G/N = G/\rho$.

Proof. If N is a normal subgroup of G, then define the relation ρ on G by $(x,y) \in \rho$ iff $xN = yN$ for all $x,y \in G$. Since $xN = xN$ for each $x \in G$, then $(x,x) \in \rho$ and so ρ is reflexive. If $(x,y) \in \rho$, then $xN = yN$. Therefore $yN = xN$, so that $(y,x) \in \rho$ and ρ is symmetric. If $(x,y),(y,z) \in \rho$ then $xN = yN$ and $yN = zN$, so that $xN = zN$, $(x,z) \in \rho$, and ρ is transitive. Furthermore, if $(w,x) \in \rho$ and $(y,z) \in \rho$, then $wN = xN$ and $yN = zN$. Therefore $(wy)N = (wN)(yN) = (xN)(zN) = (xz)N$, so that $(wy,xz) \in \rho$ and ρ is a congruence on G. Thus G/ρ is the quotient semigroup whose elements are the disjoint ρ-classes. To verify that $G/\rho = G/N$, notice that the definition of ρ states that if $x,y \varepsilon G$, then x and y are in the same ρ-class iff x and y are in the same left coset of N. Indeed, if $a \varepsilon G$, then $a_\rho = \{x \varepsilon G | (x,a) \varepsilon \rho\} = \{x \varepsilon G | xN = aN\} = aN$, so that the ρ-classes and left cosets of N coincide. Therefore, if $a,b \varepsilon G$, then $a_\rho = aN$, $b_\rho = bN$, and $(ab)_\rho = (ab)N$, so that $(a_\rho)(b_\rho) = (ab)_\rho = (ab)N = (aN)(bN)$. Thus each ρ-class corresponds to an identical (set-wise) left coset, each left coset corresponds to an identical ρ-class, and the product of two ρ-classes is the same as the product of the corresponding left cosets, so that $G/\rho = G/N$. Conversely, if ρ is a congruence on a group G, then ρ partitions G into disjoint ρ-classes. Therefore, if 1 is the identity for G, then $1_\rho \neq \phi$ since $1 \varepsilon 1_\rho$. Also, if $x,y \varepsilon 1_\rho$, then $(x,1) \varepsilon \rho$ and $(y,1) \varepsilon \rho$, so that $(1,y) \varepsilon \rho$ by symmetry. Thus $(x,y) = (x \cdot 1, 1 \cdot y) = (x,1)(1,y) \varepsilon \rho$. However, since $(y^{-1}, y^{-1}) \varepsilon \rho$, then $(xy^{-1},1) = (xy^{-1},yy^{-1}) = (x,y)(y^{-1},y^{-1}) \varepsilon \rho$. Therefore $xy^{-1} \varepsilon 1_\rho$ and so 1_ρ is a subgroup of G. Now if $x \varepsilon G$ and $a \varepsilon 1_\rho$, then $a_\rho = 1_\rho$. Therefore $(xax^{-1})_\rho = x_\rho a_\rho x_\rho^{-1} = x_\rho 1_\rho x_\rho^{-1} = (x1x^{-1})_\rho = 1_\rho$, so that $xax^{-1} \varepsilon 1_\rho$ and 1_ρ is normal in G. For each $a \varepsilon G$, if $x \varepsilon a1_\rho$, then there exists $y \varepsilon 1_\rho$ such that $x = ay$. Therefore $x_\rho = (ay)_\rho = a_\rho y_\rho = a_\rho 1_\rho = (a1)_\rho = a_\rho$, so that $x \varepsilon a_\rho$ and $a1_\rho \subseteq a_\rho$. For each $x \varepsilon a_\rho$, $x_\rho = a_\rho = (a1)_\rho = a_\rho 1_\rho$, so that $(a^{-1}x)_\rho = a_\rho^{-1} x_\rho = a_\rho^{-1} (a_\rho 1_\rho) = (a_\rho^{-1} a_\rho) 1_\rho = (a^{-1}a)_\rho 1_\rho = 1_\rho 1_\rho = 1_\rho$. Therefore $a^{-1}x \varepsilon 1_\rho$, so that $x \varepsilon a1_\rho$ and $a_\rho \subseteq a1_\rho$.

Thus $a1_\rho = a_\rho$, and the left cosets of 1_ρ coincide with the ρ-classes. Furthermore, for each $a,b \in G$, since $(ab)1_\rho = (ab)_\rho$, then $(a1_\rho)(b1_\rho) = (ab)1_\rho = (ab)_\rho = (a_\rho)(b_\rho)$, so that the product of cosets in $G/1_\rho$ is identical (set-wise) to the product of the corresponding ρ-classes in G/ρ, and so $G/1_\rho = G/\rho$.

Before the next notion is introduced, it should be pointed out that the intersection of any collection of congruences on a semigroup S is also a congruence on S. This fact is stated in the following lemma.

Lemma 2.20. If $\{\rho_\alpha\}_{\alpha\in A}$ is a collection of congruences on a semigroup S, then $\bigcap_{\alpha\in A}\rho_\alpha$ is a congruence on S.

Proof. If $x \in S$ then $(x,x) \in \rho_\alpha$ for each $\alpha \in A$, so that $(x,x) \in \bigcap_{\alpha\in A}\rho_\alpha$ and $\bigcap_{\alpha\in A}\rho_\alpha$ is reflexive. If $(x,y) \in \bigcap_{\alpha\in A}\rho_\alpha$, then $(x,y) \in \rho_\alpha$ for each $\alpha \in A$. Therefore $(y,x) \in \rho_\alpha$ for each $\alpha \in A$, so that $(y,x) \in \bigcap_{\alpha\in A}\rho_\alpha$ and $\bigcap_{\alpha\in A}\rho_\alpha$ is symmetric. If $(x,y), (y,z) \in \bigcap_{\alpha\in A}\rho_\alpha$, then $(x,y) \in \rho_\alpha$ and $(y,z) \in \rho_\alpha$ for each $\alpha \in A$. Therefore $(x,z) \in \rho_\alpha$ for each $\alpha \in A$, so that $(x,z) \in \bigcap_{\alpha\in A}\rho_\alpha$, and $\bigcap_{\alpha\in A}\rho_\alpha$ is transitive. Finally, if $(w,x), (y,z) \in \bigcap_{\alpha\in A}\rho_\alpha$, then $(w,x) \in \rho_\alpha$ and $(y,z) \in \rho_\alpha$ for each $\alpha \in A$. Therefore $(wy,xz) \in \rho_\alpha$ for each $\alpha \in A$, so that $(wy,xz) \in \bigcap_{\alpha\in A}\rho_\alpha$ and $\bigcap_{\alpha\in A}\rho_\alpha$ is a congruence on S.

Definition 2.21. If ρ is a binary relation on a semigroup S, then the congruence on S generated by ρ is the intersection of all congruences on S containing ρ.

Definition 2.22. If S and T are semigroups, then a function f mapping S into T is a homomorphism of S into T iff $f(x)\cdot f(y) = f(xy)$ for each $x,y \in S$. A function $f:S \to T$ is an embedding of S into T iff f is a one-to-one homomorphism, and S is said to be embeddable in T. The semigroup T is a homomorphic image of S iff there exists a homomorphism of S onto T. A function $f:S \to T$ is an isomorphism of S onto T iff f is a one-to-one onto homomorphism, in which case S and T are said to be isomorphic, written $S \cong T$. A function $f:S \to S$ is an endomorphism iff f is a homomorphism, and $f:S \to S$ is an automorphism iff f is an isomorphism.

Notation: If f is a function from a set A into a set B, then the domain A of f will be denoted by D_f, and the range B of f will be denoted by R_f.

Lemma 2.23 (Fundamental Theorem of Semigroup Homomorphisms). If f is a homomorphism of a semigroup S into a semigroup T, then the relation ρ on S defined by $(a,b) \in \rho$ iff $f(a) = f(b)$ for all $a,b \in S$ is a congruence on S and $S/\rho \cong f(S)$. Conversely, if ρ is a congruence on a semigroup S, then the function $f:S \to S/\rho$ defined by $f(a) = a_\rho$ for each $a \in S$ is a homomorphism of S onto S/ρ.

Proof. Let f be a homomorphism from a semigroup S into a semigroup T. Define the relation ρ on S by $(a,b) \in \rho$ iff $f(a) = f(b)$ for all $a,b \in S$. Since $f(x) = f(x)$ for each $x \in S$, then $(x,x) \in \rho$ and ρ is reflexive. If $(x,y) \in \rho$ then $f(x) = f(y)$, so that $f(y) = f(x)$. Therefore $(y,x) \in \rho$ and ρ is symmetric. If $(x,y), (y,z) \in \rho$ then $f(x) = f(y)$ and $f(y) = f(z)$, so that $f(x) = f(z)$, $(x,z) \in \rho$, and ρ is transitive. If $(w,x), (y,z) \in \rho$ then $f(w) = f(x)$ and $f(y) = f(z)$, so that

$f(wy) = f(w)\cdot f(y) = f(x)\cdot f(z) = f(xz)$, and thus ρ is a congruence on S by lemma 2.17. Now define $g: S/\rho \rightarrow f(S)$ by $g(a_\rho) = f(a)$ for all $a_\rho \in S/\rho$. If $(x,y) \in g$ then $x \in S/\rho$, and so there exists $a \in S$ such that $x = a_\rho$. Therefore $y = g(x) = g(a_\rho) = f(a) \in f(S)$, and so $g \subseteq S/\rho \times f(S)$. If $a,b \in S$ such that $a_\rho = b_\rho$, then $(a,b) \in \rho$, so that $f(a) = f(b)$. Thus $g(a_\rho) = g(b_\rho)$, and so g is a well-defined function. If $a,b \in S$ such that $g(a_\rho) = g(b_\rho)$, then $f(a) = f(b)$. Therefore $(a,b) \in \rho$, so that $a_\rho = b_\rho$ and g is one-to-one. If $x \in f(S)$ then there exists $a \in S$ such that $x = f(a)$. Since $a \in S$, then $a_\rho \in S/\rho$, so that $g(a_\rho) = f(a) = x$, and so g is onto. Finally, if $a_\rho, b_\rho \in S/\rho$, then $g(a_\rho b_\rho) = g[(ab)_\rho] = f(ab) = f(a)\cdot f(b) = g(a_\rho)\cdot g(b_\rho)$, so that g is a homomorphism. Thus $g: S/\rho \rightarrow f(S)$ is an isomorphism and $S/\rho \cong f(S)$.

Conversely, if ρ is a congruence on a semigroup S, then define $f: S \rightarrow S/\rho$ by $f(a) = a_\rho$ for all $a \in S$. If $(x,y) \in f$, then $x \in S$, so that $y = f(x) = x_\rho \in S/\rho$ and $f \subseteq S \times S/\rho$. If $a,b \in S$ such that $a = b$, then $(a,b) \in \rho$ since ρ is reflexive. Therefore $a_\rho = b_\rho$, so that $f(a) = f(b)$, and thus f is a well-defined function. If $y \in S/\rho$, then there exists $x \in S$ such that $y = x_\rho$. Since $x \in S$, then $f(x) = x_\rho = y$, and so f is onto. Finally, if $a,b \in S$, then $f(ab) = (ab)_\rho = (a_\rho)\cdot(b_\rho) = f(a)\cdot f(b)$, so that f is a homomorphism.

Definition 2.24. If f is a homomorphism of a semigroup S into a semigroup T, then the congruence ρ on S defined by

$(a,b) \varepsilon \rho$ iff $f(a) = f(b)$ for all $a,b \varepsilon S$ is called the congruence on S induced by f.

Definition 2.25. If ρ is a congruence on a semigroup S, then the homomorphism $f:S \to S/\rho$ of S onto S/ρ defined by $f(a) = a_\rho$ for all $a \varepsilon S$ is called the natural homomorphism of S onto S/ρ.

Lemma 2.26. Let ρ be a congruence on a semigroup S. For each congruence α on S containing ρ, define a binary relation α' on S/ρ by $(x_\rho, y_\rho) \varepsilon \alpha'$ iff $(x,y) \varepsilon \alpha$ for all $x,y \varepsilon S$. Then the mapping f defined by $f(\alpha) = \alpha'$ is a one-to-one, order preserving mapping of the set of all congruences on S containing ρ onto the set of all congruences on S/ρ.

Proof. Let ρ be a congruence on a semigroup S. Define $A = \{\alpha | \alpha$ is a congruence on S and $\rho \subseteq \alpha\}$. For each $\alpha \varepsilon A$, define α' on S/ρ by $(x_\rho, y_\rho) \varepsilon \alpha'$ iff $(x,y) \varepsilon \alpha$. Define $B = \{\alpha' | \alpha \varepsilon A\}$, and define the mapping $f:A \to B$ by $f(\alpha) = \alpha'$ for all $\alpha \varepsilon A$. Define $P = \{\delta | \delta$ is a congruence on $S/\rho\}$. The first objective will be to show that the set B of all images of elements of A under f is actually the same as P.

Part I: If $\alpha' \varepsilon B$ then there exists $\alpha \varepsilon A$ such that $\alpha' = f(\alpha)$. Now if $x_\rho \varepsilon S/\rho$ then $x \varepsilon S$, so that $(x,x) \varepsilon \alpha$. Therefore $(x_\rho, x_\rho) \varepsilon \alpha'$ and so α' is reflexive. If $x_\rho, y_\rho \varepsilon S/\rho$ such that $(x_\rho, y_\rho) \varepsilon \alpha'$, then $(x,y) \varepsilon \alpha$. Thus $(y,x) \varepsilon \alpha$, so that $(y_\rho, x_\rho) \varepsilon \alpha'$ and α' is symmetric. If $x_\rho, y_\rho, z_\rho \varepsilon S/\rho$ such that $(x_\rho, y_\rho) \varepsilon \alpha'$ and $(y_\rho, z_\rho) \varepsilon \alpha'$, then $(x,y) \varepsilon \alpha$ and $(y,z) \varepsilon \alpha$. Therefore $(x,z) \varepsilon \alpha$, so that $(x_\rho, z_\rho) \varepsilon \alpha'$ and α' is transitive. Finally, if $w_\rho, x_\rho, y_\rho, z_\rho \varepsilon S/\rho$ such that

$(w_\rho, x_\rho) \varepsilon \alpha'$ and $(y_\rho, z_\rho) \varepsilon \alpha'$, then $(w,x) \varepsilon \alpha$ and $(y,z) \varepsilon \alpha$. Therefore $(wy,xz) \varepsilon \alpha$, so that

$$(w_\rho y_\rho, x_\rho z_\rho) = ((wy)_\rho, (xz)_\rho) \varepsilon \alpha'.$$

Thus α' is a congruence on S/ρ, so that $\alpha' \varepsilon P$ and $B \subseteq P$. Conversely, if $\delta \varepsilon P$, then δ is a congruence on S/ρ. Define λ on S by $(x,y) \varepsilon \lambda$ iff $(x_\rho, y_\rho) \varepsilon \delta$ for all $x,y \varepsilon S$. If $x \varepsilon S$ then $x_\rho \varepsilon S/\rho$. Therefore $(x_\rho, x_\rho) \varepsilon \delta$, so that $(x,x) \varepsilon \lambda$ and λ is reflexive. If $(x,y) \varepsilon \lambda$ then $(x_\rho, y_\rho) \varepsilon \delta$. Thus $(y_\rho, x_\rho) \varepsilon \delta$, so that $(y,x) \varepsilon \lambda$ and λ is symmetric. If (x,y), $(y,z) \varepsilon \lambda$, then $(x_\rho, y_\rho) \varepsilon \delta$ and $(y_\rho, z_\rho) \varepsilon \delta$. Therefore $(x_\rho, z_\rho) \varepsilon \delta$, so that $(x,z) \varepsilon \lambda$ and λ is transitive. Furthermore, if (w,x), $(y,z) \varepsilon \lambda$, then $(w_\rho, x_\rho) \varepsilon \delta$ and $(y_\rho, z_\rho) \varepsilon \delta$. Therefore $((wy)_\rho, (xz)_\rho) = (w_\rho y_\rho, x_\rho z_\rho) \varepsilon \delta$, so that $(wy, xz) \varepsilon \lambda$ and λ is a congruence on S. Finally, if $x,y \varepsilon S$ such that $(x,y) \varepsilon \rho$, then $x_\rho = y_\rho$. Thus $(x_\rho, y_\rho) = (x_\rho, x_\rho) \varepsilon \delta$, so that $(x,y) \varepsilon \lambda$ and $\rho \subseteq \lambda$. Therefore λ is a congruence on S containing ρ, and so there exists $\alpha \varepsilon A$ such that $\lambda = \alpha$. Since $(x_\rho, y_\rho) \varepsilon \delta$ iff $(x,y) \varepsilon \lambda = \alpha$, then $\delta = \alpha' \varepsilon B$, so that $P \subseteq B$. This concludes that $B = P = \{\delta | \delta \text{ is a congruence on } S/\rho\}$.

Part II: Now if $(x,y) \varepsilon f$, then $x \varepsilon A$. Therefore $f(x) = x' \varepsilon B$, so that $f \subseteq A \times B$. If $\alpha_1, \alpha_2 \varepsilon A$ such that $\alpha_1 = \alpha_2$, then $(a_\rho, b_\rho) \varepsilon \alpha_1'$ iff $(a,b) \varepsilon \alpha_1 = \alpha_2$ iff $(a_\rho, b_\rho) \varepsilon \alpha_2'$. Therefore $\alpha_1' = \alpha_2'$, so that $f(\alpha_1) = f(\alpha_2)$ and f is a well-defined function. If $\alpha_1, \alpha_2 \varepsilon A$ such that $f(\alpha_1) = f(\alpha_2)$, then $\alpha_1' = \alpha_2'$. Thus $(a,b) \varepsilon \alpha_1$ iff $(a_\rho, b_\rho) \varepsilon \alpha_1' = \alpha_2'$ iff $(a,b) \varepsilon \alpha_2$, so that $\alpha_1 = \alpha_2$ and f is one-to-one. If $\alpha' \varepsilon B$, then by definition of B there exists $\alpha \varepsilon A$ such that $f(\alpha) = \alpha'$, so that f is onto. Finally, suppose $\alpha_1, \alpha_2 \varepsilon A$ such that $\alpha_1 \subseteq \alpha_2$. If $(a_\rho, b_\rho) \varepsilon f(\alpha_1) = \alpha_1'$, then $(a,b) \varepsilon \alpha_1 \subseteq \alpha_2$, so that $(a_\rho, b_\rho) \varepsilon \alpha_2' = f(\alpha_2)$ and f preserves the order of A and B relative to set containment.

<u>Definition 2.27</u>. If A is a set, then the function i_A on A defined by $i_A(x) = x$ for all $x \varepsilon A$ is the identity function on A.

<u>Definition 2.28</u>. If f is a function and $\phi \neq A \subseteq D_f$, then $f|A = \{(x,y) \varepsilon f | x \varepsilon A\}$. Thus $f|A$ is a function from the subset A of D_f into R_f so that $f|A(x) = f(x)$ for each $x \varepsilon D_{f|A} = A \subseteq D_f$.

<u>Definition 2.29</u>. If A is a set, then 2^A, called the power set of A, will denote the collection of all subsets of A.

<u>Definition 2.30</u>. A transformation on a set A is a function $f: A \to A$ from A into A.

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CHAPTER III

SUMMARY OF GENERAL PROPERTIES, EXAMPLES, AND THE EMBEDDING THEOREM

Example 3.1. The set $\tau(A)$ of all transformations on a nonempty set A under the operation $\circ$ of composition of functions is a semigroup.

Proof. If A is nonempty, then the identity mapping $i_A : A \to A$ is an element of $\tau(A)$, and so $\tau(A)$ is nonempty. Furthermore, if $f,g,h \in \tau(A)$, then $f:A \to A$ and $g:A \to A$. Therefore $f \circ g : A \to A$, so that $f \circ g \in \tau(A)$. Finally, for each $x \in A$, $[f \circ (g \circ h)](x) = f[(g \circ h)(x)] = f[g(h(x))] = (f \circ g)[h(x)] = [(f \circ g) \circ h](x)$, so that $f \circ (g \circ h) = (f \circ g) \circ h$. Therefore $\tau(A)$ is associative under composition of functions and is thus a semigroup.

Example 3.2. Under the operation $\circ$ of composition of functions, the collection K(A) of all constant transformations in $\tau(A)$ is a left zero subsemigroup of $\tau(A)$, where $A \neq \phi$.

Proof. Since $A \neq \phi$, then there exists $p \in A$. Therefore the function $f:A \to A$ defined by $f(x) = p$ for all $x \in A$ is an element of K(A), so that $K(A) \neq \phi$. Furthermore, if $f,g \in K(A)$, then there exists $p,q \in A$ such that $f(x) = p$ and $g(x) = q$ for all $x \in A$. Therefore, $f \circ g(x) = f[g(x)] = f(q) = p = f(x)$ for all $x \in A$, so that $f \circ g = f \in K(a)$. Associativity in K(A) is inherited from $\tau(A)$. Since it is obvious that $K(A) \subseteq \tau(A)$, then $K(A)$ is a subsemigroup of $\tau(A)$. However, since it has already been shown that $f \circ g = f$ for each $f, g \in K(A)$, then $K(A)$ is a left zero subsemigroup of $\tau(A)$.

Example 3.3. If $A \neq \phi$, then $K(A)$ is an ideal of $\tau(A)$.

Proof. If $f \in K(A)$ and $g \in \tau(A)$, then there exists $p \in A$ such that $f(x) = p$ for all $x \in A$. However, since $p \in A$, then there exists $q \in A$ such that $g(p) = q$. Therefore, for all $x \in A$, $(f \circ g)(x) = f[g(x)] = p$ since $g(x) \in A$, and so $f \circ g \in K(A)$. Also, for all $x \in A$, $(g \circ f)(x) = g[f(x)] = g(p) = q$, and so $g \circ f \in K(A)$. Thus $K(A)$ is an ideal in $\tau(A)$.

Lemma 3.4. Let $M, N \in Z^+$, and let A be a set such that $|A| = N$; then $B = \{f \in \tau(A) \mid |f(A)| \leq M\}$ is an ideal of $\tau(A)$.

Proof. If $f \in B$ and $g \in \tau(A)$, then there exists $M \leq N$, such that $|f(A)| = M$. Therefore, there exists $\{a_i\}_{i=1}^{M} \subseteq A$ such that for all $x \in A$, $f(x) \in \{a_i\}_{i=1}^{M}$. If $x \in A$, then $(f \circ g)(x) = f[g(x)] \in \{a_i\}_{i=1}^{M}$ since $g(x) \in A$. Therefore $|(f \circ g)(A)| \leq M \leq N$, so that $f \circ g \in B$. Furthermore, if $x \in A$, then $(g \circ f)(x) = g[f(x)] = g(a_i)$ for some i, $i \leq i \leq M$. Therefore, $(g \circ f)(x) \in \{g(a_i)\}_{i=1}^{M}$ for all $x \in A$, so that $|(g \circ f)(A)| \leq M \leq N$ and $g \circ f \in B$. Finally, since $|A| = N > 0$, then there exists $p \in A$. Therefore, the function $f: A \to A$ defined by $f(x) = p$ for all $x \in A$ is an element of B, since $|f(A)| = 1$ and $N \in Z^+$ imply $|f(A)| \leq N$. Thus $B \neq \phi$, and so B is an ideal of $\tau(A)$.

<u>Theorem 3.5</u>. If $\tau(A)$ is the semigroup of transformations on a nonempty set A and $\alpha \in \tau(A)$, then $\alpha\tau(A) = \tau(A)$ iff $\tau(A)\alpha = \tau(A)$ iff $\alpha : A \to A$ is onto.

<u>Proof</u>. If $\alpha \in \tau(A)$ such that $\alpha : A \to A$ is onto and $\beta \in \tau(A)$, then for each $y \in \beta(A)$ there exists a unique $x_y \in A$ such that $\alpha(x_y) = y$. Let $\Gamma \in \tau(A)$ such that $\Gamma(x) = x_{\beta(x)}$ for each $x \in A$. Therefore, for all $x \in A$, $\alpha \circ \Gamma(x) = \alpha[\Gamma(x)] = \alpha[x_{\beta(x)}] = \beta(x)$, so that $\beta = \alpha \circ \Gamma \in \alpha\tau(A)$ and $\tau(A) \subseteq \alpha\tau(A)$. Since $\alpha\tau(A) \subseteq \tau(A)$ as well, then $\alpha\tau(A) = \tau(A)$.

If $\alpha \in \tau(A)$ such that $\alpha\tau(A) = \tau(A)$, then there exists $\Gamma \in \tau(A)$ such that $\alpha \circ \Gamma = i_A$. Therefore, for each $y \in A$ there exists $\Gamma(y) \in A$ such that $\alpha[\Gamma(y)] = \alpha \circ \Gamma(y) = i_A(y) = y$, and so $\alpha : A \to A$ is onto.

If $\alpha \in \tau(A)$ such that $\alpha : A \to A$ is onto and $\beta \in \tau(A)$, then for each $y \in A$ there exists a unique $x_y \in A$ such that $\alpha(x_y) = y$, so that $x_y = \alpha^{-1}(y)$. Let $\Gamma \in \tau(A)$ such that $\Gamma(y) = \beta[\alpha^{-1}(y)]$ for each $y \in A$. Notice that since $\alpha : A \to A$ is onto, then α is one-to-one, so that $\alpha^{-1}(y)$ is unique and Γ is indeed a function on A. Therefore, for all $x \in A$, $\Gamma \circ \alpha(x) = \Gamma[\alpha(x)] = \beta(\alpha^{-1}[\alpha(x)]) = \beta(x)$, so that $\beta = \Gamma \circ \alpha \in \tau(A)\alpha$. Thus $\tau(A) \subseteq \tau(A)\alpha$, and so $\tau(A)\alpha = \tau(A)$.

Finally, if $\alpha \in \tau(A)$ such that $\tau(A)\alpha = \tau(A)$, then there exists $\Gamma \in \tau(A)$ such that $\Gamma \circ \alpha = i_A$, which is one-to-one. Therefore Γ is one-to-one as well. Now if $y \in A$, then $x = \Gamma(y) \in A$. Thus $\Gamma[\alpha(x)] = \Gamma \circ \alpha(x) = i_A(x) = x = \Gamma(y)$, so that $\alpha(x) = y$ and $\alpha : A \to A$ is onto.

<u>Theorem 3.6</u>. If A is a nonempty set, then:

(1) $E_{\tau(A)} = \{\alpha \in \tau(A) \mid x \in \alpha^{-1}(x)$ or $\alpha^{-1}(x) = \phi$ for all $x \in A\}$,

(2) if $\alpha \in E_{\tau(A)}$, then $G_{\alpha} = \{f \in \tau(A) \mid f$ is regular and $\alpha = f \circ f^{-1} = f^{-1} \circ f\}$,

(3) if $\alpha, \beta \in E_{\tau(A)}$, then $\alpha \leq \beta$ iff $\alpha(A) \subseteq \beta(A)$ and $\beta^{-1}(x) \subseteq \alpha^{-1} \circ \alpha(x)$ for all $x \in A$,

(4) if $\alpha \in \tau(A)$, then α is a left zero of $\tau(A)$ iff α is a constant function,

(5) $\tau(A)$ has no right zeros,

(6) the kernel of $\tau(A)$ is the collection of all constant functions, or left zeros, of $\tau(A)$, and

(7) $\tau(A)$ is regular.

<u>Proof</u>. Part I: Let $\alpha \in \tau(A)$ such that for each $x \in A$, either $x \in \alpha^{-1}(x)$ or $\alpha^{-1}(x) = \phi$. If $x \in A$, then $y = \alpha(x) \in A$, so that $x \in \alpha^{-1}(y)$. Since $\alpha^{-1}(y) \neq \phi$, then $y \in \alpha^{-1}(y)$, and so $\alpha(y) = y$. Therefore $\alpha \circ \alpha(x) = \alpha[\alpha(x)] = \alpha(y) = y = \alpha(x)$, for each $x \in A$, so that $\alpha \circ \alpha = \alpha$ and α is idempotent.

Conversely, if α is an idempotent of $\tau(A)$, then $\alpha \circ \alpha = \alpha$. If $x \in A$ such that $\alpha^{-1}(x) \neq \phi$, then there exists $y \in \alpha^{-1}(x)$, so that $\alpha(y) = x$. Therefore $\alpha(x) = \alpha[\alpha(y)] = \alpha \circ \alpha(y) = \alpha(y) = x$, and so $x \in \alpha^{-1}(x)$. Thus α is idempotent in $\tau(A)$ iff either $x \in \alpha^{-1}(x)$ or $\alpha^{-1}(x) = \phi$ for all $x \in A$, so that $E_{\tau(A)} = \{\alpha \in \tau(A) \mid x \in \alpha^{-1}(x)$ or $\alpha^{-1}(x) = \phi$ for all $x \in A\}$.

Part II: Furthermore, if $\alpha \in E_{\tau(A)}$, then the corresponding maximal subgroup of $\tau(A)$ is

$G_\alpha = \{f \varepsilon \tau(A) | f = \alpha \circ f = f \circ \alpha,\ \alpha = f \circ g = g \circ f$ for some $g \varepsilon \tau(A)\} = \{f \varepsilon \tau(A) | f = f \circ \alpha = f \circ (g \circ f) = f \circ g \circ f$ for some $g \varepsilon \tau(A)$, and $\alpha = f \circ g = g \circ f\}$.

However, if $f, g \varepsilon \tau(A)$ such that $f = f \circ g \circ f$, then f is regular and the inverse for f is $f^{-1} = g \circ f \circ g$ by theorem 1.35. Therefore $f \circ f^{-1} = f \circ (g \circ f \circ g) = (f \circ g) \circ (f \circ g) = \alpha \circ \alpha = \alpha$, and $f^{-1} \circ f = (g \circ f \circ g) \circ f = (g \circ f) \circ (g \circ f) = \alpha \circ \alpha = \alpha$, so that $G_\alpha = \{f \varepsilon \tau(A) | f$ is regular and $\alpha = f \circ f^{-1} = f^{-1} \circ f\}$.

Part III: By lemma 2.14, the partial order $\leq$ for $E_{\tau(A)}$ is defined by $\alpha \leq \beta$ iff $\alpha = \alpha \circ \beta = \beta \circ \alpha$ for all $\alpha, \beta \varepsilon E_{\tau(A)}$. If $\alpha = \beta \circ \alpha$, then for each $x \varepsilon A$, $\alpha(x) = \beta \circ \alpha(x) = \beta[\alpha(x)] \varepsilon \beta(A)$, so that $\alpha(A) \subseteq \beta(A)$.

Conversely, if $\alpha(A) \subseteq \beta(A)$, then $\alpha(x) \varepsilon \beta(A)$ for each $x \varepsilon A$, so that there exists $p \varepsilon A$ such that $\beta(p) = \alpha(x)$. Therefore $\beta \circ \alpha(x) = \beta[\alpha(x)] = \beta[\beta(p)] = \beta \circ \beta(p) = \beta(p) = \alpha(x)$ for each $x \varepsilon A$, so that $\beta \circ \alpha = \alpha$.

Now if $\alpha = \alpha \circ \beta$, then let $x \varepsilon A$ and let $a \varepsilon \beta^{-1}(x)$ if $\beta^{-1}(x) \neq \phi$, so that $\beta(a) = x$. Therefore $\alpha(a) = \alpha \circ \beta(a) = \alpha[\beta(a)] = \alpha(x)$, so that $a \varepsilon \alpha^{-1}[\alpha(x)]$ and thus $\beta^{-1}(x) \subseteq \alpha^{-1} \circ \alpha(x)$. Also, if $\beta^{-1}(x) = \phi$, then $\beta^{-1}(x) \subseteq \alpha^{-1} \circ \alpha(x)$.

Conversely, if $\beta^{-1}(x) \subseteq \alpha^{-1} \circ \alpha(x)$ for each $x \varepsilon A$, then $x \varepsilon \beta^{-1}[\beta(x)] \subseteq \alpha^{-1} \circ \alpha[\beta(x)]$. Therefore $\alpha(x) = \alpha \circ \alpha^{-1} \circ \alpha[\beta(x)] = \alpha[\beta(x)] = \alpha \circ \beta(x)$ for each $x \varepsilon A$, so that $\alpha = \alpha \circ \beta$. Thus for each $\alpha, \beta \varepsilon E_{\tau(A)}$, $\alpha \leq \beta$ iff $\alpha = \alpha \circ \beta = \beta \circ \alpha$ iff $\beta^{-1}(x) \subseteq \alpha^{-1} \circ \alpha(x)$ for all $x \varepsilon A$ and $\alpha(A) \subseteq \beta(A)$.

Part IV: If α is a constant function in $\tau(A)$, then there exists $k \in A$ such that $\alpha(x) = k$ for all $x \in A$. Therefore, if $\beta \in \tau(A)$ then $\beta(x) \in A$ for all $x \in A$, so that $\alpha \circ \beta(x) = \alpha[\beta(x)] = k = \alpha(x)$. Thus $\alpha \circ \beta = \alpha$ for each $\beta \in \tau(A)$, so that α is a left zero of $\tau(A)$.

Conversely, if $\alpha \in \tau(A)$ is not a constant function, then there exists $a,b,x,y \in A$ such that $a \neq b$, $x \neq y$, $\alpha(a) = x$, and $\alpha(b) = y$. If $\beta \in \tau(A)$ such that $\beta(a) = b$, then $\alpha \circ \beta(a) = \alpha[\beta(a)] = \alpha(b) = y \neq x = \alpha(a)$. Therefore $\alpha \circ \beta \neq \alpha$, so that α is not a left zero of $\tau(A)$.

Part V: If $|A| > 1$, then let $\alpha \in \tau(A)$ and let $a \in A$, so that $b = \alpha(a) \in A$. Since $|A| > 1$, then there exists $c \in A$ such that $c \neq b$. Define $\beta \in \tau(A)$ such that $\beta(x) = c$ for all $x \in A$. Therefore $\beta \circ \alpha(a) = \beta[\alpha(a)] = \beta(b) = c \neq b = \alpha(a)$, so that $\beta \circ \alpha \neq \alpha$. Thus no element $\alpha \in \tau(A)$ is a right zero of $\tau(A)$.

Part VI: Lemma 3.4 established that $\{\alpha \in \tau(A) \,|\, |\alpha(A)| \leq n$ for some $n \in Z^+\}$ is a collection of ideals in $\tau(A)$. Define $J_n = \{\alpha \in \tau(A) \,|\, |\alpha(A)| \leq n\}$ for each $n \in Z^+$. Therefore, if $K = \bigcap\{G \,|\, G$ is an ideal of $\tau(A)\}$ is the kernel of $\tau(A)$, then $K \subseteq \bigcap_{n=1}^{\infty} J_n \subseteq J_1$. Now if G is an ideal of $\tau(A)$ and $\alpha \in J_1$, then α is a constant function, and so there exists $p \in A$ such that $\alpha(x) = p$ for all $x \in A$. Therefore, if $\beta \in G$, then $\alpha \circ \beta \in G$ since G is an ideal. However, since $\beta(x) \in A$ for each $x \in A$, then $\alpha \circ \beta(x) = \alpha[\beta(x)] = p = \alpha(x)$, so that $\alpha = \alpha \circ \beta \in G$. Thus if $\alpha \in J_1$, then $\alpha \in G$, so that $J_1 \subseteq G$. Since $J_1 \subseteq G$ for each ideal G of $\tau(A)$, then $J_1 \subseteq \bigcap\{G | G$ is an ideal of $\tau(A)\} = K$. Therefore $K \subseteq J_1 \subseteq K$, so that $K = J_1$. Thus the kernel K of $\tau(A)$ is the collection of all constant functions, or left zeros, of $\tau(A)$.

Part VII: If $f \in \tau(A)$, then for each $y \in f(A)$, $f^{-1}(y) \neq \phi$, and so there exists $a_y \in f^{-1}(y)$. Define

$$g \in \tau(A) \text{ by } g(y) = \begin{cases} a_y & \text{if } y \in f(A) \\ y & \text{if } y \notin f(A) \text{ for each } y \in A. \end{cases}$$

Therefore, for all $x \in A$, $f \circ g \circ f(x) = f(g[f(x)]) = f(a_{f(x)})$ (since $f(x) \in f(A)$) $= f(x)$ (since $a_{f(x)} \in f^{-1}[f(x)]$), so that $f = f \circ g \circ f$. Thus f is regular for each $f \in \tau(A)$, and so $\tau(A)$ is regular.

Theorem 3.7. Every infinite cyclic semigroup is isomorphic to the semigroup of positive integers under addition.

Proof. Let S be an infinite cyclic semigroup with generator $a \in S$. Therefore, for each $x \in S$, there exists $n \in Z^+$ such that $a^n = x$. Define $f: Z^+ \to S$ by $f(n) = a^n$ for all $n \in Z^+$. If $(p,q) \in f$, then $p \in Z^+$, so that $q = f(p) = a^p \in S$ and $f \subseteq Z^+ \times S$. If $m,n \in Z^+$ such that $m = n$, then $a^m = a^n$, so that $f(m) = f(n)$ and f is well defined. If $m,n \in Z^+$ such that $f(m) = f(n)$, then $a^m = a^n$. Assuming that $m \neq n$, then either $m > n$ or $m < n$. If $m > n$, then consider $\{a^i\}_{i=1}^m \subseteq S$. Since $a \in S$ is a generator for S, then $S = \{a^i\}_{i=1}^m \cup \{a^{m+k}\}_{k=1}^{\infty}$. If $k = 1$, then $a^{m+k} = a^{m+1} = a^m \cdot a^1 = a^n \cdot a^1 = a^{n+1}$. Since $n \leqslant m$, then $n + 1 \leq m$, so that $a^{m+k} = a^{m+1} = a^{n+1} \in \{a^i\}_{i=1}^m$ for $k = 1$. Now assume that for $k - 1 \in Z^+$, $a^{m+k-1} \in \{a^i\}_{i=1}^m$.

Therefore, there exists $p \in Z^+$, $1 \leq p \leq m$, such that $a^{m+k-1} = a^p$. Thus $a^{m+k} = a^{m+k-1+1} = a^{m+k-1} \cdot a^1 = a^p \cdot a^1 = a^{p+1}$. Since $1 \leq p \leq m$, then $2 \leq p + 1 \leq m + 1$. If $2 \leq p + 1 \leq m$, then $a^{m+k} = a^{p+1} \in \{a^i\}_{i=1}^m$. If $p + 1 = m + 1$, then by previous results, $a^{m+k} = a^{p+1} = a^{m+1} \in \{a^i\}_{i=1}^m$. Therefore, by mathematical induction, for each $k \in Z^+$, $a^{m+k} \in \{a^i\}_{i=1}^m$, so that $\{a^{m+k}\}_{k=1}^\infty \subseteq \{a^i\}_{i=1}^m$. Thus $S = \{a^i\}_{i=1}^m$, and so S is finite. Similarly, if $m < n$, then S is finite. Therefore, by contradiction, if $f(m) = f(n)$, then $m = n$ for all $m,n \in Z^+$, so that f is one-to-one. If $x \in S$, then there exists $n \in Z^+$ such that $a^n = x$. Therefore $f(n) = a^n = x$, and so f is onto. Finally, if $m,n \in Z^+$, then $f(m+n) = a^{m+n} = a^m \cdot a^n = f(m) \cdot f(n)$, so that f is a homomorphism. Thus $f: Z^+ \to S$ is an isomorphism and $S \cong Z^+$.

Example 3.8. The property of cyclic is not hereditary to subsemigroups of a cyclic semigroup.

Proof. The semigroup $(Z^+,+)$ of positive integers under addition is cyclic with generator 1. Now $K = Z^+ \setminus \{1\} \subseteq Z^+$ and if $m,n \in K$, then $m > 1$ and $n > 1$. Therefore $m + n > m > 1$, so that $m + n \in Z^+ \setminus \{1\} = K$ and K is a subsemigroup of Z^+. However, K is not cyclic since 2 generates only even positive integers and no integer that exceeds 2 can generate 2.

Theorem 3.9. If S is an infinite cyclic semigroup with generator $a \in S$, and $f_k: S \to S$ is the function defined by $f_k(a^n) = a^{kn}$ for all $n \in Z^+$, then $\{f_k\}_{k \in Z^+}$ is the semigroup of endomorphisms on S and is thus a subsemigroup of $\tau(S)$.

Proof. Since S is generated by $a \in S$, then for each $x \in S$, there exists $n \in Z^+$ such that $x = a^n$. If $f: S \to S$ is a function, then there exists $k \in Z^+$ such that $f(a) = a^k$. Therefore, if f is also a homomorphism, then for each $n \in Z^+$, $f(a^n) = [f(a)]^n = [a^k]^n = a^{kn}$, so that $f = f_k$. Since f_k is an endomorphism on S for all $k \in Z^+$, then $\{f_k\}_{k \in Z^+}$ is the semigroup of all endomorphisms on S.

Theorem 3.10. Every finite semigroup is periodic.

Proof. If S is a finite semigroup and $x \in S$, then the order of x is the order of the cyclic subsemigroup of S generated by x, namely $\{x^n | n \in Z^+\}$. Therefore, since $\{x^n | n \in Z^+\} \subseteq S$, then $|<x>| = |\{x^n | n \in Z^+\}| \leq |S|$, which is finite. Thus x is of finite order, and so S is periodic.

The following example shows that the converse of this theorem is false.

Example 3.11. Let S be the set of non-negative integers and define multiplication on S by

$$x \cdot y = \begin{cases} x \text{ if } x = y \\ 0 \text{ if } x \neq y. \end{cases}$$

Then S is periodic since $|<x>| = 1$ for all $x \in S$, but S is not finite.

Theorem 3.12. A semigroup S is a group iff S is both left and right simple.

Proof. If S is a group with identity e and P is a left ideal in S, then $P \neq \phi$ so that there exists $a \in P$. Therefore, for all $x \in S$, $x = xe = x(a^{-1}a) = (xa^{-1})a \in P$, so that $P = S$.

Similarly, if Q is a right ideal in S, then $Q \neq \phi$ so that there exists $b \in Q$. Therefore, for all $x \in S$, $x = ex = (bb^{-1})x = b(b^{-1}x) \in Q$, so that $Q = S$. Thus S is the only left or right ideal in S, and so S is both left and right simple. Conversely, suppose S is both left simple and right simple, and let $a \in S$. If $p \in Sa$ and $q \in S$, then $p = ka$ for some $k \in S$. Therefore $qp = q(ka) = (qk)a \in Sa$ since $qk \in S$, so that Sa is a left ideal in S. Since S is left simple, then $Sa = S$. Similarly, $aS = S$ for each $a \in S$ since S is right simple. Therefore, if $a \in S = aS$, then there exists $e \in S$ such that $a = ae$. But since $e \in S = Sa$, then there exists $y \in S$ such that $e = ya$. Furthermore, since $e \in S = eS$, then there exists $z \in S$ such that $e = ez$. Therefore $ee = (ya)(ez) = [y(ae)]z = (ya)z = ez = e$, so that e is idempotent in S. By proposition 1.29, e is the identity for the subgroup G_e of S defined by $G_e = \{a \in S \mid a \in eS \cap Se,\ e \in aS \cap Sa\}$. Since $aS = Sa = S$ and $eS = Se = S$, then $G_e = \{a \in S \mid a \in S \cap S, e \in S \cap S\} = \{a \in S \mid a \in S,\ e \in S\} = S$, and so S is the group G_e.

However, if S is a semigroup which is left simple or right simple, but not both, then S will not be a group.

<u>Example 3.13</u>. Let S be a left zero semigroup such that $|S| > 1$, and let P be a left ideal in S. If $x \in S$, $y \in P$, then $x = xy \in P$, so that $S \subseteq P$. Therefore $P = S$, and so S is left simple. If there exists an identity element $e \in S$, then there also exists $k \in S$ such that $k \neq e$ since $|S| > 1$. Therefore $e \cdot k = e \neq k$ since S is a left zero semigroup, so that e is

not a left identity of k. This is a contradiction since e is the identity for S. Therefore S contains no identity element and thus cannot be a group.

Example 3.14. If $(F,+,\cdot)$ is a field, then $(F,\cdot)$ is a zero simple semigroup.

Proof. If $(F,+,\ )$ is a field, then $(F,\cdot)$ is a semigroup with zero 0, the identity for +. Therefore, there exists $1 \varepsilon F$ such that $x \cdot 1 = 1 \cdot x = x$ for all $x \varepsilon F$, and if $x \varepsilon F\setminus\{0\}$, then there exists $x^{-1} \varepsilon F$ such that $x \cdot x^{-1} = x^{-1} \cdot x = 1$. If J is a nonzero ideal in $(F,\cdot)$, then there exists $p \varepsilon J$ such that $p \neq 0$. Therefore there exists $p^{-1} \varepsilon F$ such that $p \cdot p^{-1} = p^{-1} \cdot p = 1$. If $x \varepsilon F$, then $x = x \cdot 1 = x \cdot (p^{-1} \cdot p) = (x \cdot p^{-1}) \cdot p \ \varepsilon J$ since $p \varepsilon J$ and J is an ideal in F, so that $F \subseteq J$. Therefore $J = F$, and so $(F,\cdot)$ is zero simple.

The next two theorems will characterize specific types of ideals in semigroups. Theorem 3.15 uses the notation S^1 for a semigroup S with adjoined identity 1 in order to generalize lemma 1.11. Theorem 3.16 characterizes all left, right, and two-sided ideals in zero semigroups and left zero semigroups.

Theorem 3.15. If A is a nonempty subset of a semigroup S, then $L_A = A \cup SA = S^1A$, $R_A = A \cup AS = AS^1$, and $J_A = A \cup SA \cup AS \cup SAS = S^1AS^1$.

Proof. Part I: If $\{G_\alpha\}_{\alpha \varepsilon \Gamma}$ is the collection of all left ideals of S containing A, then $L_A = \bigcap_{\alpha \varepsilon \Gamma} G_\alpha$. Now for each $\alpha \varepsilon \Gamma$, $A \subseteq G_\alpha$, so that $A \subseteq \bigcap_{\alpha \varepsilon \Gamma} G_\alpha = L_A$. Also, since L_A is a left ideal of S and $A \subseteq L_A$, then $xa \in L_A$ for each $x \in S$, $a \in A$. Therefore $SA \subseteq L_A$, and so $A \cup SA \subseteq L_A$.

If $p \in S^1A$ then there exists $x \in S^1$, $y \in A$ such that $p = xy$. If $x \notin S$ then $x = 1$, so that $p = xy = 1y = y \in A$. If $x \in S$, then $p = xy \in SA$. Therefore, if $p \in S^1A$, then $p \in A \cup SA$, so that $S^1A \subseteq A \cup SA$.

Now $A \neq \phi$, so that there exists $p \in A$. Therefore $p = 1p \in S^1A$, and so $S^1A \neq \phi$. Also, if $x \in S$ and $y \in S^1A$, then there exist $r \in S^1$, $t \in A$ such that $y = rt$. If $r \notin S$ then $r = 1$, so that $xy = x(rt) = x(1t) = xt \in SA \subseteq S^1A$, and if $r \in S$ then $xr \in S$, so that $xy = x(rt) = (xr)t \in SA \subseteq S^1A$. Therefore, if $x \in S$ and $y \in S^1A$, then $xy \in S^1A$. Finally, $A = \{a | a \in A\} = \{1a | a \in A\} = \{1\}A \subseteq S^1A$, so that S^1A is a left ideal of S containing A. Therefore there exists $\beta \in \Gamma$ such that $S^1A = G_\beta$, and so $L_A = \bigcap_{\alpha \in \Gamma} G_\alpha \subseteq G_\beta = S^1A$. Thus $L_A \subseteq S^1A \subseteq A \cup SA \subseteq L_A$, and so $L_A = A \cup SA = S^1A$.

Part II: Similarly, if $\{G_\alpha\}_{\alpha \in B}$ is the collection of all right ideals of S containing A, then $R_A = A \cup AS = AS^1$.

Part III: If $\{G_\alpha\}_{\alpha \in \Omega}$ is the collection of all ideals of S containing A, then $J_A = \bigcap_{\alpha \in \Omega} G_\alpha$. Now for each $\alpha \in \Omega$, $A \subseteq G_\alpha$, so that $A \subseteq \bigcap_{\alpha \in \Omega} G_\alpha = J_A$. Also, if $x \in S$ and $a \in A$, then $xa \in J_A$ and $ax \in J_A$ since J_A is an ideal of S containing A, so that $SA \subseteq J_A$ and $AS \subseteq J_A$. Furthermore, if $x \in SA \subseteq J_A$ and $y \in S$, then $xy \in J_A$ since J_A is an ideal of S. Therefore $SAS = (SA)S \subseteq J_A$, and so $A \cup SA \cup AS \cup SAS \subseteq J_A$.

If $p \in S^1AS^1$, then there exist $x,z \in S^1$, $y \in A$ such that $p = xyz$. If $x \notin S$ and $z \notin S$, then $x = 1 = z$, so that $p = xyz = 1y1 = y \in A \subseteq A \cup SA \cup AS \cup SAS$. If $x \in S$ and $z \notin S$, then $z = 1$, so that $p = xyz = xy1 = xy \in SA \subseteq A \cup SA \cup AS \cup SAS$. If $x \notin S$ and $z \in S$, then $x = 1$, so that $p = xyz = 1yz = yz \in AS \subseteq A \cup SA \cup AS \cup SAS$. If $x \in S$ and $z \in S$, then $p = xyz \in SAS \subseteq A \cup SA \cup AS \cup SAS$. Therefore if $p \in S^1AS^1$, then $p \in A \cup SA \cup AS \cup SAS$, so that $S^1AS^1 \subseteq A \cup SA \cup AS \cup SAS$.

Now $A \neq \phi$ and $A = \{1\}A\{1\} \subseteq S^1AS^1$, so that $S^1AS^1 \neq \phi$ and $A \subseteq S^1AS^1$. Furthermore, if $x \in S$ and $y \in S^1AS^1$, then there exist $p,q \in S^1$, $a \in A$ such that $y = paq$. Now $xp \in S \subseteq S^1$ whether $p \in S$ or $p = 1$, and $qx \in S \subseteq S^1$ whether $q \in S$ or $q = 1$. Therefore $xy = x(paq) = (xp)aq \in S^1AS^1$ and $yx = (paq)x = pa(qx) \in S^1AS^1$, and so S^1AS^1 is an ideal of S containing A. Hence there exists $\beta \in \Omega$ such that $S^1AS^1 = G_\beta$, so that $J_A = \bigcap_{\alpha \in \Omega} G_\alpha \subseteq G_\beta = S^1AS^1$. Thus

$$J_A \subseteq S^1AS^1 \subseteq A \cup SA \cup SA \cup SAS \subseteq J_A,$$

and so $J_A = A \cup SA \cup AS \cup SAS = S^1AS^1$.

<u>Theorem 3.16</u>. If S is a zero semigroup, then the left, right, and two-sided ideals of S are those subsets of S containing the zero. If S is a left zero semigroup, then S is a left simple (and thus simple), while any nonempty subset of S is a right ideal of S.

<u>Proof</u>. Part I: If S is a zero semigroup with zero 0, then $ab = 0$ for each $a,b \in S$. Therefore, if A and B are nonempty subsets of S, then

$AB = \{ab \mid a \in A, b \in B\} = \{0 \mid a \in A, b \in B\} = \{0\}$.

Thus $\{L \subseteq S \mid L$ is a left ideal of $S\} = \{L \subseteq S \mid SL \subseteq L \neq \phi\} = \{L \subseteq S \mid \{0\} \subseteq L\} = \{L \subseteq S \mid 0 \in L\}$, $\{R \subseteq S \mid R$ is a right ideal of $S\} = \{R \subseteq S \mid 0 \in R\}$ similarly, and so $\{J \subseteq S \mid J$ is an ideal of $S\} = \{L \subseteq S \mid 0 \in L\} \cap \{R \subseteq S \mid 0 \in R\} = \{J \subseteq S \mid 0 \in J\}$. Therefore, the left, right, and two-sided ideals of S coincide and are exactly those subsets of S containing 0.

Part II: If S is a left zero semigroup, then $ab = a$ for each $a, b \in S$. Therefore, if A and B are nonempty subsets of S, then $AB = \{ab \mid a \in A, b \in B\} = \{a \mid a \in A, b \in B\} = A$. Thus $\{L \subseteq S \mid L$ is a left ideal of $S\} = \{L \subseteq S \mid SL \subseteq L \neq \phi\} = \{L \subseteq S \mid S \subseteq L\} = \{S\}$, so that S is left simple. Furthermore, $\{R \subseteq S \mid R$ is a right ideal of $S\} = \{R \subseteq S \mid RS \subseteq R \neq \phi\} = \{R \subseteq S \mid R \subseteq R \neq \phi\} = \{R \subseteq S \mid R \neq \phi\}$, so that any nonempty subset of S is a right ideal of S. Therefore, $\{J \subseteq S \mid J$ is an ideal of $S\} = \{S\} \cap \{R \subseteq S \mid R \neq \phi\} = \{S\}$, so that S is simple.

<u>Definition 3.17</u>. A subset T of Z^+ is an interval in Z^+ iff when $x, z \in T$, $x \leq y \leq z$, and $y \in Z^+$, then $y \in T$.

<u>Theorem 3.18</u>. If Z^+ is the semigroup of positive integers with multiplication defined by $xy = \max\{x,y\}$ for each $x, y \in Z^+$, then $\{\{n \in Z^+ \mid n \geq k\} \mid k \in Z^+\}$ is the collection of all ideals in Z^+. Furthermore, the congruences on Z^+ consist of all partitions of Z^+ each of whose elements are intervals in Z^+.

<u>Proof</u>. Part I: Let $k \in Z^+$ and define $P = \{n \in Z^+ \mid n \geq k\}$. Now $P \subseteq Z^+$ and $P \neq \phi$ since $k \in P$. If $x \in P$ and $y \in Z^+$, then

$x \geq k$, so that $xy = \max\{x,y\} \geq x \geq k$, and $yx = \max\{y,x\} \geq x \geq k$. Therefore $xy \in P$ and $yx \in P$, so that P is an ideal of Z^+.

Conversely, if P is an ideal of Z^+, then $P \subseteq Z^+$ such that $P \neq \phi$. Since Z^+ is well-ordered, there exists $k \in P$ such that $k \leq t$ for all $t \in P$. Therefore, if $n \in Z^+$ such that $n \geq k$, then $n = \max\{n,k\} = nk \in P$ since P is an ideal, so that $\{n \in Z^+ | n \geq k\} \subseteq P$. However, since $k \leq t$ for all $t \in P$, then $n \notin P$ for all $n \in Z^+$ such that $n < k$, and so $P = \{n \in Z^+ | n \geq k\}$. Therefore, P is an ideal in Z^+ iff there exists $k \in Z^+$ such that $P = \{n \in Z^+ | n \geq k\}$, so that $\{\{n \in Z^+ | n \geq k\} | k \in Z^+\}$ is the collection of all ideals in Z^+.

Part II: Let P be a partition of Z^+, each of whose elements are intervals in Z^+. Since P is a partition of Z^+, then P identifies an equivalence relation ρ on Z^+, with the elements of P as the ρ-classes. Thus each ρ-class is an interval in Z^+. If $w,x,y,z \in Z^+$, such that $(w,x) \in \rho$ and $(y,z) \in \rho$, then $w_\rho = x_\rho$ and $y_\rho = z_\rho$. If $w_\rho = y_\rho$, then $w_\rho = x_\rho = y_\rho = z_\rho$, and so $w,x,y,z \in w_\rho$. Therefore $wy = \max\{w,y\} \in w_\rho$ and $xz = \max\{x,z\} \in w_\rho$, so that $(wy,xz) \in \rho$. However, if $w_\rho \neq y_\rho$, then $w \neq y$, so that $w < y$ or $w > y$. Without loss of generality, assume $w < y$. Since each ρ-class is an interval in Z^+, then $a < b$ for each $a \in w_\rho$, $b \in y_\rho$. Therefore, since $w_\rho = x_\rho$ and $y_\rho = z_\rho$, then $w,x \in w_\rho$ and $y,z \in y_\rho$, so that $w < y$ and $x < z$. Thus $wy = \max\{w,y\} = y \in y_\rho$, and $xz = \max\{x,z\} = z \in z_\rho = y_\rho$, so that $(wy,xz) \in \rho$. Similarly, if $w > y$, then $(wy,xz) \in \rho$, so that ρ is a congruence on Z^+.

Conversely, if ρ is a congruence on Z^+, then let $a \varepsilon Z^+$, and consider a_ρ. Assume that there exist $x,y,z \varepsilon Z^+$ such that $x,z \varepsilon a_\rho$ and $x \leq y \leq z$, but $y \not\varepsilon a_\rho$. Therefore $x \neq y$ and $y \neq z$, so that $x < y < z$. Since $x,z \varepsilon a_\rho$, then $(x,z) \varepsilon \rho$. However, $(y,y) \varepsilon \rho$, since ρ is reflexive, so that $(xy,zy) \varepsilon \rho$. Thus $(y,z) = (\max\{x,y\}, \max\{z,y\}) = (xy,zy) \varepsilon \rho$, so that $y_\rho = z_\rho = a_\rho$. This is a contradiction, since $y \not\varepsilon a_\rho$. Therefore, for each $a \varepsilon Z^+$, if $x \varepsilon a_\rho$ and $z \varepsilon a_\rho$, then $y \varepsilon a_\rho$ for all $y \varepsilon Z^+$ such that $x \leq y \leq z$, and so each ρ-class is an interval in Z^+.

Theorem 3.19. Every equivalence relation is a congruence in: (1) a zero semigroup, (2) a left zero semigroup, (3) a right zero semigroup, (4) a semilattice of order 2.

Proof. Part I: Let S be a zero semigroup with zero 0, and let ρ be an equivalence relation on S. If $(a,b) \varepsilon \rho$ and $(c,d) \varepsilon \rho$, then $(ac,bd) = (0,0) \varepsilon \rho$ since ρ is reflexive, and so ρ is a congruence on S.

Part II: Let S be a left zero semigroup, and let ρ be an equivalence relation on S. If $(a,b) \varepsilon \rho$ and $(c,d) \varepsilon \rho$, then $(ac,bd) = (a,b) \varepsilon \rho$, and so ρ is a congruence on S.

Part III: Let S be a right zero semigroup, and let ρ be an equivalence relation on S. If $(a,b) \varepsilon \rho$ and $(c,d) \varepsilon \rho$, then $(ac,bd) = (c,d) \varepsilon \rho$, and so ρ is a congruence on S.

Part IV: If $S = \{a,b\}$ is a semilattice of order 2, and ρ is an equivalence relation on S, then either $\rho = S \times S$, or $\rho = \{(a,a), (b,b)\}$. If $\rho = S \times S$, then ρ is a congruence on S. If $\rho = \{(a,a), (b,b)\}$, then

1. $(a,a)*(a,a) = (aa,aa) = (a,a) \in \rho$,

2. $(b,b)*(b,b) = (bb,bb) = (b,b) \in \rho$,

3. $(a,a)*(b,b) = (ab,ab) \in \{(a,a),(b,b)\} = \rho$, and

4. $(b,b)*(a,a) = (ba,ba) = (ab,ab) \in \rho$ by part 3.

Therefore $(wy,xz) = (w,x)*(y,z) \in \rho$ for all $(w,x),(y,z) \in \rho$, so that ρ is a congruence on S. Thus every equivalence relation on S is a congruence on S.

Theorem 3.20. The set of all congruences on a semigroup S containing a fixed congruence on S is a lattice under set inclusion (an upper and a lower semilattice).

Proof. Let ρ be a congruence on a semigroup S, and let $\{\rho_\alpha\}_{\alpha\in A}$ be the set of all congruences on S containing ρ. Thus $\{\rho_\alpha\}_{\alpha\in A} \neq \phi$, since $\rho \in \{\rho_\alpha\}_{\alpha\in A}$. Let $\{\rho_{\alpha_1}, \rho_{\alpha_2}\} \subseteq \{\rho_\alpha\}_{\alpha\in A}$, and define $T \subseteq \{\rho_\alpha\}_{\alpha\in A}$ by $T = \{\rho_\alpha | \rho_\alpha$ is an upper bound of $\{\rho_{\alpha_1},\rho_{\alpha_2}\}\}$. Now $S \times S$ is a congruence on S containing ρ, and so $S \times S \in \{\rho_\alpha\}_{\alpha\in A}$. Furthermore, $\rho_{\alpha_1} \subseteq S \times S$ and $\rho_{\alpha_2} \subseteq S \times S$, so that $S \times S$ is an upper bound of $\{\rho_{\alpha_1},\rho_{\alpha_2}\}$. Therefore $S \times S \in T$, and so $T \neq \phi$. By lemma 2.20, $\beta = \bigcap_{\rho_\alpha \in T} \rho_\alpha$ is a congruence on S. Also, since $\rho \subseteq \rho_\alpha$ for all $\alpha \in A$, then $\rho \subseteq \bigcap_{\rho_\alpha \in T} \rho_\alpha = \beta$, so that $\beta \in \{\rho_\alpha\}_{\alpha\in A}$. Furthermore, since $\rho_{\alpha_1} \subseteq \rho_\alpha$ and $\rho_{\alpha_2} \subseteq \rho_\alpha$ for all $\rho_\alpha \in T$, then $\rho_{\alpha_1} \subseteq \bigcap_{\rho_\alpha \in T} \rho_\alpha = \beta$ and $\rho_{\alpha_2} \subseteq \bigcap_{\rho_\alpha \in T} \rho_\alpha = \beta$, so that β is an upper bound for for $\{\rho_{\alpha_1},\rho_{\alpha_2}\}$. Finally, if ρ_{α_0} is an upper bound of $\{\rho_{\alpha_1}, \rho_{\alpha_2}\}$, then $\rho_{\alpha_0} \in T$, and so $\beta = \bigcap_{\rho_\alpha \in T} \rho_\alpha \subseteq \rho_{\alpha_0}$. Therefore $\beta = \text{lub}\{\rho_{\alpha_1}, \rho_{\alpha_2}\}$.

Now since ρ_{α_1} and ρ_{α_2} are congruences on S, then by lemma 2.20, $\lambda = \rho_{\alpha_1} \cap \rho_{\alpha_2}$ is a congruence on S. Therefore, since $\rho \subseteq \rho_{\alpha_1}$ and $\rho \subseteq \rho_{\alpha_2}$, then $\rho \subseteq \rho_{\alpha_1} \cap \rho_{\alpha_2} = \lambda$, so that $\lambda \varepsilon \{\rho_\alpha\}_{\alpha \varepsilon A}$. Furthermore, $\lambda = \rho_{\alpha_1} \cap \rho_{\alpha_2} \subseteq \rho_{\alpha_1}$ and $\lambda = \rho_{\alpha_1} \cap \rho_{\alpha_2} \subseteq \rho_{\alpha_2}$, so that λ is a lower bound for $\{\rho_{\alpha_1}, \rho_{\alpha_2}\}$. Finally, if ρ_{α_0} is a lower bound for $\{\rho_{\alpha_1}, \rho_{\alpha_2}\}$, then $\rho_{\alpha_0} \subseteq \rho_{\alpha_1}$ and $\rho_{\alpha_0} \subseteq \rho_{\alpha_2}$, so that $\rho_{\alpha_0} \subseteq \rho_{\alpha_1} \cap \rho_{\alpha_2} = \lambda$. Therefore $\lambda = \text{glb}\{\rho_{\alpha_1}, \rho_{\alpha_2}\}$.

Thus if $\{\rho_{\alpha_1}\ \rho_{\alpha_2}\} \subseteq \{\rho_\alpha\}_{\alpha \varepsilon A}$, then there exist $\beta, \lambda \varepsilon \{\rho_\alpha\}_{\alpha \varepsilon A}$ such that $\beta = \text{lub}\{\rho_{\alpha_1}, \rho_{\alpha_2}\}$ and $\lambda = \text{glb}\{\rho_{\alpha_1}, \rho_{\alpha_2}\}$. Hence $\{\rho_\alpha\}_{\alpha \varepsilon A}$ is both an upper and a lower semilattice, and is thus a lattice.

<u>Lemma 3.21</u>. If $(R,+,\cdot)$ is a ring and $(S,*)$ is a semigroup, then let $RS = \{f:S \to R \mid |f^{-1}(R\backslash\{0\})| < \infty\}$. Define + and $\cdot$ on RS by $(f + g)(\gamma) = f(\gamma) + g(\gamma)$, and

$$(f \cdot g)(\gamma) = \sum_{\substack{(\alpha,\beta)\varepsilon S \times S \\ \alpha * \beta = \gamma}} f(\alpha)\cdot g(\beta), \text{ for all } \gamma \varepsilon S.$$

Then $(RS,+,\cdot)$ is a ring, called the semigroup ring of R by S.

<u>Proof</u>. Let $f,g,h \varepsilon RS$.

(i) If $(a,b) \varepsilon f + g$, then $a \varepsilon S$ and $b = (f + g)(a) = f(a) + g(a) \varepsilon R$, since $f(a), g(a) \varepsilon R$. Therefore $f + g \subseteq S \times R$.

(ii) If $a,b \varepsilon S$ such that $a = b$, then $f(a) = f(b)$ and $g(a) = g(b)$, so that $(f + g)(a) = f(a) + g(a) = f(b) + g(b) = (f + g)(b)$.

(iii) Since $f,g \varepsilon RS$, then there exist integers $M \geq 0$ and $N \geq 0$ such that $f^{-1}(R\backslash\{0\}) = \{x_i\}_{i=1}^{M} \subseteq S$ and

$g^{-1}(R\setminus\{0\}) = \{y_i\}_{i=1}^{N} \subseteq S$. For each i, $1 \leq i \leq N$, let $y_i = x_{M+i}$, so that $\{y_i\}_{i=1}^{N} = \{x_i\}_{i=M+1}^{M+N}$. Therefore, if $x \in S\setminus\{x_i\}_{i=1}^{M+N}$, then $x \notin \{x_i\}_{i=1}^{M} \cup \{y_i\}_{i=1}^{N}$, so that $f(x) = 0$ and $g(x) = 0$. Thus $(f + g)(x) = f(x) + g(x) = 0 + 0 = 0$, so that $(f + g)^{-1}(R\setminus\{0\}) \subseteq \{x_i\}_{i=1}^{M+N}$, and so $|(f + g)^{-1}(R\setminus\{0\})| \leq |\{x_i\}_{i=1}^{M+N}| = |\{x_i\}_{i=1}^{M} \cup \{y_i\}_{i=1}^{N}| \leq |\{x_i\}_{i=1}^{M}| + |\{y_i\}_{i=1}^{N}| = M + N < \infty$. Thus + is a closed binary operation on RS.

(iv) For each $x \in S$, $[(f + g) + h](x) = (f + g)(x) + h(x) = [f(x) + g(x)] + h(x) = f(x) + [g(x) + h(x)] = f(x) + [(g+h)(x)] = [f + (g + h)](x)$, so that $(f + g) + h = f + (g + h)$ and (RS, +) is associative.

(v) For each $x \in S$, $(f + g)(x) = f(x) + g(x) = g(x) + f(x) = (g + f)(x)$, so that $f + g = g + f$, and RS is commutative under + .

(vi) If $z: S \to R$ is defined by $z(x) = 0$ for all $x \in S$, then $z \in RS$, since $|z^{-1}(R\setminus\{0\})| = 0 < \infty$. Therefore, for each $f \in RS$, $(f + z)(x) = f(x) + z(x) = f(x) + 0 = f(x)$ for all $x \in S$, so that $f + z = f$. Furthermore, $z + f = f$ since RS is commutative under +, so that z is the identity for + .

(vii) Since $f \in RS$, then define $\overline{f}: S \to R$ by $\overline{f}(x) = -f(x)$ for all $x \in S$. Therefore $\overline{f}(x) = 0$ iff $-f(x) = 0$ iff $f(x) = 0$, so that $|\overline{f}^{-1}(R\setminus\{0\})| = |f^{-1}(R\setminus\{0\})| < \infty$, and $\overline{f} \in RS$. Furthermore, $(\overline{f} + f)(x) = \overline{f}(x) + f(x) = -f(x) + f(x) = 0 = z(x)$ for all $x \in S$. Therefore, for each $f \in RS$, there exists $\overline{f} \in RS$ such that $f + \overline{f} = \overline{f} + f = z$.

(viii) If $(a,b) \in f \cdot g$, then $a \in S$ and

$$b = (f \cdot g)(a) = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=a}} f(\alpha) \cdot g(\beta).$$

However, if $(\alpha,\beta) \in S \times S$ such that $\alpha*\beta = a$, then $\alpha \in S$ and $\beta \in S$, so that $f(\alpha) \in R$ and $g(\beta) \in R$, and so $f(\alpha) \cdot g(\beta) \in R$. Furthermore, since $|f^{-1}(R\setminus\{0\})| < \infty$ and $|g^{-1}(R\setminus\{0\})| < \infty$, then $|\{(\alpha,\beta) \in S \times S \,|\, \alpha*\beta = a \text{ and } f(\alpha)\cdot g(\beta) \neq 0\}| < \infty$, so that $b = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=a}} f(\alpha)\cdot g(\beta) \in R$. Therefore $f \cdot g \subseteq S \times R$.

(ix) If $a,b \in S$ such that $a = b$, then $\alpha*\beta = a$ iff $\alpha*\beta = b$ for all $(\alpha,\beta) \in S \times S$. Therefore,

$$(f \cdot g)(a) = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=a}} f(\alpha)\cdot g(\beta) = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=b}} f(\alpha)\cdot g(\beta) = (f \cdot g)(b).$$

(x) Since $f,g \in RS$, then there exist integers $M \geq 0$ and $N \geq 0$ such that $f^{-1}(R\setminus\{0\}) = \{x_i\}_{i=1}^{M} \subseteq S$ and $g^{-1}(R\setminus\{0\}) = \{y_i\}_{i+1}^{N} \subseteq S$. Therefore, if $\alpha \in S\setminus\{x_i\}_{i=1}^{M}$, then $f(\alpha) = 0$, so that $f(\alpha)\cdot g(\beta) = 0\cdot g(\beta) = 0$. Similarly, if $\beta \in S\setminus\{y_i\}_{i=1}^{N}$, then $g(\beta) = 0$, so that $f(\alpha)\cdot g(\beta) = f(\alpha)\cdot 0 = 0$. Thus, if $\gamma \in S$ such that $(f \cdot g)(\gamma) = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} f(\alpha)\cdot g(\beta) \neq 0$, then there exists $\phi \neq T \subseteq \{x_i\}_{i=1}^{M} \times \{y_i\}_{i=1}^{N}$ such that $(f \cdot g)(\gamma) = \sum_{(\alpha,\beta)\in T} f(\alpha)\cdot g(\beta)$. Since $|\{x_i\}_{i=1}^{M}| = M$ and $|\{y_i\}_{i=1}^{N}| = N$, then $|\{x_i\}_{i=1}^{M} \times \{y_i\}_{i=1}^{N}| = MN$, so that

$$|(f \cdot g)^{-1}(R\setminus\{0\})| \leq |\{P \subseteq \{x_i\}_{i=1}^{M} \times \{y_i\}_{i=1}^{N} \,|\, P \neq \phi\}| < \sum_{i=1}^{MN} \binom{MN}{i} < \infty.$$

Therefore $\cdot$ is a closed binary operation on RS.

(xi) For all $\gamma \in S$, $[(f \cdot g) \cdot h](\gamma) = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} [(f \cdot g)(\alpha)] \cdot [h(\beta)] =$

$$\sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} \left[\left(\sum_{\substack{(\lambda,\delta)\in S\times S \\ \lambda*\delta=\alpha}} [f(\lambda)\cdot g(\delta)]\right)\right] \cdot h(\beta) =$$

$$\sum_{\substack{(\lambda,\delta,\beta)\in S\times S\times S \\ \lambda*\delta*\beta=\gamma}} [f(\lambda)\cdot g(\delta)\cdot h(\beta)] = \sum_{\substack{(\alpha,\lambda,\delta)\in S\times S\times S \\ \alpha*\lambda*\delta=\gamma}} [f(\alpha)\cdot g(\lambda)\cdot h(\delta)] =$$

$$\sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} \left[f(\alpha)\cdot \left(\sum_{\substack{(\lambda,\delta)\quad S\times S \\ \lambda*\delta=\beta}} [g(\lambda)\cdot h(\delta)]\right)\right] =$$

$$\sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} [f(\alpha)]\cdot[(g \cdot h)(\beta)] = [f \cdot (g \cdot h)](\gamma).$$

Therefore, $(f \cdot g) \cdot h = f \cdot (g \cdot h)$, so that $(RS, \cdot)$ is associative.

(xii) For all $\gamma \in S$, $[f \cdot (g + h)](\gamma) =$

$$\sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} [f(\alpha)]\cdot[(g + h)(\beta)] = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} f(\alpha)\cdot[g(\beta) + h(\beta)] =$$

$$\sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} ([f(\alpha)\cdot g(\beta)]+[f(\alpha)\cdot h(\beta)]) = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} f(\alpha)\cdot g(\beta) + \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} f(\alpha)\cdot h(\beta) =$$

$[(f \cdot g)(\gamma)] + [(f \cdot h)(\gamma)] = [(f \cdot g) + (f \cdot h)](\gamma)$. Therefore, $f \cdot (g + h) = (f \cdot g) + (f \cdot h)$. Similarly, for all $\gamma \in S$, $[(f + g) \cdot h](\gamma) = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} [(f + g)(\alpha)]\cdot h(\beta) =$

$$\sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} [f(\alpha)+g(\alpha)]\cdot h(\beta) = \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} ([f(\alpha)\cdot h(\beta)]+[g(\alpha)\cdot h(\beta)]) =$$

$$\sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} f(\alpha)\cdot h(\beta) + \sum_{\substack{(\alpha,\beta)\in S\times S \\ \alpha*\beta=\gamma}} g(\alpha)\cdot h(\beta) = [(f\cdot h)(\gamma)] + [(g\cdot h)(\gamma)] =$$

$[(f \cdot h) + (g \cdot h)](\gamma)$. Therefore $(f + g)\cdot h = (f\cdot h)+(g\cdot h)$, so that $\cdot$ distributes over $+$ from the left and right in RS, and thus $(RS,+,\cdot)$ is a ring. In view of this lemma, the following example and theorem are introduced.

Example 3.22. If $(R,+,\cdot)$ is a ring, then $(R,\cdot)$ is a semigroup, called the multiplicative semigroup of R.

Embedding Theorem 3.23. Every semigroup is isomorphic to a subsemigroup of the multiplicative semigroup of some ring.

Proof. Let $(S,*)$ be a semigroup, let $(Z,+,\cdot)$ be the ring of integers, and let $(ZS,+,\cdot)$ be the semigroup ring of Z by S. Define $\theta:S\to ZS$ by $\theta(a) = f:S\to Z$, where

$$f(x) = \begin{cases} 1 \text{ if } x = a \\ 0 \text{ if } x \neq a, \text{ for all } x \in S \end{cases} \qquad \text{for all } a \in S.$$

(i) If $(a,b)\in\theta$, then $a\in S$, so that $b = \theta(a) = f:S\to Z$, where $f(x) = \begin{cases} 1 \text{ if } x = a \\ 0 \text{ if } x \neq a, \end{cases}$ for all $x\in S$. Now if $(p,q)\in f$, then $p\in S$ and $q = f(p)\in\{1,0\}\subseteq Z$, so that $f \subseteq S\times Z$. Also, if $p\in S$ and $r\in S$ such that $p = r$, then either $p = a$ or $p \neq a$. If $p = a$, then $r = p = a$, so that $f(p) = f(a) = 1$, and $f(r) = f(a) = 1 = f(p)$. If $p \neq a$, then $r = p \neq a$, so that $f(p) = 0$, and $f(r) = 0 = f(p)$. In either case, if $p = r$, then $f(p) = f(r)$. Therefore $f:S\to Z$ is a well-defined function. Furthermore, $|f^{-1}(Z\setminus\{0\})| = |\{a\}| = 1 < \infty$, and so $b = \theta(a) = f\in ZS$. Thus, if $(a,b)\in\theta$, then $a\in S$ and $b\in ZS$, so that $\theta \subseteq S\times ZS$.

(ii) If $p\in S$ and $q\in S$ such that $p = q$, then $\theta(p) = f:S\to Z$, where $f(x) = \begin{cases} 1 \text{ if } x = p \\ 0 \text{ if } x \neq p, \end{cases}$ and $\theta(q) = g:S\to Z$, where $g(x) = \begin{cases} 1 \text{ if } x = q \\ 0 \text{ if } x \neq q. \end{cases}$ If $x = p$, then $x = q$, and so $f(x) = 1 = g(x)$. If $x \neq p = q$, then $x \neq q$, so that $f(x) = 0 = g(x)$. Therefore $f(x) = g(x)$ for all $x \in S$, so that $\theta(p) = f = g = \theta(q)$, and so $\theta: S \to ZS$ is well-defined.

(iii) If $a \in S$ and $b \in S$ such that $a \neq b$, then $\theta(a) = f: S \to Z$ and $\theta(b) = g: S \to Z$, where $f(x) = \begin{cases} 1 \text{ if } x = a \\ 0 \text{ if } x \neq a \end{cases}$ and $g(x) = \begin{cases} 1 \text{ if } x = b \\ 0 \text{ if } x \neq b \end{cases}$ for all $x \in S$. Therefore $f(a) = 1$, but $g(a) = 0$ since $a \neq b$, so that $\theta(a) = f \neq g = \theta(b)$. Thus θ is one-to-one.

(iv) If $a \in S$ and $b \in S$, then $\theta(ab) = f: S \to Z$, $\theta(a) = g: S \to Z$, and $\theta(b) = h: S \to Z$, where $f(x) = \begin{cases} 1 \text{ if } x = ab \\ 0 \text{ if } x \neq ab, \end{cases}$ $g(x) = \begin{cases} 1 \text{ if } x = a \\ 0 \text{ if } x \neq a, \end{cases}$ and $h(x) = \begin{cases} 1 \text{ if } x = b \\ 0 \text{ if } x \neq b. \end{cases}$ Therefore $\theta(a) \cdot \theta(b) = (g \cdot h): S \to Z$. Now

$$(g \cdot h)(ab) = \sum_{\substack{(x,y) \in S \times S \\ x*y=ab}} g(x) \cdot h(y) = g(a) \cdot h(b) + \sum_{\substack{(x,y) \in S \times S \setminus \{(a,b)\} \\ x*y=ab}} g(x) \cdot h(y).$$

However, for all $(x,y) \in S \times S \setminus \{(a,b)\}$, either $x \neq a$ or $y \neq b$. Therefore either $g(x) = 0$ or $h(y) = 0$, so that $g(x) \cdot h(y) = 0$.

Thus $(g \cdot h)(ab) = g(a) \cdot h(b) + \sum_{\substack{(x,y) \in S \times S \setminus \{(a,b)\} \\ x*y=ab}} g(x) \cdot h(y) =$

$1 \cdot 1 + \sum_{\substack{(x,y) \in S \times S \setminus \{(a,b)\} \\ x*y=ab}} (0) = 1 + 0 = 1 = f(ab)$. Furthermore,

if $p \neq ab$, then $f(p) = 0$ and $\{(x,y) \in S \times S \mid x*y=p\} \subseteq S \times S \setminus \{(a,b)\}$.

Thus $(g \cdot h)(p) = \sum_{\substack{(x,y)\in S\times S \\ x*y=p}} g(x)\cdot h(y) \leq \sum_{(x,y)\in S\times S\setminus\{(a,b)\}} g(x)\cdot h(y) = 0$,

since $g(x)\cdot h(y) = 0$ for all $(x,y) \in S\times S\setminus\{(a,b)\}$ as before, so that $(g \cdot h)(p) = 0 = f(p)$. Therefore $(g\cdot h)(ab) = f(ab)$ and $(g \cdot h)(p) = f(p)$ for all $p \in S\setminus\{ab\}$, so that $(g \cdot h)(p) = f(p)$ for all $p \in S$. Hence $\theta(a) \cdot \theta(b) = g \cdot h = f = \theta(ab)$, so that θ is a homomorphism, and thus an embedding. Since $\theta : S \to \theta(S)$ is onto as well, then $S \cong \theta(S)$.

Since $\theta : S \to ZS$, then $\theta(S) \subseteq ZS$, and $\theta(S)$ is nonempty since S is nonempty. Furthermore, if $g \in \theta(S)$ and $h \in \theta(S)$, then there exist $a \in S$ and $b \in S$ such that $\theta(a) = g$ and $\theta(b) = h$. Since θ is a homomorphism, then $g \cdot h = \theta(a)\cdot\theta(b) = \theta(ab) \in \theta(S)$ since $ab \in S$. Finally, if $f,g,h \in \theta(S)$, then there exist $a,b,c \in S$ such that $\theta(a) = f, \theta(b) = g$, and $\theta(c) = h$. Since θ is a homomorphism, then $(f \cdot g)\cdot h = [\theta(a) \cdot \theta(b)] \cdot \theta(c) = \theta(ab) \cdot \theta(c) = \theta[(ab)c] = \theta[a(bc)] = \theta(a) \cdot \theta(bc) = \theta(a) \cdot [\theta(b) \cdot \theta(c)] = f \cdot (g \cdot h)$. Therefore $(\theta(S), \cdot)$ is associative, and is thus a subsemigroup of $(ZS, \cdot)$. Thus $S \cong \theta(S)$, where $\theta(S)$ is a subsemigroup of the multiplicative semigroup $(ZS, \cdot)$ of the ring $(ZS, +, \cdot)$.

Unfortunately, it is not true that every semigroup is isomorphic to the multiplicative semigroup of some ring. The following example verifies this statement.

Example 3.24. Let S be any semigroup which contains no zero. If $(R,+,\cdot)$ is a ring, then there exists $0 \in R$ such that $0\cdot x = x\cdot 0 = 0$ for all $x \in R$. If S is isomorphic to the multiplicative semigroup $(R,\cdot)$ of $(R,+,\cdot)$, then there exists an isomorphism $f:R \to S$, so that $z = f(0) \varepsilon S$. Now for each $y \varepsilon S$, there exists $x \varepsilon R$ such that $f(x) = y$, since f is onto. Therefore, $zy = f(0)\, f(x) = f(0\cdot x) = f(0) = z$, and $yz = f(x)f(0) = f(x\cdot 0) = f(0) = z$, so that z is a zero for S. This is a contradiction since S has no zero, and so S cannot be isomorphic to $(R,\cdot)$.

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CHAPTER IV

SUBDIRECTLY IRREDUCIBLE SEMIGROUPS

Definition 4.1. If $\{S_\alpha\}_{\alpha\varepsilon A}$ is a nonempty collection of nonempty sets, then the Cartesian product of $\{S_\alpha\}_{\alpha\varepsilon A}$ is $\{f: A \to \bigcup_{\alpha\varepsilon A} S_\alpha \mid f(\alpha) \varepsilon S_\alpha$ for each $\alpha \varepsilon A\}$, and will be denoted by $\prod_{\alpha\varepsilon A} S_\alpha$. If $x \varepsilon \prod_{\alpha\varepsilon A} S_\alpha$, then $x(\alpha)$ is the α^{th} component (or coordinate) of x and will be denoted by x_α. For each $\alpha\varepsilon A$, the function $\pi_\alpha : \prod_{\alpha\varepsilon A} S_\alpha \to S_\alpha$ defined by $\pi_\alpha(x) = x_\alpha$ for all $x \varepsilon \prod_{\alpha\varepsilon A} S_\alpha$ is the α^{th} projection map of $\prod_{\alpha\varepsilon A} S_\alpha$ onto the α^{th} factor set S_α.

Lemma 4.2. Let $\{S_\alpha\}_{\alpha\varepsilon A}$ be a nonempty collection of semigroups and let $S = \prod_{\alpha\varepsilon A} S_\alpha$. Define multiplication on S as follows: if $x \varepsilon S$ and $y \varepsilon S$, then $xy = z$, where $z_\alpha = x_\alpha y_\alpha$ for all $\alpha\varepsilon A$. Then S is a semigroup, called the direct product of $\{S_\alpha\}_{\alpha\varepsilon A}$.

Proof. If $x \varepsilon S$ and $y \varepsilon S$, then $x_\alpha \varepsilon S_\alpha$ and $y_\alpha \varepsilon S_\alpha$ for all $\alpha \varepsilon A$, so that $z_\alpha = x_\alpha y_\alpha \varepsilon S_\alpha$ and $z = xy \varepsilon S$. If $x,y,z \varepsilon S$, then $x_\alpha, y_\alpha, z_\alpha \varepsilon S_\alpha$ for all $\alpha\varepsilon A$, so that $(x_\alpha y_\alpha)z_\alpha = x_\alpha(y_\alpha z_\alpha)$. Therefore $(xy)_\alpha z_\alpha = (x_\alpha y_\alpha)z_\alpha = x_\alpha(y_\alpha z_\alpha) = x_\alpha(yz)_\alpha$ for all

$\alpha\varepsilon A$, so that $(xy)z = x(yz)$. Thus multiplication in S is associative, and so S is a semigroup.

Lemma 4.3. If $\{S_\alpha\}_{\alpha\varepsilon A}$ is a nonempty collection of semigroups and $S = \prod_{\alpha\varepsilon A} S_\alpha$, then $\pi_\alpha : S \to S_\alpha$ is an onto homomorphism for each $\alpha\varepsilon A$.

Proof. If $\beta\varepsilon A$ and $(x,y) \varepsilon \pi_\beta$, then $x \varepsilon S$ and $y = \pi_\beta(x) = x_\beta = x(\beta) \varepsilon S_\beta$, and so $\pi_\beta \subseteq S \times S_\beta$. If $a \varepsilon S$ and $b \varepsilon S$ such that $a = b$, then $a_\alpha = b_\alpha$ for each $\alpha\varepsilon A$, so that $\pi_\beta(a) = a_\beta = b_\beta = \pi_\beta(b)$. Therefore, π_β is a well-defined function from S to S_β.

Let $x \varepsilon S_\beta$. Since S_α is a semigroup for each $\alpha\varepsilon A$, and thus nonempty, then select $a_\alpha \varepsilon S_\alpha$ for each $\alpha\varepsilon A$, where $a_\beta = x$. Define $a \varepsilon S$ such that $a(\alpha) = a_\alpha$ for all $\alpha\varepsilon A$, so that $\pi_\beta(a) = a_\beta = x$, and thus π_β is onto.

If $a \varepsilon S$ and $b \varepsilon S$, then $\pi_\beta(ab) = (ab)_\beta = a_\beta b_\beta = \pi_\beta(a)\pi_\beta(b)$, so that π_β is a homomorphism.

Definition 4.4. Let $\{S_\alpha\}_{\alpha\varepsilon A}$ be a collection of nontrivial semigroups. A semigroup S is a subdirect product of $\{S_\alpha\}_{\alpha\varepsilon A}$ iff there exists a subsemigroup T of $\prod_{\alpha\varepsilon A} S_\alpha$ such that $\pi_\alpha(T) = S_\alpha$ for all $\alpha\varepsilon A$ and $S \cong T$.

Definition 4.5. A nontrivial semigroup S is subdirectly irreducible iff whenever S is the subdirect product of semigroups $\{S_\alpha\}_{\alpha\varepsilon A}$ and T is a subsemigroup of $\prod_{\alpha\varepsilon A} S_\alpha$ such that $S \cong T$, then there exists $\beta\varepsilon A$ such that $\pi_\beta : T \to S_\beta$ is an isomorphism.

Definition 4.6. If σ is a congruence on a semigroup S and $x,y \in S$, then σ separates x and y iff $x_\sigma \neq y_\sigma$ (or, equivalently, $(x,y) \notin \sigma$).

Definition 4.7. A collection Σ of congruences on a semigroup S separates elements of S iff whenever $x,y \in S$ such that $x \neq y$, then there exists $\sigma \in \Sigma$ such that $x_\sigma \neq y_\sigma$.

Lemma 4.8. If Σ is a collection of congruences on a semigroup S, then Σ separates elements of S iff $\bigcap_{\sigma\in\Sigma} \sigma = \varepsilon_S$, the equality relation on S.

Proof. If Σ separates elements of S and $x,y \in S$ such that $(x,y) \notin \varepsilon_S$, then $x \neq y$. Therefore, there exists $\sigma \in \Sigma$ such that $x_\sigma \neq y_\sigma$, so that $(x,y) \notin \sigma$ and thus $(x,y) \notin \bigcap_{\sigma\in\Sigma} \sigma$. By contrapositive, if $(x,y) \in \bigcap_{\sigma\in\Sigma} \sigma$, then $(x,y) \in \varepsilon_S$, so that $\bigcap_{\sigma\in\Sigma} \sigma \subseteq \varepsilon_S$. Furthermore, if $x,y \in S$ such that $(x,y) \in \varepsilon_S$, then $x = y$. Therefore, $(x,y) = (x,x) \in \sigma$ for each $\sigma \in \Sigma$, so that $(x,y) \in \bigcap_{\sigma\in\Sigma} \sigma$ and $\varepsilon_S \subseteq \bigcap_{\sigma\in\Sigma} \sigma$. Hence $\bigcap_{\sigma\in\Sigma} \sigma = \varepsilon_S$.

Conversely, suppose $\bigcap_{\sigma\in\Sigma} \sigma = \varepsilon_S$. If $x,y \in S$, such that $x \neq y$, then $(x,y) \notin \varepsilon_S = \bigcap_{\sigma\in\Sigma} \sigma$. Therefore, there exists $\sigma \in \Sigma$ such that $(x,y) \notin \sigma$, so that $x_\sigma \neq y_\sigma$. Thus Σ separates elements of S.

Definition 4.9. If $\{S_\alpha\}_{\alpha\in A}$ is a collection of semigroups and $\beta \in A$, then the congruence σ on $\prod_{\alpha\in A} S_\alpha$ defined by $(x,y) \in \sigma$ iff $\pi_\beta(x) = \pi_\beta(y)$ for all $x,y \in \prod_{\alpha\in A} S_\alpha$ is the congruence on $\prod_{\alpha\in A} S_\alpha$ induced by π_β.

Theorem 4.10. If a semigroup S is a subdirect product of semigroups $\{S_\alpha\}_{\alpha\in A}$, then the set $\{\sigma_\alpha\}_{\alpha\in A}$ of congruences on S induced by the projection mappings $\{\pi_\alpha\}_{\alpha\varepsilon A}$ separates elements of S. Conversely, if $\{\sigma_\alpha\}_{\alpha\varepsilon A}$ is a set of congruences on S, all different from the universal relation, which separates elements of S, then S is a subdirect product of the semigroups $\{S/\sigma_\alpha\}_{\alpha\varepsilon A}$.

<u>Proof</u>. If S is a subdirect product of $\{S_\alpha\}_{\alpha\varepsilon A}$, then there exists $T \subseteq \prod_{\alpha\varepsilon A} S_\alpha$ such that $S \cong T$ and $\pi_\alpha(T) = S_\alpha$ for all $\alpha\varepsilon A$. If $x \varepsilon T$ and $y \varepsilon T$ such that $x \neq y$, then there exists $\beta \varepsilon A$ such that $x_\beta \neq y_\beta$, and so $\pi_\beta(x) \neq \pi_\beta(y)$. Therefore, $(x,y) \notin \sigma_\beta$, so that $x_{\sigma_\beta} \neq y_{\sigma_\beta}$, and thus $\{\sigma_\alpha\}_{\alpha\varepsilon A}$ separates elements of S.

Conversely, if $\{\sigma_\alpha\}_{\alpha\varepsilon A}$ is a set of congruences on a semigroup S and $\{\sigma_\alpha\}_{\alpha\varepsilon A}$ separates elements of S, then $\bigcap_{\alpha\varepsilon A}\sigma_\alpha = \varepsilon_s$ by lemma 4.8. Define $\theta: S \to \prod_{\alpha\varepsilon A} S/\sigma_\alpha$ by $\theta(x) = \overline{x}$, where $\overline{x}_\alpha = x_{\sigma_\alpha}$ for all $\alpha\varepsilon A$.

If $(p,q)\varepsilon\ \theta$, then $p \varepsilon S$ and $q = \theta(p) = \overline{p}$, where $q_\alpha = \overline{p}_\alpha = p_{\sigma_\alpha}$ for all $\alpha \varepsilon A$. Therefore, $q \varepsilon \prod_{\alpha\varepsilon A} S/\sigma_\alpha$, and so $\theta \subseteq S \times \prod_{\alpha\varepsilon A} S/\sigma_\alpha$. Moreover, if $x \varepsilon S$ and $y \varepsilon S$ such that $x = y$, then $[\theta(x)]_\alpha = \overline{x}_\alpha = x_{\sigma_\alpha} = y_{\sigma_\alpha}$ (since $x=y$) $= \overline{y}_\alpha = [\theta(y)]_\alpha$ for all $\alpha\varepsilon A$. Therefore, $\theta(x) = \theta(y)$, and so θ is a well-defined function.

If $x \varepsilon S$ and $y \varepsilon S$ such that $x \neq y$, then there exists $\beta \varepsilon A$ such that $x_{\sigma_\beta} \neq y_{\sigma_\beta}$ since $\{\sigma_\alpha\}_{\alpha\varepsilon A}$ separates elements of S. Therefore, $[\theta(x)]_\beta = \overline{x}_\beta = x_{\sigma_\beta} \neq y_{\sigma_\beta} = \overline{y}_\beta = [\theta(y)]_\beta$, so that $\theta(x) \neq \theta(y)$, and hence θ is one-to-one.

If $z \varepsilon \theta(S)$, then there exists $x \varepsilon S$ such that $\theta(x) = z$, and so $\theta: S \to \theta(S)$ is onto.

If $x \varepsilon S$ and $y \varepsilon S$, then $[\theta(xy)]_\alpha = (\overline{xy})_\alpha = (xy)_{\sigma_\alpha} = (x_{\sigma_\alpha})(y_{\sigma_\alpha}) = (\overline{x}_\alpha)(\overline{y}_\alpha) = [\theta(x)]_\alpha[\theta(y)]_\alpha$ for all $\alpha \varepsilon A$. Therefore, $\theta(xy) = [\theta(x)][\theta(y)]$ for each $x,y \varepsilon S$, so that $\theta: S \to \theta(S)$ is an isomorphism, and $S \cong \theta(S)$.

Now if $y \varepsilon \theta(S)$ and $z \varepsilon \theta(S)$, then there exist $a \varepsilon S$ and $b \varepsilon S$ such that $\theta(a) = y$ and $\theta(b) = z$. Since $a \varepsilon S$ and $b \varepsilon S$ imply $ab \varepsilon S$, then $yz = [\theta(a)][\theta(b)] = \theta(ab) \varepsilon \theta(S)$.

Furthermore, since S is associative, then S/σ_α is associative for each $\alpha \varepsilon A$. Therefore, $\prod_{\alpha \varepsilon A} S/\sigma_\alpha$ is associative, and since $\theta(S) \subseteq \prod_{\alpha \varepsilon A} S/_{\sigma_\alpha}$, then $\theta(S)$ is associative. Hence, $\theta(S)$ is a subsemigroup of $\prod_{\alpha \varepsilon A} S/\sigma_\alpha$.

Finally, if $\alpha \varepsilon A$ and $x_{\sigma_\alpha} \varepsilon S/\sigma_\alpha$, then $x \varepsilon S$, and so $\theta(x) \varepsilon \theta(S)$. Furthermore, $\pi_\alpha[\theta(x)] = [\theta(x)]_\alpha = \overline{x}_\alpha = x_{\sigma_\alpha}$. Therefore, $\pi_\alpha: \theta(S) \to S/\sigma_\alpha$ is onto for each $\alpha \varepsilon A$, and so S is a subdirect product of $\{S/\sigma_\alpha\}_{\alpha \varepsilon A}$.

<u>Lemma 4.11</u>. The homomorphic image of a commutative or idempotent semigroup is a commutative or idempotent semigroup, respectively.

<u>Proof</u>. Let $(S,\cdot)$ be a semigroup, $(T,*)$ a binary system, and $f: S \to T$ a homomorphism. If $x \varepsilon f(S)$ and $y \varepsilon f(S)$, then there exists $a \varepsilon S$ and $b \varepsilon S$ such that $f(a) = x$ and $f(b) = y$. Therefore, $x*y = f(a)*f(b) = f(a\cdot b) \varepsilon f(S)$ since $a\cdot b \varepsilon S$. If $z \varepsilon f(S)$ also, then there exists $c \varepsilon S$ such that $f(c) = z$.

Therefore, $(x*y)*z = [f(a)*f(b)]*f(c) = f(a\cdot b)*f(c) = f[(a\cdot b)\cdot c] = f[a\cdot(b\cdot c)] = f(a)*f(b\cdot c) = f(a)*[f(b)*f(c)] = x*(y*z)$, and so $(f(S),*)$ is a semigroup. If $(S,\cdot)$ is commutative, then $x*y = f(a)*f(b) = f(a\cdot b) = f(b\cdot a) = f(b)*f(a) = y*x$, so that $(f(S),*)$ is commutative. If $(S,\cdot)$ is idempotent, then $x*x = f(a)*f(a) = f(a\cdot a) = f(a) = x$, so that $(f(S),*)$ is idempotent.

Theorem 4.12. The following conditions on a nontrivial semigroup S are equivalent: (i) S is subdirectly irreducible, (ii) the intersection of any collection of proper congruences on S is a proper congruence on S, and (iii) S has a least proper congruence.

Proof. Suppose S is subdirectly irreducible. If $\{\sigma_\alpha\}_{\alpha\varepsilon A}$ is a collection of proper congruences on S such that $\bigcap_{\alpha\varepsilon A}\sigma_\alpha = \varepsilon_S$, then $\{\sigma_\alpha\}_{\alpha\varepsilon A}$ separates elements of S by lemma 4.8. Therefore, S is the subdirect product of $\{S/\sigma_\alpha\}_{\alpha\varepsilon A}$ by theorem 4.10, so that there exists an embedding $\theta: S\to \prod_{\alpha\varepsilon A} S/\sigma_\alpha$ such that $S\cong\theta(S)$. Now for each $\alpha\varepsilon A$, $\sigma_\alpha \neq \varepsilon_S$. Therefore, if $\beta\varepsilon A$, then there exist $x\varepsilon S$ and $y\varepsilon S$, $x \neq y$, such that $(x,y)\varepsilon\sigma_\beta$, and so $x_{\sigma_\beta} = y_{\sigma_\beta}$. Furthermore, since $S\cong\theta(S)$ and $x \neq y$, then $\overline{x} = \theta(x) \neq \theta(y) = \overline{y}$. However, $\pi_\beta(\overline{x}) = \overline{x}_\beta = x_{\sigma_\beta} = y_{\sigma_\beta} = \overline{y}_\beta = \pi_\beta(\overline{y})$. Therefore, for each $\alpha\varepsilon A$, there exist $\overline{x}\varepsilon\theta(S)$ and $\overline{y}\varepsilon\theta(S)$ such that $\overline{x} \neq \overline{y}$ but $\pi_\alpha(\overline{x}) = \pi_\alpha(\overline{y})$, so that $\pi_\alpha:\theta(S)\to S/\sigma_\alpha$ is not one-to-one. Thus $\pi_\alpha:\theta(S)\to S/\sigma_\alpha$ is not an isomorphism for each $\alpha\varepsilon A$, and so S is not subdirectly irreducible. Since this contradicts the hypothesis, then $\bigcap_{\alpha\in A}\sigma_\alpha \neq \varepsilon_S$, so that $\bigcap_{\alpha\in A}\sigma_\alpha$ is a proper congruence on S by lemma 2.20.

Suppose that the intersection of any collection of proper congruences on S is a proper congruence on S. If P is the collection of all proper congruences on S, then $P \neq \phi$ since $S\times S \in P$. Therefore, $\bigcap_{\sigma\in P}\sigma$ is a proper congruence on S by hypothesis. Furthermore, if ρ is any proper congruence on S, then $\rho \in P$, so that $\bigcap_{\sigma\in P}\sigma \subseteq \rho$. Thus $\bigcap_{\sigma\in P}\sigma$ is a least proper congruence on S.

Suppose there exists a least proper congruence σ on S. If S is not subdirectly irreducible, then there exists a collection $\{S_\alpha\}_{\alpha\in A}$ of semigroups such that S is the subdirect product of $\{S_\alpha\}_{\alpha\in A}$ by the embedding $\theta: S \to \prod_{\alpha\in A} S_\alpha$, but $\pi_\alpha: \theta(S) \to S_\alpha$ is not an isomorphism for each $\alpha \in A$, where $S \cong \theta(S) \subseteq \prod_{\alpha\in A} S_\alpha$. Since $\pi_\alpha[\theta(S)] = S_\alpha$ for each $\alpha \in A$, then $\pi_\alpha: \theta(S) \to S$ is an onto homomorphism for each $\alpha \in A$ by lemma 4.3. Therefore, since π_α is not an isomorphism, then π_α is not one-to-one for each $\alpha \in A$. Let $\{\sigma_\alpha\}_{\alpha\in A}$ be the collection of congruences induced on $\theta(S)$ by $\{\pi_\alpha\}_{\alpha\in A}$. For each $\alpha \in A$, there exist $\overline{x}, \overline{y} \in \theta(S)$ such that $\overline{x} \neq \overline{y}$, but $\pi_\alpha(\overline{x}) = \pi_\alpha(\overline{y})$ since π_α is not one-to-one. Therefore, $(\overline{x}, \overline{y}) \in \sigma_\alpha$, so that $\sigma_\alpha \neq \varepsilon_{\theta(S)}$ since $\overline{x} \neq \overline{y}$, and so σ_α is a proper congruence on $\theta(S)$ for each $\alpha \in A$. However, since S is the subdirect product of $\{S_\alpha\}_{\alpha\in A}$, then $\{\sigma_\alpha\}_{\alpha\in A}$ separates elements of $\theta(S)$

by theorem 4.10, so that $\bigcap_{\alpha\in A}\sigma_\alpha = \varepsilon_{\theta(S)}$ by lemma 4.8. Therefore, since σ is a least proper congruence on $\theta(S)$, then $\sigma \subseteq \sigma_\alpha$ for each $\alpha \in A$, so that $\varepsilon_{\theta(S)} \subset \sigma \subseteq \bigcap_{\alpha\in A}\sigma_\alpha = \varepsilon_{\theta(S)}$. This is a contradiction, and so S is subdirectly irreducible.

Corollary 4.13. A semigroup S is a subdirect product of semigroups $\{S_\alpha\}_{\alpha\in A}$ iff there exists an onto homomorphism $f_\alpha : S \to S_\alpha$ for each $\alpha \in A$, and the family $\{\rho_\alpha\}_{\alpha\in A}$ of congruences induced by $\{f_\alpha\}_{\alpha\in A}$ separates elements of S.

Proof. If S is a subdirect product of $\{S_\alpha\}_{\alpha\in A}$, then there exists a subsemigroup T of $\prod_{\alpha\in A} S_\alpha$ such that $S \cong T$ and $\pi_\alpha(T) = S_\alpha$ for each $\alpha \in A$. Therefore, there exists an isomorphism $\theta : S \to T$ such that $T = \theta(S)$. Since $\theta : S \to T$ and $\pi_\alpha : T \to S_\alpha$ are onto homomorphisms for each $\alpha \in A$, then $\pi_\alpha \circ \theta : S \to S_\alpha$ is an onto homomorphism for each $\alpha \in A$. Let $\{\rho_\alpha\}_{\alpha\in A}$ and $\{\sigma_\alpha\}_{\alpha\in A}$ be the families of congruences induced on S and $\theta(S)$ by $\{\pi_\alpha \circ \theta\}_{\alpha\in A}$ and $\{\pi_\alpha\}_{\alpha\in A}$, respectively. Therefore, if $x \in S$ and $y \in S$ such that $x \neq y$, then $\theta(x) \neq \theta(y)$ since θ is one-to-one. Since $\{\sigma_\alpha\}_{\alpha\in A}$ separates elements of $\theta(S)$ by theorem 4.10, then there exists $\beta \in A$ such that $(\theta(x), \theta(y)) \notin \sigma_\beta$, so that $\pi_\beta \circ \theta(x) \neq \pi_\beta \circ \theta(y)$, and hence $(x,y) \notin \rho_\beta$. Thus $\pi_\alpha \circ \theta : S \to S_\alpha$ is an onto homomorphism for each $\alpha \in A$, and $\{\rho_\alpha\}_{\alpha \in A}$ separates elements of S.

Conversely, suppose that $f_\alpha : S \to S_\alpha$ is an onto homomorphism for each $\alpha \in A$, and the family $\{\rho_\alpha\}_{\alpha\in A}$ of congruences on S induced by $\{f_\alpha\}_{\alpha\in A}$ separates elements of S. Define

$\theta : S \to \prod_{\alpha \varepsilon A} S_\alpha$ by $[\theta(x)]_\alpha = f_\alpha(x)$ for each $x \varepsilon S$, $\alpha \varepsilon A$. If $(p,q) \varepsilon \theta$, then $p \varepsilon S$ and $q_\alpha = [\theta(p)]_\alpha = f_\alpha(p) \varepsilon S_\alpha$ for each $\alpha \varepsilon A$, so that $q \varepsilon \prod_{\alpha \varepsilon A} S_\alpha$, and so $\theta \subseteq S \times \prod_{\alpha \varepsilon A} S_\alpha$. Furthermore, if $x \varepsilon S$ and $y \varepsilon S$ such that $x = y$, then $[\theta(x)]_\alpha = f_\alpha(x) = f_\alpha(y) = [\theta(y)]_\alpha$ for each $\alpha \varepsilon A$ since f_α is well-defined, so that $\theta(x) = \theta(y)$. Therefore, θ is well-defined. If $x \varepsilon S$ and $y \varepsilon S$ such that $\theta(x) = \theta(y)$, then $f_\alpha(x) = [\theta(x)]_\alpha = [\theta(y)_\alpha] = f_\alpha(y)$ for each $\alpha \varepsilon A$. Therefore, $(x,y) \varepsilon \rho_\alpha$ for each $\alpha \varepsilon A$, so that $x = y$ since $\{\rho_\alpha\}_{\alpha \varepsilon A}$ separates elements of S. Hence θ is one-to-one. If $x \varepsilon S$ and $y \varepsilon S$, then $[\theta(xy)]_\alpha = f_\alpha(xy) = [f_\alpha(x)][f_\alpha(y)] = [\theta(x)]_\alpha [\theta(y)]_\alpha$ for each $\alpha \varepsilon A$, so that $\theta(xy) = [\theta(x)][\theta(y)]$, and so θ is a homomorphism. Thus $\theta : S \to \prod_{\alpha \varepsilon A} S_\alpha$ is an embedding, so that $S \cong \theta(S) \subseteq \prod_{\alpha \varepsilon A} S_\alpha$. Furthermore, since S is a semigroup and $S \cong \theta(S)$, then $\theta(S)$ is a semigroup by lemma 4.11, and thus a subsemigroup of $\prod_{\alpha \varepsilon A} S_\alpha$. Finally, let $\beta \varepsilon A$ and let $z \varepsilon S_\beta$. Since $f_\beta : S \to S_\beta$ is onto, then there exists $x \varepsilon S$ such that $f_\beta(x) = z$. Now $\theta(x) \varepsilon \theta(S)$, and $\pi_\beta[\theta(x)] = [\theta(x)]_\beta = f_\beta(x) = z$. Therefore, $\pi_\alpha : \theta(S) \to S_\alpha$ is onto for each $\alpha \varepsilon A$, so that $\pi_\alpha[\theta(S)] = S_\alpha$. Thus S is the subdirect product of $\{S_\alpha\}_{\alpha \varepsilon A}$.

<u>Corollary 4.14</u>. If a semigroup S is a subdirect product of semigroups $\{S_\alpha\}_{\alpha \varepsilon A}$, and S_α is a subdirect product of semigroups $\{S_{\alpha,\beta}\}_{\beta \varepsilon A_\alpha}$ for each $\alpha \varepsilon A$, then S is a subdirect product of $\{S_{\alpha,\beta}\}_{\alpha \varepsilon A, \beta \varepsilon A_\alpha}$.

Proof. If S is a subdirect product of $\{S_\alpha\}_{\alpha\varepsilon A}$, then there exists an onto homomorphism $f_\alpha : S \to S_\alpha$ for each $\alpha \varepsilon A$, and the collection $\{\rho_\alpha\}_{\alpha\varepsilon A}$ of congruences on S induced by $\{f_\alpha\}_{\alpha\varepsilon A}$ separates elements of S by corollary 4.13. Furthermore, S_α is a subdirect product of $\{S_{\alpha,\beta}\}_{\beta\varepsilon A_\alpha}$ for each $\alpha \varepsilon A$, so that if $\alpha\varepsilon A$, then there exists an onto homomorphism $g_{\alpha,\beta} : S_\alpha \to S_{\alpha,\beta}$ for each $\beta \varepsilon A_\alpha$, and the collection $\{\sigma_{\alpha,\beta}\}_{\beta\varepsilon A_\alpha}$ of congruences on S_α induced by $\{g_{\alpha,\beta}\}_{\beta\varepsilon A_\alpha}$ separates elements of S_α.

If $\alpha \varepsilon A$ and $\beta \varepsilon A_\alpha$, then $f_\alpha : S \to S_\alpha$ and $g_{\alpha,\beta} : S_\alpha \to S_{\alpha,\beta}$, so that $g_{\alpha,\beta} \circ f_\alpha : S \to S_{\alpha,\beta}$. Since f_α and $g_{\alpha,\beta}$ are onto homomorphisms, then $g_{\alpha,\beta} \circ f_\alpha$ is an onto homomorphism, and thus induces a congruence $\gamma_{\alpha,\beta}$ on S. Furthermore, if $x \varepsilon S$ and $y \varepsilon S$ such that $x \neq y$, then there exists $\alpha_\circ \varepsilon A$ such that $(x,y) \notin \rho_{\alpha_\circ}$ since $\{\rho_\alpha\}_{\alpha\varepsilon A}$ separates elements of S. Therefore, $f_{\alpha_\circ}(x) \varepsilon S_{\alpha_\circ}$ and $f_{\alpha_\circ}(y) \varepsilon S_{\alpha_\circ}$ such that $f_{\alpha_\circ}(x) \neq f_{\alpha_\circ}(y)$, and so there exists $\beta_\circ \varepsilon A_{\alpha_\circ}$ such that $(f_{\alpha_\circ}(x), f_{\alpha_\circ}(y)) \notin \sigma_{\alpha_\circ,\beta_\circ}$ since $\{\sigma_{\alpha,\beta}\}_{\beta\varepsilon A_\alpha}$ separates elements of S_α for each $\alpha \varepsilon A$. Therefore, $g_{\alpha_\circ,\beta_\circ} \circ f_{\alpha_\circ}(x) = g_{\alpha_\circ,\beta_\circ}[f_{\alpha_\circ}(x)] \neq g_{\alpha_\circ,\beta_\circ}[f_{\alpha_\circ}(y)] = g_{\alpha_\circ,\beta_\circ} \circ f_{\alpha_\circ}(y)$, so that $(x,y) \notin \gamma_{\alpha_\circ,\beta_\circ}$. Thus

$g_{\alpha,\beta} \circ f_\alpha : S \to S_{\alpha,\beta}$ is an onto homomorphism for each $\alpha\varepsilon A$ and $\beta\varepsilon A_\alpha$, and the collection $\{\gamma_{\alpha,\beta}\}_{\alpha\varepsilon A, \beta\varepsilon A_\alpha}$ of congruences on S induced by $\{g_{\alpha,\beta} \circ f_\alpha\}_{\alpha\varepsilon A, \beta\varepsilon A_\alpha}$ separates elements of S, so that S is the subdirect product of $\{S_{\alpha,\beta}\}_{\alpha\varepsilon A, \beta\varepsilon A_\alpha}$ by corollary 4.13.

The proof of the following theorem is found on p. 24 of Introduction to Semigroups, by Mario Petrich.

Theorem 4.15. Every semigroup is a subdirect product of subdirectly irreducible semigroups.

Proof. If S is a semigroup, $a \in S$, and $b \in S$ such that $a \neq b$, then define $M(a,b) = \{\rho \text{ congruence on } S \mid \rho \text{ separates } a \text{ and } b\}$. Therefore, $M(a,b) \neq \phi$ since $\varepsilon_S \in M(a,b)$. Let Γ be a chain in $M(a,b)$, and define $\lambda = \bigcup_{\rho\in\Gamma} \rho \subseteq S \times S$. If $x \in S$, then $(x,x) \in \rho$ for each $\rho \in \Gamma$, so that $(x,x) \in \bigcup_{\rho\in\Gamma} \rho = \lambda$ and λ is reflexive. If $x \in S$ and $y \in S$ such that $(x,y) \in \lambda$, then there exists $\rho \in \Gamma$ such that $(x,y) \in \rho$. Therefore, $(y,x) \in \rho \subseteq \bigcup_{\rho\in\Gamma} \rho = \lambda$, and so λ is symmetric. If $x,y,z \in S$ such that $(x,y) \in \lambda$ and $(y,z) \in \lambda$, then there exist $\rho_1 \in \Gamma$ and $\rho_2 \in \Gamma$, such that $(x,y) \in \rho_1$ and $(y,z) \in \rho_2$. Since Γ is a chain, then either $\rho_1 \subseteq \rho_2$ or $\rho_2 \subseteq \rho_1$. If $\rho_1 \subseteq \rho_2$, then $(x,y) \in \rho_2$ and $(y,z) \in \rho_2$, so that $(x,z) \in \rho_2 \subseteq \bigcup_{\rho\in\Gamma} \rho = \lambda$; and if $\rho_2 \subseteq \rho_1$, then $(x,y) \in \rho_1$ and $(y,z) \in \rho_1$, so that $(x,z) \in \rho_1 \subseteq \bigcup_{\rho\in\Gamma} \rho = \lambda$. Therefore, if $(x,y) \in \lambda$ and $(y,z) \in \lambda$, then $(x,z) \in \lambda$, and so λ is an equivalence relation on S. If $(w,x) \in \lambda$ and $(y,z) \in \lambda$, then there exists $\rho_3 \in \Gamma$ and $\rho_4 \in \Gamma$ such that $(w,x) \in \rho_3$ and $(y,z) \in \rho_4$. As before, either $\rho_3 \subseteq \rho_4$ or $\rho_4 \subseteq \rho_3$ since Γ is a chain. If $\rho_3 \subseteq \rho_4$, then $(w,x) \in \rho_4$ and $(y,z) \in \rho_4$, so that $(wy,xz) \in \rho_4 \subseteq \bigcup_{\rho\in\Gamma} \rho = \lambda$; and if $\rho_4 \subseteq \rho_3$, then $(w,x) \in \rho_3$ and $(y,z) \in \rho_3$, so that

$(wy, xz) \in \rho_3 \subseteq \bigcup_{\rho\in\Gamma} \rho = \lambda$. Thus λ is a congruence on S. Furthermore, since ρ separates a and b for each $\rho \in \Gamma$, then $(a,b) \notin \rho$ for each $\rho \in \Gamma$, so that $(a,b) \notin \bigcup_{\rho\in\Gamma} \rho = \lambda$. Therefore, λ separates a and b, and so $\lambda \in M(a,b)$. Obviously, $\rho \subseteq \bigcup_{\rho\in\Gamma} \rho = \lambda$ for each $\rho \in \Gamma$, so that λ is an upper bound for Γ. Thus every chain Γ in $M(a,b)$ has an upper bound $\lambda \in M(a,b)$, so that $M(a,b)$ has a maximal element $\sigma(a,b)$ by Zorn's Lemma. Hence, for each $(x,y) \in S \times S$ such that $x \neq y$, there exists a maximal congruence $\sigma(x,y)$ on S which separates x and y. Define $A = \{\sigma(x,y) \mid x \in S, y \in S, x \neq y\}$, so that A is a family of congruences on S which separates elements of S. Therefore, S is a subdirect product of semigroups $\{S/_{\sigma(x,y)}\}_{\sigma(x,y)\in A}$ by theorem 4.10.

Now if $a \in S$ and $b \in S$ such that $a \neq b$, then define $P = \{\rho \text{ congruence on } S \mid \sigma(a,b) \subseteq \rho\}$. For each $\rho \in P$, define ρ' on $S/_{\sigma(a,b)}$ by $(x_{\sigma(a,b)}, y_{\sigma(a,b)}) \in \rho'$ iff $(x,y) \in \rho$, for all $x \in S$, $y \in S$. Define $P' = \{\rho' \mid \rho \in P\}$. By lemma 2.26, $f: P \to P'$ defined by $f(\rho) = \rho'$ for all $\rho \in P$ is a one-to-one, order-preserving function, with $f(\sigma(a,b)) = \varepsilon_{S/_{\sigma(a,b)}}$. Therefore, if $\rho \in P$ such that $\sigma(a,b) \subset \rho$, then $\rho \neq \sigma(a,b)$, so that $\rho' = f(\rho) \neq f(\sigma(a,b)) = \varepsilon_{S/_{\sigma(a,b)}}$, since f is one-to-one. Thus $f: P \setminus \{\sigma(a,b)\} \to P' \setminus \{\varepsilon_{S/_{\sigma(a,b)}}\}$, so that

$$f: \{\rho \text{ congruence on } S \mid \sigma(a,b) \subset \rho\} \to \{\rho' \text{ congruence on } S/_{\sigma(a,b)} \mid \rho' \neq \varepsilon_{S/_{\sigma(a,b)}}\}.$$

Define $\alpha = \bigcap_{\rho \varepsilon P \setminus \{\sigma(a,b)\}} \rho$, $\alpha' = \bigcap_{\rho' \varepsilon P' \setminus \{\varepsilon_{S/\sigma(a,b)}\}} \rho'$.

Since f is one-to-one, then

$$f(\alpha) = f[\bigcap_{\rho \varepsilon P \setminus \{\sigma(a,b)\}} \rho] = \bigcap_{\rho \varepsilon P \setminus \{\sigma(a,b)\}} f(\rho) = \bigcap_{\rho' \varepsilon P' \setminus \{\varepsilon_{S/\sigma(a,b)}\}} \rho' = \alpha'.$$

However, if $\rho \varepsilon P \setminus \{\sigma(a,b)\}$, then $\sigma(a,b) \subset \rho$, so that ρ does not separate a and b, since $\sigma(a,b)$ is maximal. Thus $a_\rho = b_\rho$, and so $(a,b) \varepsilon \rho$. Therefore, $(a,b) \varepsilon \rho$ for all $\rho \varepsilon P \setminus \{\sigma(a,b)\}$, so that $(a,b) \varepsilon \bigcap_{\rho \varepsilon P \setminus \{\sigma(a,b)\}} \rho = \alpha$. Hence α does not separate a and b, so that $\alpha \neq \sigma(a,b)$. However, $\sigma(a,b) \subset \rho$ for all $\rho \varepsilon P \setminus \{\sigma(a,b)\}$, so that $\sigma(a,b) \subseteq \bigcap_{\rho \varepsilon P \setminus \{\sigma(a,b)\}} \rho = \alpha$. Thus $\sigma(a,b) \subset \alpha$, so that $\alpha \varepsilon P \setminus \{\sigma(a,b)\}$, and so

$$\alpha' \neq \bigcap_{\rho' \varepsilon P' \setminus \{\varepsilon_{S/\sigma(a,b)}\}} \rho' = f(\alpha) \varepsilon P' \setminus \{\varepsilon_{S/\sigma(a,b)}\}.$$

Therefore, the intersection α' of all proper congruences ρ' on $S/_{\sigma(a,b)}$ is a proper congruence on $S/_{\sigma(a,b)}$, so that $S/_{\sigma(a,b)}$ is subdirectly irreducible by theorem 4.12. Thus S is a subdirect product of $\{S/_{\sigma(x,y)}\}_{\sigma(x,y) \varepsilon A}$, where $S/_{\sigma(x,y)}$ is subdirectly irreducible for each $\sigma(x,y) \varepsilon A$.

Corollary 4.16. Every commutative or idempotent semigroup is a subdirect product of subdirectly irreducible commutative or idempotent semigroups, respectively.

Proof. If S is a semigroup, then S is a subdirect product of subdirectly irreducible semigroups $\{S_\alpha\}_{\alpha \varepsilon A}$ by theorem 4.15. By corollary 4.13, there exists a collection $\{f_\alpha\}_{\alpha \varepsilon A}$ such that $f_\alpha : S \to S_\alpha$ is a homomorphism of S onto S_α for each $\alpha \varepsilon A$. Therefore, $f_\alpha(S) = S_\alpha$ for each $\alpha \varepsilon A$, so that S_α is a homomorphic image of S for each $\alpha \varepsilon A$. Thus if S is commutative or idempotent, then S_α is commutative or idempotent, respectively, by lemma 4.11.

The following theorem characterizes all subdirectly irreducible finite abelian groups.

Theorem 4.17. If G is a finite abelian group, then G is subdirectly irreducible iff G is cyclic and there exist $p \varepsilon Z^+$ and $n \varepsilon Z^+$ such that p is prime and $|G| = p^n$.

Proof. Suppose G is cyclic, $p \varepsilon Z^+$, and $n \varepsilon Z^+$ such that p is a prime and $|G| = p^n$. Since G is cyclic, then there exists $a \varepsilon G$ such that $G = \langle a \rangle$, the subgroup generated by $\{a\}$.

Case I: Suppose n = 1. If H is a subgroup of G, then H is also cyclic, so that there exists $x \varepsilon H$ such that $H = \langle x \rangle$. If x = e, the identity for G, then $H = \langle x \rangle = \{e\}$. If $x \neq e$, then x is a generator for G, since G is of prime order, so that $H = \langle x \rangle = G$. Thus the only nontrivial normal subgroup (and hence proper congruence, by theorem 2.19) of G is G itself. Therefore, G is the least proper congruence on G, and so G is subdirectly irreducible by theorem 4.12.

Case II: Suppose n >1. By Sylow's theorem, there exists a normal subgroup H of $\langle a \rangle$ such that $|H| = p$. If $m \varepsilon Z^+$ and $a^m = e$, then $m \geq p^n$ since $|\langle a \rangle| = p^n$. However, $H \neq \{e\}$, and so there exists $a^w \varepsilon \langle a \rangle \backslash \{e\} = \{a^i\}_{i=1}^{p^n - 1}$ such that $a^w \varepsilon H$, where $w \leq p^n-1 < p^n \leq m$. Thus if $m \varepsilon Z^+$ and $a^m = e$, then there exists $w \varepsilon Z^+$ such that $w < m$ and $a^w \varepsilon H$. By contrapositive, if m is the smallest positive integer such that $a^m \varepsilon H$, then $a^m \neq e$. Since H is of prime order, then any non-identity element of H is a generator for H. Therefore, $H = \langle a^m \rangle = \{(a^m)^i\}_{i=1}^p$, where $1 \leq im \leq p^n$ for all i, $1 \leq i \leq p$. Since $|\langle a^m \rangle| = |H| = p$, then $a^{mp} = (a^m)^p = e$.

Assume that $m > p^{n-1}$. Then $mp > p^n$. Let q be the least positive integer in $\{1,2,\cdots,p\}$ such that $mq > p^n$. Therefore there exists $t \varepsilon Z^+$ and $r \varepsilon Z^+$, $0 \leq r < m$, such that $mq = tp^n + r$. If $r = 0$, then $mq = tp^n$, so that $m = \frac{tp^n}{q}$ and $a^m = (a^{p^n})^{\frac{t}{q}} = (e)^{\frac{t}{q}} = e$. However, $a^m \neq e$, so that $r \neq 0$, and so $0 < r < m$. Since $mq = tp^n + r$, then $mq - tp^n = r$. Now $a^{mq} = (a^m)^q \varepsilon H$ since $a^m \varepsilon H$, and $a^{-tp^n} = (a^{p^n})^{-t} = e^{-t} = e \varepsilon H$. Therefore, $a^r = a^{mq-tp^n} = a^{mq} \cdot a^{-tp^n} \varepsilon H$, where $0 < r < m$. This is a contradiction, since m is the smallest positive integer such that $a^m \varepsilon H$. Thus $m \leq p^{n-1}$, so that $mp \leq p^{n-1}p = p^n$. Furthermore, $|\langle a^m \rangle| = |H| = p$, so that $a^{mp} = e$. However, $|\langle a \rangle| = p^n$, so that p^n is the smallest positive integer such that $a^{p^n} = e$, and so $mp \geq p^n$. Therefore, $mp = p^n$, so that $m = p^{n-1}$, and so $H = \langle a^m \rangle = \langle a^{p^{n-1}} \rangle$. Thus $\langle a^{p^{n-1}} \rangle$ is the unique normal subgroup of $\langle a \rangle$ of order p.

Now if D is a normal subgroup of $\langle a \rangle$, then $|D|$ divides $|\langle a \rangle|$ by Lagrange's theorem. Therefore, $|D|$ divides p^n so that $|D| = p^t$ for some $t \varepsilon Z$, $0 \leq t \leq n$. Furthermore, if D is nontrivial, the $p^t = |D| > 1$, so that $1 \leq t \leq n$. Thus D has a normal subgroup C such that $|C| = p$ by Sylow's theorem. But then C is a normal subgroup of $<a>$. Since $<a^{p^{n-1}}>$ is the unique normal subgroup of $<a>$ of order p, then $<a^{p^{n-1}}> = C \subseteq D$. Therefore, if D is any nontrivial normal subgroup of $<a>$, then $<a^{p^{n-1}}> \subseteq D$. Hence $<a^{p^{n-1}}>$ is the least nontrivial normal subgroup of $<a> = G$, so that there corresponds a least proper congruence on G by theorem 2.19, and so G is subdirectly irreducible by theorem 4.12.

Conversely, suppose G is a subdirectly irreducible finite abelian group with identity e. If G is not of order p^n, where p is prime and $n \in Z^+$, then there exist distinct primes p and q such that p divides $|G|$ and q divides $|G|$. By Cauchy's theorem, there exist normal subgroups H and K of G such that $|H| = p$ and $|K| = q$. Since H and K are of prime order, then H and K are cyclic, and so there exist $a \in G$ and $b \in G$ such that $H = <a>$ and $K = <b>$. Now $e \in H \cap K$. However, if there exists $x \in H \cap K$ such that $x \neq e$, then x is a generator for H and K. Therefore, $H = <x> = K$, and so $p = |H| = |K| = q$. This is a contradiction since p and q are distinct primes, so that $H \cap K = \{e\}$, and so $\{H,K\}$ is a collection of nontrivial normal subgroups of G whose intersection is the trivial normal subgroup $\{e\}$ of G. Hence, there exists a collection of corresponding proper congruences on G whose intersection is the improper congruence ε_G on G, and so G is not subdirectly irreducible by theorem 4.12. Since this contradicts the original hypothesis, then $|G| = p^n$, where p is a prime and $n \varepsilon Z^+$.

If Q is a subdirectly irreducible finite abelian group and $|Q| = p^1$, then Q is of prime order, and so Q is cyclic. Now assume that for each $i \varepsilon Z^+$, $1 \leq i \leq k-1$, if Q is a subdirectly irreducible finite abelian group and $|Q| = p^i$, then Q is cyclic. Let Q be a subdirectly irreducible finite abelian group such that $|Q| = p^k$. Define $H = \{x^p | x \varepsilon Q\}$, so that $H \subseteq Q$. Define $f:Q \to H$ by $f(x) = x^p$ for each $x \varepsilon Q$. Since $Q \neq \phi$, then there exists $x \varepsilon Q$, so that $f(x) = x^p \varepsilon H$. Therefore, $(x,x^p) \varepsilon f$, and so $f \neq \phi$. Moreover, if $(x,y) \varepsilon f$, then $x \varepsilon Q$ and $y = f(x) = x^p \varepsilon H$, so that $f \subseteq Q \times H$. Furthermore, if $x \varepsilon Q$ and $y \varepsilon Q$ such that $x = y$, then $f(x) = x^p = y^p = f(y)$, and so f is a well-defined function. If $z \varepsilon H$, then there exists $x \varepsilon Q$ such that $z = x^p = f(x)$, so that f is onto H. Finally, if $x \varepsilon Q$ and $y \varepsilon Q$, then $f(xy) = (xy)^p = x^p y^p$ (since Q is abelian) $= f(x)\ f(y)$. Therefore, $f:Q \to H$ is a well-defined, onto homomorphism, and so $H = f(Q)$ is a group since Q is a group. Hence, H is a subgroup of G. Furthermore, since Q is subdirectly irreducible and $|Q| = p^k$, then Q has a least proper congruence, and so there exists a corresponding unique nontrivial normal subgroup T of Q such that $|T| = p$. Since T is of prime order, then any non-identity element of T is a generator for T. Since $|T| = p$, then $f(x) = x^p = e$ for all $x \varepsilon T$, so that $T \subseteq \ker(f)$. Assume there exists $x \varepsilon Q \backslash T$ such that $x \varepsilon \ker(f)$. Therefore

$x^p = f(x) = e$, so that $|\langle x\rangle| \leq p$. Since $|Q| = p^k$, then $|\langle x\rangle|$ divides p^k, so that either $|\langle x\rangle| = 1$ or $|\langle x\rangle| = p$. If $|\langle x\rangle| = 1$, then $\langle x\rangle = \{e\}$, so that $x = e \in T$. This is a contradiction since $x \in Q\backslash T$. Therefore, $|\langle x\rangle| = p$. Since $x \in \langle x\rangle$ but $x \notin T$, then $\langle x\rangle \neq T$. Furthermore, $\langle x\rangle$ is a normal subgroup of Q since Q is abelian. Thus $\langle x\rangle$ and T are distinct normal subgroups of Q of order p. However, this is also a contradiction since T is the unique normal subgroup of Q of order p. Therefore, if $x \in Q\backslash T$, then $x \notin \ker(f)$, so that $\ker(f) \subseteq T$. Hence $T = \ker(f)$. Since $f: Q \to H$ is an onto homomorphism, then $H \cong Q/\ker(f)$ by the fundamental theorem of group homomorphisms, so that

$$|H| = |Q/\ker(f)| = |Q/T| = \frac{|Q|}{|T|} = \frac{p^k}{p} = p^{k-1}.$$

Assume that H is not subdirectly irreducible, so that there exists a collection $\{\rho_\alpha\}_{\alpha\varepsilon A}$ of proper congruences on H such that $\bigcap_{\alpha\varepsilon A} \rho_\alpha = \varepsilon_H$. Therefore, there exists a collection $\{B_\alpha\}_{\alpha\varepsilon A}$ of corresponding nontrival normal subgroups of H such that $\bigcap_{\alpha\varepsilon A} B_\alpha = \{e\}$ by theorem 2.19. However, since B_α is a nontrivial subgroup of H for each $\alpha \varepsilon A$, and H is a subgroup of Q, then $\{B_\alpha\}_{\alpha\varepsilon A}$ is a collection of nontrivial subgroups of Q. Furthermore, B_α is normal in Q for all $\alpha \varepsilon A$ since Q is abelian. Therefore, since $\bigcap_{\alpha\varepsilon A} B_\alpha = \{e\}$, then there exists a collection $\{\sigma_\alpha\}_{\alpha\varepsilon A}$ of corresponding proper congruences on Q such that $\bigcap_{\alpha\varepsilon A} \sigma_\alpha = \varepsilon_Q$ by theorem 2.19, and so Q is not subdirectly irreducible. This contradicts the hypothesis, and so H is subdirectly irreducible. Since $|H| = p^{k-1}$, then H is cyclic by hypothesis. Therefore, there exists $x \varepsilon Q$ such that $x^p \varepsilon H$ and $\langle x^p \rangle = H$, so that $|\langle x^p \rangle| = |H| = p^{k-1}$, and so $x^{p^k} = (x^p)^{p^{k-1}} = e$. Since $|\langle x \rangle|$ divides $|Q| = p^k$, then there exists $t \varepsilon Z$, $0 \leq t \leq k$, such that $|\langle x \rangle| = p^t$. If $t < k$, then $t-1 < k-1$, and so $p^{t-1} < p^{k-1}$. Therefore, since $|\langle x^p \rangle| = p^{k-1}$, then $x^{p^t} = (x^p)^{p^{t-1}} \neq e$. This is a contradiction, since $|\langle x \rangle| = p^t$, and so $t = k$. Hence $|\langle x \rangle| = p^k = |Q|$, so that $\langle x \rangle = Q$, and so Q is cyclic. Therefore, by mathematical induction, if Q is a subdirectly irreducible finite abelian group, p is a prime, $m \varepsilon Z^+$, and $|Q| = p^m$, then Q is cyclic. Thus, since G is a subdirectly irreducible finite abelian group and $|G| = p^n$, where p is a prime and $n \varepsilon Z^+$, then G is cyclic.

Theorem 4.18. A zero semigroup is subdirectly irreducible iff $|S| = 2$.

Proof. Suppose S is a subdirectly irreducible zero semigroup with zero 0. If $|S| \neq 2$, then either $|S| = 1$ or $|S| \geq 3$. If $|S| = 1$, then there does not exist a proper congruence on S, and so S is not subdirectly irreducible. This is a contradiction, and so $|S| \neq 1$. If $|S| \geq 3$, then there exists $a \varepsilon S$ and $b \varepsilon S$ such that $a \neq 0$, $b \neq 0$, and $a \neq b$. Define relations ρ and γ on S by

$$x_\rho = \begin{cases} \{x\} \text{ for each } x \varepsilon S \setminus \{a,0\} \\ \{a,0\} \text{ for each } x \varepsilon \{a,0\} \end{cases}$$

and

$$x_\gamma = \begin{cases} \{x\} \text{ for each } x \in S \setminus \{b,0\} \\ \{b,0\} \text{ for each } x \in \{b,0\}. \end{cases}$$

Since ρ partitions S, then ρ induces an equivalence relation on S. Furthermore, if $w,x,y,z \in S$ such that $(w,x) \in \rho$ and $(y,z) \in \rho$, then $(wy,xz) = (0,0) \in \rho$, and so ρ is a congruence on S. Similarly, γ is also a congruence on S. Now $\rho \setminus \varepsilon_S = \{(a,0),(0,a)\}$ and $\gamma \setminus \varepsilon_S = \{(b,0),(0,b)\}$. Since $a \neq b$ and $a \neq 0$, then $(a,0) \notin \gamma \setminus \varepsilon_S$ and $(0,a) \notin \gamma \setminus \varepsilon_S$, so that $(\rho \setminus \varepsilon_S) \cap (\gamma \setminus \varepsilon_S) = \phi$, and thus $\rho \cap \gamma = \varepsilon_S$. Hence, ρ and γ are proper congruences on S whose intersection is an improper congruence on S, and so S is not subdirectly irreducible. This contradicts the hypothesis, so that $|S| < 3$. Therefore, since $|S| \neq 1$ and $|S| < 3$, then $|S| = 2$.

Conversely, if $|S| = 2$, then the universal relation $w_S = S \times S$ is the only proper congruence on S, and is thus the least proper congruence on S. Therefore, S is subdirectly irreducible by theorem 4.12.

Lemma 4.19. Every cyclic semigroup S with zero z is finite. Furthermore, if N is the smallest positive integer t such that $a^t = z$, where $\langle a \rangle = S$, then $|S| = N$.

Proof. Since S is cyclic, then there exists $a \in S$ such that $\langle a \rangle = S$. If z is the zero for S, then $z \in \langle a \rangle$, and so there exists $n \in Z^+$ such that $a^n = z$. For each $m > n$, $m - n > 0$, so that $a^{m-n} \in S$. Therefore, $a^m = a^{n+(m-n)} = a^n \cdot a^{m-n} = z \cdot a^{m-n} = z$, so that $|S| \leq n$, and thus S is finite.

Define $B = \{x \in Z^+ | a^x = z\}$, so that $B \neq \phi$ since $n \in B$. Since Z^+ is well-ordered, then there exists a least element N of B. Therefore, $a^m = z$ for each $m \geq N$, so that $|S| \leq N$. Assume that there exist $i \in Z^+$ and $j \in Z^+$ such that $1 \leq i < j \leq N$ and $a^i = a^j$. Since N is the least element of B and $i < j$, then $j \neq N$. Hence, $1 \leq i < j < N$, so that $N-j > 0$ and $a^{N-j} \in S$. Therefore,
$z = a^N = a^{j+N-j} = a^j \cdot a^{N-j} = a^i \cdot a^{N-j} = a^{i+N-j} = a^{N-(j-i)}$,
and so $N-(j-i) \in B$. However, $j > i$, so that $j-i > 0$, and $N-(j-i) < N$. This is a contradiction, since N is the least element of B. Therefore, if $i \in Z^+$ and $j \in Z^+$, such that $1 \leq i \leq N$, $1 \leq j \leq N$, and $i \neq j$, then $a^i \neq a^j$, and so $|S| = N$.

Theorem 4.20. Every nontrivial cyclic semigroup with zero is subdirectly irreducible.

Proof. Let S be a nontrivial cyclic semigroup with zero z; then there exists $a \in S$ such that $\langle a \rangle = S$. By lemma 4.19, S is finite, and if n is the smallest positive integer t such that $a^t = z$, then $|S| = n$, so that $S = \{a^1, a^2, \cdots, a^{n-1}, a^n\}$. Define ρ on S by

$$a^i_\rho = \begin{cases} \{a^i\}, & 1 \leq i \leq n-2 \\ \{a^{n-1}, a^n\}, & n-1 \leq i \leq n. \end{cases}$$

Since ρ partitions S, then ρ induces an equivalence relation on S. Suppose $a^i, a^j, a^k, a^m \in S$ such that $(a^i, a^j) \in \rho$, and $(a^k, a^m) \in \rho$. If $1 \leq i \leq n-2$ and $1 \leq k \leq n-2$, then $\{a^i\} = a^i_\rho = a^j_\rho = \{a^j\}$ and $\{a^k\} = a^k_\rho = a^m_\rho = \{a^m\}$. Therefore, $i = j$ and $k = m$, so that $i + k = j + m$. Hence, $a^i a^k =$

$a^{i+k} = a^{j+m} = a^j a^m$, and so $(a^i a^k, a^j a^m) \varepsilon \rho$ since ρ is reflexive. If $i \geq n-1$, then $j \geq n-1$ since $(a^i, a^j) \varepsilon \rho$. Since $k \geq 1$ and $m \geq 1$, then $i+k \geq n$ and $j+m \geq n$, so that $a^i a^k = a^{i+k} = z = a^{j+m} = a^j a^m$, and hence $(a^i a^k, a^j a^m) \varepsilon \rho$. Similarly, if $k \geq n-1$, then $(a^i a^k, a^j a^m) \varepsilon \rho$. Thus ρ is a congruence on S. Furthermore, since $n-1 < n$, and n is the least positive integer t such that $a^t = z$, then $a^{n-1} \neq z = a^n$. Therefore, since $(a^{n-1}, a^n) \varepsilon \rho$, then ρ is a proper congruence on S. Note that $\rho = \varepsilon_S \cup \{(a^{n-1}, a^n), (a^n, a^{n-1})\}$. Now if γ is any proper congruence on S, then there exist $i \varepsilon Z^+$ and $j \varepsilon Z^+$ such that $1 \leq i < j \leq n$ and $(a^i, a^j) \varepsilon \rho$. Since $i < j \leq n$, then $i \leq n-1$. If $i = n-1$, then $j = n$, since $i < j$. Therefore, since $(a^i, a^j) \varepsilon \gamma$, then $(a^{n-1}, a^n) \varepsilon \gamma$, and so $(a^n, a^{n-1}) \varepsilon \gamma$ since γ is symmetric. Hence, $\varepsilon_S \subseteq \gamma$, $(a^{n-1}, a^n) \varepsilon \gamma$, and $(a^n, a^{n-1}) \varepsilon \gamma$, so that $\rho \subseteq \gamma$. On the other hand, if $i < n-1$, then $n-1-i > 0$, so that $a^{n-1-i} \varepsilon S$, and hence $(a^{n-1-i}, a^{n-1-i}) \varepsilon \gamma$ since γ is reflexive. Since $(a^i, a^j) \varepsilon \gamma$ as well, then $(a^{n-1}, a^{n-1+j-i}) = (a^i a^{n-1-i}, a^j a^{n-1-i}) \varepsilon \gamma$. However, $j-i > 0$ since $i < j$, so that $n-1+j-i > n-1$, and hence $n-1+j-i \geq n$. Therefore, $a^{n-1+j-i} = z = a^n$, so that $(a^{n-1}, a^n) = (a^{n-1}, a^{n-1+j-i}) \varepsilon \gamma$, and so $(a^n, a^{n-1}) \varepsilon \gamma$, since γ is symmetric. Since $\varepsilon_S \subseteq \gamma$, $(a^{n-1}, a^n) \varepsilon \gamma$, and $(a^n, a^{n-1}) \varepsilon \gamma$, then $\rho \subseteq \gamma$ as before. Thus ρ is a proper congruence on S, and if γ is any proper congruence on S, then $\rho \subseteq \gamma$. Hence ρ is the least proper congruence on S, and so S is subdirectly irreducible.

Lemma 4.21. Let S be a nontrivial semigroup with zero 0. If N is an ideal of S, and ρ is the equivalence relation on S defined by

$$x_\rho = \begin{cases} N & \text{for each } x \in N \\ \{x\} & \text{for each } x \in S\setminus N, \end{cases}$$

then ρ is a congruence on S with $0_\rho = N$. Conversely, if ρ is a congruence on S, then 0_ρ is an ideal of S.

Proof. Suppose N is an ideal of S and define ρ on S by

$$x_\rho = \begin{cases} N & \text{for each } x \in N \\ \{x\} & \text{for each } x \in S\setminus N. \end{cases}$$

Since ρ partitions S, then ρ defines an equivalence relation on S. If $w,x,y,z \in S$ such that $(w,x) \in \rho$ and $(y,z) \in \rho$, then $w_\rho = x_\rho$ and $y_\rho = z_\rho$. If $w \notin N$ and $y \notin N$, then $\{w\} = w_\rho = x_\rho$ and $\{y\} = y_\rho = z_\rho$, so that $x = w$ and $z = y$. Therefore, $wy = xz$, and so $(wy,xz) \in \rho$. If $w \in N$, then $N = w_\rho = x_\rho$, so that $x \in N$ as well. Therefore, $wy \in N$ and $xz \in N$ since N is an ideal, so that $(wy)_\rho = N = (xz)_\rho$, and thus $(wy,xz) \in \rho$. Similarly, if $y \in N$, then $(wy,xz) \in \rho$. Hence, in any case, if $(w,x) \in \rho$ and $(y,z) \in \rho$, then $(wy,xz) \in \rho$, and so ρ is a congruence on S. Furthermore, since N is an ideal in S, then there exists $x \in N$, so that $0 = 0x \in N$, and thus $0_\rho = N$.

Conversely, if ρ is a congruence on S, then let $x \in S$ and $y \in 0_\rho$, so that $(y,0) \in \rho$. Since $(x,x) \in \rho$ also, then $(xy,0) = (xy,x0) \in \rho$ and $(yx,0) = (yx,0x) \in \rho$. Therefore, $xy \in 0_\rho$ and $yx \in 0_\rho$, and so 0_ρ is an ideal in S.

Definition 4.22. The congruence ρ on S defined in lemma 4.21 is the congruence on S induced by the ideal N.

Definition 4.23. An ideal N of a semigroup S is degenerate iff $|N| = 1$; N is nondegenerate iff $|N| > 1$.

Corollary 4.24. If N is a nondegenerate ideal of a semigroup S with zero 0, then the congruence ρ on S induced by N is a proper congruence.

Proof. Since N is an ideal of S, then $0 \in N$. However, $N \neq \{0\}$ since N is nondegenerate, and so there exists $a \in S\setminus\{0\}$ such that $\{0,a\} \subseteq N$. Therefore, if ρ is the congruence on S induced by N, then $0_\rho = N = a_\rho$. Hence $(0,a) \in \rho$, while $0 \neq a$ since $a \in S\setminus\{0\}$, and so $\rho \neq \varepsilon_S$. Thus, ρ is a proper congruence on S.

Theorem 4.25. If S is a semigroup with zero 0 such that: (1) there exists a least nondegenerate ideal of S, and (2) 0_ρ is a nondegenerate ideal of S whenever ρ is a proper congruence on S, then S is subdirectly irreducible.

Proof. Let N be the least nondegenerate ideal of S. By corollary 4.24, N induces a proper congruence ρ on S defined by

$$x_\rho = \begin{cases} N \text{ for each } x \in N \\ \{x\} \text{ for each } x \in S\setminus N. \end{cases}$$

If γ is any proper congruence on S, then 0_γ is a nondegenerate ideal of S by hypothesis, and so $N \subseteq 0_\gamma$. If $(a,b) \in \rho\setminus\varepsilon_S$, then $a \neq b$, and so $\{a\} \neq \{b\}$. Since $a_\rho = b_\rho$, then $a_\rho \neq \{a\}$ and $b_\rho \neq \{b\}$, so that $a_\rho = b_\rho = N$. Hence $a \in N \subseteq 0_\gamma$ and

$b \in N \subseteq 0_\gamma$, so that $a_\gamma = b_\gamma = 0_\gamma$, and thus $(a,b) \in \gamma$. Therefore, if $(a,b) \in \rho \setminus \varepsilon_S$, then $(a,b) \in \gamma$, so that $\rho \setminus \varepsilon_S \subseteq \gamma$. Since $\varepsilon_S \subseteq \gamma$ as well, then $\rho = \varepsilon_S \cup (\rho \setminus \varepsilon_S) \subseteq \gamma$. Thus ρ is the least proper congruence on S, and so S is subdirectly irreducible.

It so happens that the converse of theorem 4.25 is false. This is a consequence of the fact that the converse of corollary 4.24 is false, as shown by the following example.

Example 4.26. Let $S = \{0,1,2\}$ be the semigroup of integers modulo 3 with modular multiplication. Define ρ on S by $1_\rho = 2_\rho = \{1,2\}$; $0_\rho = \{0\}$. Then ρ is the least proper congruence on S, and so S is subdirectly irreducible. However, although ρ is a proper congruence on S, $0_\rho = \{0\}$ is a degenerate ideal of S. However, the following somewhat weaker result is true.

Theorem 4.27. Let S be a subdirectly irreducible semigroup with zero 0. If 0_ρ is a nondegenerate ideal of S whenever ρ is a proper congruence on S, then there exists a least nondegenerate ideal of S.

Proof. Since S is subdirectly irreducible, then there exists a least proper congruence ρ on S. By hypothesis, 0_ρ is a nondegenerate ideal of S. If N is any nondegenerate ideal of S, then $0 \in N$. By corollary 4.24, N induces a proper congruence γ on S defined by

$$x_\gamma = \begin{cases} N \text{ for each } x \in N \\ \{x\} \text{ for each } x \in S \setminus N, \end{cases}$$

and so $\rho \subseteq \gamma$. Therefore, if $a \in 0_\rho$, then $(a,0) \in \rho \subseteq \gamma$, so that $a_\gamma = 0_\gamma = N$ since $0 \in N$, and thus $a \in N$. Hence $0_\rho \subseteq N$, and so 0_ρ is the least nondegenerate ideal of S.

Corollary 4.28. If S is a semigroup with zero 0 in which 0_ρ is a nondegenerate ideal of S whenever ρ is a proper congruence on S, then S is subdirectly irreducible iff S has a least nondegenerate ideal.

Proof. Suppose S has a least nondegenerate ideal. Since 0_ρ is a nondegenerate ideal of S whenever ρ is a proper congruence on S, then the hypothesis of theorem 4.25 is satisfied, and so S is subdirectly irreducible.

Conversely, suppose S is subdirectly irreducible. Since 0_ρ is a nondegenerate ideal of S whenever ρ is a proper congruence on S, it follows that S has a least nondegenerate ideal by theorem 4.27.

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