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COMMUNICATION SCIENCES PROGRAM

Technical Note

Normal Monoids and Factor Monoids of Commutative Monoids

YEHOSHAFAT GIVE'ON

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Yehoshafat Give'on

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§1 Introduction

The relevance of the theory of monoids to automata theory has recently become more and more apparent. (See, for example, Mezei [2] with respect to finite automata, and Laing and Wright [1] with respect to the theory of commutative machines.) In this paper certain properties of commutative monoids are discussed; some of them are directly relevant to the theory of commutative automata. In particular, we are interested in finitely generated monoids and in finite factor monoids.

We begin with a study of three closure operations on submonoids of a commutative monoid which provides us with tools for the study of factor monoids. Next we discuss some properties of factor monoids and give certain conditions for finite factor monoids. We conclude with the proof that those closure operations lead to finitely generated monoids when they are applied on any submonoid of any finitely generated free commutative monoid. In particular this implies that any normal submonoid of any finitely generated free commutative monoid is finitely generated.

The notation used in this paper partially follows the notation used in [1] for employing regular expressions to denote commutative events. The customary notation of abelian algebras is also used. Thus B^* , x^* , and λ^* denote the commutative monoids generated by B (any non-empty set of elements of a given commutative monoid,) x (any element of a given commutative monoid) and λ (the identity element of the monoid under discussion). But "+" denotes the operation of the monoid and therefore $x+B^*$ denotes the coset determined by the monoid generated by B with x as a leader.

The problems discussed in this paper were suggested by J. B. Wright; I wish to thank him for prompting this research and for his continuous interest.

§2 The closure operators N_F , S_F and H_F .

Let F be a fixed commutative monoid.

Definition 1: Let M be a submonoid of F . We denote by $N_F(M)$ the set of all elements y of F for which $x+y \in M$ for some $x \in M$. $N_F(M)$ is said to be the normal extension of M in F and M is said to be a normal submonoid of F (in short normal) iff $N_F(M) = M$.

Lemma 1: Let M be a submonoid of F , then:

- (i) $N_F(M)$ is the minimal normal submonoid of F which includes M ;
- (ii) M is normal iff $x, x+y \in M$ implies $y \in M$ for any $x, y \in F$.

Remark: For the proof of (i) we shall prove that N_F is a closure operation on the submonoids of F .

Proof: (1) $M \subseteq N_F(M)$.

Let $y \in M$ then $y+\lambda \in M$. Since $\lambda \in M$ we get $y \in N_F(M)$.

(2) $N_F(M)$ is a submonoid of F .

Let $x_1, x_2 \in N_F(M)$, then $x_1 + y_1, x_2 + y_2 \in M$ for some $y_1, y_2 \in M$ and therefore $(x_1 + x_2) + (y_1 + y_2) \in M$ where $y_1 + y_2 \in M$, which shows that $x_1 + x_2 \in N_F(M)$. Since $\lambda \in N_F(M)$ we have that $N_F(M)$ is a submonoid of F .

(3) $N_F(N_F(M)) = N_F(M)$, hence $N_F(M)$ is normal.

By (1) we have that $N_F(M) \subseteq N_F(N_F(M))$. Let

$y \in N_F(N_F(M))$, then $y + x_1 \in N_F(M)$ for some $x_1 \in N_F(M)$. But $y + x_1 \in N_F(M)$ implies $y + x_1 + x_2 \in M$ for some $x_2 \in M$ and $x_1 \in N_F(M)$ implies $x_1 + x_3 \in M$ for some $x_3 \in M$. Hence, $y + (x_1 + x_2 + x_3) \in M$ where $x_1 + x_2 + x_3 \in M$, which shows that $y \in N_F(M)$. Thus we have $N_F(M) = N_F(N_F(M))$.

(4) Let M_1, M_2 be submonoids of F ; if $M_1 \subseteq M_2$ then

$$N_F(M_1) \subseteq N_F(M_2).$$

Let $x \in N_F(M_1)$ then $x + y \in M_1 \subseteq M_2$ for some

$y \in M_1 \subseteq M_2$ which shows that $x \in N_F(M_2)$.

To complete the proof of (i), let M' be any normal submonoid of F which includes M , then $N_F(M) \subseteq N_F(M') = M'$. This shows that $N_F(M)$ is the minimal normal submonoid of F which includes M .

The proof of (ii) follows immediately from Df. 1.

Corollary: Let M_1 be any intermediate submonoid of F between

M and $N_F(M)$, (i.e., $M \subseteq M_1 \subseteq N_F(M)$), then

$$N_F(M_1) = N_F(M).$$

Proof: Immediate.

Lemma 2: Let $\phi: F \rightarrow F_1$ be a homomorphism of F onto a monoid

F_1 . If M_1 is a normal submonoid of F_1 then $\phi^{-1}(M_1)$

is a normal submonoid of F . In particular, the kernel of ϕ is a normal submonoid of F .

Remark: Note that from the commutativity of F it follows that F_1 is commutative.

Proof: Since ϕ is a homomorphism it follows immediately that $\phi^{-1}(M_1)$ is a submonoid of F . Let $x, x+y \in \phi^{-1}(M_1)$

where $x, y \in F$, then we have $\phi(x), \phi(x+y) = \phi(x) + \phi(y) \in M_1$. Since M_1 is normal

we have that $\phi(y) \in M_1$ and therefore $y \in \phi^{-1}(M_1)$. Hence $\phi^{-1}(M_1)$ is a normal

submonoid of F .

Since $\lambda^* = \{\lambda\}$ is a normal submonoid of M_1 we get that

$\ker \phi = \phi^{-1}(\lambda) = \phi^{-1}(\lambda^*)$ is a normal submonoid of F .

Lemma 3: Let M be a submonoid of F ; then $(x+M) \cap (y+N) \neq \emptyset$
iff $(x+N_F(M)) \cap (y+N_F(M)) \neq \emptyset$

Proof: From $M \subseteq N_F(M)$ it follows that $(x+M) \cap (y+M) \neq \emptyset$
implies $(x+N_F(M)) \cap (y+N_F(M)) \neq \emptyset$. On the other hand,
let $(x+N_F(M)) \cap (y+N_F(M)) \neq \emptyset$ then we have $x+x_1 = y+y_1$ for some $x_1, y_1 \in N_F(M)$;
hence $x_1+u_1 = u_2$ and $y_1+v_1 = v_2$ for some $u_1, v_1, u_2, v_2 \in M$. Therefore,
 $x+x_1+u_1+v_1 = x+u_2+v_1$ and $x+x_1+u_1+v_1 = y+y_1+v_1+u_1 = y+v_2+u_1$, which imply
 $x+(u_2+v_1) = y+(v_2+u_1)$ and this shows that $(x+M) \cap (y+M) \neq \emptyset$ since $u_2+v_1, v_2+u_1 \in M$.

Lemma 4: Let M and N be two submonoids of F . If $M \subseteq N$
and N is normal then

$x \in N$ & $(x+M) \cap (y+M) \neq \emptyset$ implies $y \in N$.

Proof: We have $y+m_2 = x+m_1$ where $m_1, m_2 \in M \subseteq N$. Hence
 $m_2, y+m_2 \in N$ and therefore $y \in N$.

Definition 2: Let M_1 and M be two submonoids of F . We say that M_1 is subtractive onto M iff for any $x \in M_1$ there is $y \in M_1$ such that $x+y \in M$. We denote by $S_F(M)$ the set of all elements $x \in F$ such that $x+y \in M$ for some $y \in F$.

Lemma 5: Let M be a submonoid of F , then $S_F(M)$ is the maximal submonoid of F which is subtractive onto M .

Proof: Clearly $\lambda \in S_F(M)$. Let $x, y \in S_F(M)$, then we have $x+x_1, y+y_1 \in M$ for some $x_1, y_1 \in F$. Hence $(x+y)+(x_1+y_1) = (x+x_1)+(y+y_1) \in M$, which shows that $x+y \in S_F(M)$. Therefore $S_F(M)$ is a submonoid of F . By the definition of $S_F(M)$ it follows that any submonoid of F which is subtractive onto M is included in $S_F(M)$.

Corollary: $M \subseteq S_F(M)$.

Proof: M itself is subtractive onto M .

Lemma 6: Let M be a submonoid of F then $S_F(M)$ satisfies the following condition:

for any $x, y \in F$: $x+y \in S_F(M)$ implies

$x \in S_F(M)$. (In particular, $x+y \in M$ implies $x \in S_F(M)$.)

Proof: Let $x+y \in S_F(M)$ then $x+(y+z) \in M$ for some $z \in F$,
hence $x \in S_F(M)$.

Corollary: $S_F(M)$ is a normal submonoid of F . Hence, $x \in S_F(M)$ &
 $(x+M) \cap (y+M) \neq \emptyset$ implies $y \in S_F(M)$.

Proof: Immediate; the result follows from Lemma 4.

Lemma 7: S_F is a closure operation on the submonoids of F ; i.e.,

- (i) $M \subseteq S_F(M)$ and $S_F(M)$ is a submonoid of F ,
- (ii) $M_1 \subseteq M_2$ implies $S_F(M_1) \subseteq S_F(M_2)$,
- (iii) $S_F(S_F(M)) = S_F(M)$.

Proof: We had (i) as a corollary to Lemma 5. The proof

of (ii) is immediate by Df. 2. From (i) follows

that $S_F(M) \subseteq S_F(S_F(M))$; so let $x \in S_F(S_F(M))$ then we have $x+y \in S_F(M)$ for some

$y \in F$ and so we have $x+(y+z) \in M$ for some $y, z \in F$, thus $x \in S_F(M)$.

Corollary: Let M_1 be an intermediate submonoid of F between M and $S_F(M)$ then $S_F(M_1) = S_F(M)$.

Proof: Immediate.

Lemma 8: Let M_1 be an intermediate submonoid of F between M and $S_F(M)$. If M_1 is normal then it is subtractive onto M .

Proof: Let $x \in M_1 \subseteq S_F(M)$, then $x+y \in M$ for some $y \in S_F(M)$. But $M \subseteq M_1$ and so $x, x+y \in M_1$ which implies that $y \in M_1$. Hence for any $x \in M_1$ there is $y \in M_1$ such that $x+y \in M$.

Lemma 6 implies the following relation between the sets of generators for F and for $S_F(M)$

Lemma 9: Let W be a set of generators for F then $W' =_{df} \{w \in W : (w+F) \cap M \neq \emptyset\}$ is a set of generators for $S_F(M)$. In particular, if W is a basis of F then W' is a basis of $S_F(M)$.

Proof: From the definition of W' it is clear that

$W' \in S_F(M)$. Let $x \in S_F(M) \subseteq F$ then x is a finite sum of elements of W . Let w be any element of W which is a summand of x , then we have $x = w+y$ which implies by Lemma 6 that $w \in S_F(M)$ and therefore $w \in W'$. Hence x is a finite sum of elements of W' which shows that $S_F(M)$ is generated by W' .

Corollary: (i) If F is free then $S_F(M)$ is free.

(ii) If F is finitely generated then $S_F(M)$ is finitely generated.

Proof: Immediate.

The proof of the following lemma is now obvious and so is not given here.

Lemma 10: Let M , M_1 and M_2 be submonoids of F .

(i) $M_1 \in M_2$ implies that if M is subtractive onto M_1 then it is subtractive onto M_2 .

(ii) $M \subseteq M_1$ implies that M_1 is subtractive onto M iff it is subtractive onto $N_F(M)$.

Definition 3: Let M be a submonoid of F . The submonoid spanned by M in F is denoted by $H_F(M)$ and defined by

$$H_F(M) =_{df} \{x \in F : x = \lambda \vee x^* \cap N_F(M) \neq \lambda^*\}.$$

Lemma 11: Let M be a submonoid of F . $H_F(M)$ is a normal submonoid of F which includes M and is subtractive onto M and so $M \subseteq N_F(M) \subseteq H_F(M) \subseteq S_F(M) \subseteq F$.

Proof: Let $x, y \in H_F(M)$ then we have $k_1 x, k_2 y \in N_F(M)$ for some positive integers k_1 and k_2 . Therefore, $k_1 k_2 (x+y) = k_2 (k_1 x) + k_1 (k_2 y) \in N_F(M)$, hence $x+y \in H_F(M)$. Since $\lambda \in H_F(M)$ by definition, $H_F(M)$ is a submonoid of F , and from the definition of $H_F(M)$ it follows directly that $M \subseteq H_F(M)$.

Let $x, x+y \in H_F(M)$, that is $k_1 x, k_2 (x+y) \in N_F(M)$ for some positive integers k_1 and k_2 . Hence $k_2 (k_1 x), k_1 k_2 (x+y) \in N_F(M)$, that is, $k_1 k_2 x, k_1 k_2 x + k_1 k_2 y \in N_F(M)$ which implies $k_1 k_2 y \in N_F(M)$ which shows that

$y \in H_F(M)$. Thus $H_F(M)$ is normal.

Let $x \in H_F(M)$ then $kx \in N_F(M)$ for some positive integer k . Hence $x + (k-1)x \in N_F(M) \subseteq S_F(M)$ which implies by Lemma 6, that $x \in S_F(M)$. Thus $H_F(M) \subseteq S_F(M)$ and so by Lemma 8, $H_F(M)$ is subtractive onto M .

Corollary: $x \in H_F(M)$ & $(x+M) \cap (y+M) \neq \emptyset$ implies $y \in H_F(M)$.

Proof: Immediate by Lemma 4.

Remark: The relation $x^* \cap N_F(M) \neq \lambda^*$ can be interpreted as

the "linear" dependence of x on M . This interpretation is in particular obvious in the case where F is a finitely generated free commutative monoid. In this case, F can be embedded in a linear space over the rationals, \mathbb{R}^n (where n is the number of the free generators of F) and $H_F(M)$ is the intersection of F with the subspace of \mathbb{R}^n spanned by M .

Lemma 12: H_F is a closure operation on the submonoids of F ; i.e.,

- (i) $M \subseteq H_F(M)$ and $H_F(M)$ is a submonoid of F ,
- (ii) $M_1 \subseteq M_2$ implies $H_F(M_1) \subseteq H_F(M_2)$,

$$(iii) \quad H_F(H_F(M)) = H_F(M) .$$

Proof: From Lemma 11 we have (i). (ii) follows directly from the definition of $H_F(M)$. From (i) we infer that $H_F(M) \subseteq H_F(H_F(M))$, so let $x \in H_F(H_F(M))$. If $x = \lambda$ then $x \in H_F(M)$. If $x \neq \lambda$ then $x^* \cap N_F(H_F(M)) \neq \lambda^*$. By Lemma 11 we have that $H_F(M)$ is normal and therefore we have for $x \neq \lambda$ and $x \in H_F(H_F(M))$ that $x^* \cap H_F(M) \neq \lambda^*$. This implies $k_1 x \in H_F(M)$ for some positive integer k_1 ; hence $k_2 k_1 x \in N_F(M)$ for some positive integers k_1 and k_2 , which shows that $x \in H_F(M)$.

The algebraic relations among N_F , H_F and S_F are summarized in the following Lemma, some of them are implied directly by our previous discussions.

Lemma 13: The three operations N_F , H_F and S_F are commutative, idempotent and satisfy the following relations:

$$(i) \quad H_F \circ N_F = H_F$$

$$(ii) \quad S_F \circ N_F = S_F \circ H_F = S_F .$$

In other words, the semigroup of operations \mathcal{C} generated by N_F , H_F , S_F is a commutative idempotent monoid with a zero, in which N_F is the identity element

and S_F is its zero element.

Proof:

All we need to show is that the following table

is the multiplication table for \mathcal{C} :

\circ	N_F	H_F	S_F
N_F	N_F	H_F	S_F
H_F	H_F	H_F	S_F
S_F	S_F	S_F	S_F

By Lemma 1, corollary of Lemma 6 and Lemma 11, we

have the following relations:

$$N_F \circ N_F = N_F, N_F \circ S_F = S_F \text{ and } N_F \circ H_F = H_F.$$

From the corollary of Lemma 7 and Lemma 11 we get

the relations:

$$S_F \circ N_F = S_F \circ H_F = S_F.$$

From Df. 3 and the relation $N_F \circ N_F = N_F$ we get the

relation:

$$H_F \circ N_F = H_F.$$

By Lemma 7 and Lemma 12 we have the relations:

$$S_F \circ S_F = S_F \quad \text{and} \quad H_F \circ H_F = H_F .$$

Hence, we need to prove only that $H_F \circ S_F = S_F$ holds. By

Lemma 12 we know that $S_F(M) \subseteq H_F(S_F(M))$; so let $x \in H_F(S_F(M))$, then we have

$kx \in N_F(S_F(M)) = S_F(M)$ for some positive integer k . But $kx = x + (k-1)x$ and so

by Lemma 6 we have that $x \in S_F(M)$. Hence we have $H_F \circ S_F = S_F$.

§3 Factor monoids.

The method by which factor groups are defined in group theory cannot be applied directly to our context in order to get a definition of factor monoids. This is due to the fact that in our case we do not have the property that two cosets are either disjoint or identical. However, by defining a suitable equivalence relation in F we can define F/M to be the abstraction of F by that equivalence relation and the term "factor monoid" will be appropriate for F/M in the sense that factor groups become special cases of factor monoids and the theory of factor monoids will be similar to theory of factor groups. With this aim in mind we follow the suggestion of Mezei [2] for the equivalence relation ρ_M and introduce the following definition.

Definition 4: Let M be a submonoid of F , we define a binary relation

ρ_M in F by

$$x \rho_M y \text{ iff } (x+M) \cap (y+M) \neq \emptyset.$$

Furthermore, we shall use the following notations:

(i) for any equivalence relation ρ which is

defined in F :

$$\rho(x) =_{df} \{y \in F : x \rho y\}.$$

(ii) for any submonoid M' of F we define

$$M'/M \stackrel{\text{df}}{=} M'/\rho_M = \{\rho_M(x) : x \in M'\}.$$

Theorem 1: (Mezei) For any submonoid M of F , ρ_M is the minimal congruence relation ρ which is defined

in F such that $\rho(\lambda) = N_F(M)$.

Proof: From the definition of ρ_M it follows immediately that

ρ_M is symmetric and reflexive. Let $x \rho_M y$ and $y \rho_M z$,

then we have $x + m_1 = y + m_2$ and $y + m_3 = z + m_4$ for some $m_1, m_2, m_3, m_4 \in M$.

Hence $x + m_1 + m_3 = z + m_2 + m_4$ and $m_1 + m_3, m_2 + m_4 \in M$ which imply $x \rho_M z$.

Thus ρ_M is an equivalence relation.

Let $x \rho_M y$ and z be any element of F , then we have

$x + m_1 = y + m_2$ for some $m_1, m_2 \in M$. Hence $(x+z) + m_1 = (y+z) + m_2$ which shows

that $(x+z) \rho_M (y+z)$. Therefore ρ_M is a congruence relation defined in F .

By Lemma 3 we have that $x \in \rho_M(\lambda)$ iff $(x + N_F(M)) \cap N_F(M) \neq \emptyset$.

But since $N_F(M)$ is normal we have $(x + N_F(M)) \cap N_F(M) \neq \emptyset$ iff $x \in N_F(M)$. Hence

$$\rho_M(\lambda) = N_F(M).$$

Now let ρ be any congruence relation which is defined in

F such that $\rho(\lambda) = N_F(M)$. By Lemma 3 we have that $x \rho_M y$ implies

$x + m_1 = y + m_2$ for some $m_1, m_2 \in N_F(M) = \rho(\lambda)$. Since ρ is a congruence relation we have $x + m_1 \rho x$ and $y + m_2 \rho y$, which together with the equality $x + m_1 = y + m_2$ imply $x \rho y$. Hence $x \rho_M y$ implies $x \rho y$.

Another connection among congruence relations which are defined in F , is given in the following lemma.

Lemma 14: Let M_1 and M_2 be two submonoids of F such that $M_1 \subseteq M_2$ and let $x, y \in F$, then $x \rho_{M_1} y$ implies $x \rho_{M_2} y$.

Proof: Immediate by Df. 4.

Definition 5: Let M be a submonoid of F , we define a binary operation \otimes in F/M by:

$$\rho_M(x) \otimes \rho_M(y) =_{df} \rho_M(x+y)$$

Theorem 2: Let M be a submonoid of F , then:

(i) $\langle F/M, \otimes \rangle$ is a commutative monoid with $\rho_M(\lambda)$

as its identity element;

(ii) $\langle F/M, \Theta \rangle$ is the image of $\langle F, + \rangle$ under the homomorphism $r_M(x) =_{df} \rho_M(x)$ whose kernel is $N_F(M)$;

(iii) the maximal submonoid of $\langle F/M, \Theta \rangle$ which is a group is $\langle S_F(M)/M, \Theta \rangle$;

(iv) if F is a cancellative monoid (i.e., if $x + z = y + z$ implies $x = y$ for all $x, y, z \in F$), then $\langle S_F(M)/M, \Theta \rangle$ is the maximal subsemigroup of $\langle F/M, \Theta \rangle$ which is a group.

Remark: As it is usually done, we shall use the symbols

" F/M ", " $S_F(M)/M$ " and " $H_F(M)/M$ " to denote the

sets of the equivalence classes and the algebraic systems consisting

of these sets and the operation Θ .

Proof: Since ρ_M is a congruence relation we get that

$x_1 \rho_M x$ and $y_1 \rho_M y$ imply $(x_1 + y_1) \rho_M (x+y)$ and

therefore Θ is well defined.

(i) Clearly F/M is a commutative semigroup, and

$\rho_M(x) \Theta \rho_M(\lambda) = \rho_M(x)$ holds for any $x \in F$ since ρ_M is a congruence relation.

Hence F/M is a commutative monoid with $\rho_M(\lambda)$ as its identity element.

(ii) Immediate.

(iii) $\rho_M(x)$ is a unit in F/M iff there is $y \in F$

such that $\rho_M(x+y) = \rho_M(\lambda)$. Hence, by Lemma 6 and Lemma 11, $\rho_M(x)$ is a unit in F/M iff $x \in S_F(M)$. Since $S_F(M)/M$ forms a group we get that it is the maximal submonoid of F/M which is a group.

(iv) We have to show that in the case where F is cancellative, $\rho_M(x) + \rho_M(u) = \rho_M(\lambda)$ implies $\rho_M(u) = \rho_M(\lambda)$. From $(x+u) \rho_M x$ follows $x + u + m_1 = x + m_2$ (for some $m_1, m_2 \in M$), hence, by the law of cancellation we get $u + m_1 = m_2$ which shows that $\rho_M(u) = \rho_M(\lambda)$.

We can strengthen the result stated in Theorem 2 (iii)

as follows:

Lemma 15: Let M and M_1 be submonoids of F , then M_1/M is a submonoid of F/M which is a group iff M is subtractive onto $N_F(M)$.

Proof:

If M_1/M is a group then for any $x \in M_1$ there is $y \in M_1$ such that $\rho_M(x+y) = \rho_M(\lambda)$. Thus, for any $x \in M_1$ there is $y \in M_1$ such that $x + y \in \rho_M(\lambda) = N_F(M)$. Hence M is subtractive onto $N_F(M)$.

If M_1 is subtractive onto $N_F(M)$ then for any $x \in M_1$ there is $y \in M_1$ such that $x + y \in N_F(M)$. Hence for any $a \in M_1/M$ there is

$b \in M_1/M$ such that $a \oplus b = \rho_M(\lambda)$ and since M_1/M is a commutative monoid, this implies that M_1/M is a group.

Corollary: If $M \subseteq M_1$ then M_1/M is a group iff M_1 is subtractive onto M .

Proof: Immediate by Lemma 10 (ii) .

Most of the expected connections between homomorphisms of monoids, factor monoids, congruence relations and normal submonoids can be established similarly to the corresponding results of group theory.

Theorem 3: Let F and F_1 be commutative monoids and let

$f : F \rightarrow F_1$ be a homomorphism of F onto F_1 .

(i) K_f , the kernel of f is a normal submonoid of F .

(ii) The relation ρ_f determined in F by f :

$$x \rho_f y \iff_{df} f(x) = f(y) ,$$

is a congruence relation and $\rho_f(\lambda) = K_f$.

(iii) F is unit-free (i.e., $u + v = \lambda$ implies

$u = \lambda$ for all $u, v \in F$,) iff $S_F(K_f) = K_f$.

Proof: (i) See Lemma 2.

(ii) Immediate.

(iii) Let $x + y \in K_f$ then in F_1 we have $f(x) + f(y) = \lambda$.

Hence, if F_1 is unit-free then $x + y \in K_f$ implies $x \in K_f$ which shows that

$S_F(K_f) = K_f$. On the other hand if we have in F_1 $u + v = \lambda$ then $u = f(x)$

and $v = f(y)$ for some $x, y \in F$ and $f(x+y) = f(x) + f(y) = u + v = \lambda$; i.e.,

$x + y \in K_f$. Hence if $S_F(K_f) = K_f$ then we have $x \in K_f$ and therefore $u = f(x) = \lambda$

and thus F_1 is unit-free.

Theorem 4: Let F and F_1 be commutative monoids and let $f: F \rightarrow F_1$

be a homomorphism of F onto F_1 . There exists a unique

homomorphism $\phi: F/K_f \rightarrow F_1$ such that the following diagram is commutative,

$$\begin{array}{ccc}
 F & \xrightarrow{f} & F_1 \\
 \downarrow r_{K_f} & \searrow \phi & \\
 F/K_f & &
 \end{array}$$

that is, $\phi \circ r_{K_f} = f$ (where $r_{K_f}(x) =_{df} \rho_{K_f}(x)$). Moreover, ϕ is onto and it has

a trivial kernel, namely $K_\phi = \{K_f\}$. However, ϕ is an isomorphism of F/K_f

onto F_1 iff $\rho_f = \rho_{K_f}$.

Proof: Clearly, we define ϕ by $\phi(\rho_{K_f}(x)) =_{df} f(x)$.

By Theorem 1 and according to Theorem 3(i), we have that ρ_{K_f} is the minimal congruence relation ρ which is defined in F such that $\rho(\lambda) = K_f$. By Theorem 3(ii) we have that ρ_f is a congruence relation which is defined in F such that $\rho_f(\lambda) = K_f$. Hence ρ_{K_f} implies ρ_f , which shows that ϕ is well defined. It is obvious that ϕ is the only mapping from F/K_f to F_1 which satisfies the relation $\phi \circ r_{K_f} = f$.

From the fact that r_{K_f} and f are both homomorphisms of F and f is onto, and from the relation $\phi \circ r_{K_f} = f$ it follows that ϕ is a homomorphism of F/K_f onto F_1 .

Note that

$$\rho_{K_f}(x) \in K_\phi \quad \text{iff} \quad f(x) = \lambda \quad \text{in} \quad F_1,$$

$$\text{i.e., iff } x \in K_f,$$

$$\text{i.e., iff } \rho_{K_f}(x) = K_f.$$

Hence, $K_\phi = \{K_f\}$.

Now, if $\rho_f = \rho_{K_f}$ and $\phi(\rho_{K_f}(x)) = \phi(\rho_{K_f}(y))$, then $f(x) = f(y)$ and therefore $\rho_f(x) = \rho_{K_f}(x) = \rho_{K_f}(y) = \rho_f(y)$. Hence $\rho_f = \rho_{K_f}$ implies that ϕ is an isomorphism of F/K_f onto F_1 . On the other hand, if ϕ is an

isomorphism then

$$f(x) = \phi(\rho_{K_f}(x)) = \phi(\rho_{K_f}(y)) = f(y) \text{ implies } \rho_{K_f}(x) = \rho_{K_f}(y)$$

that is, that ρ_f implies ρ_{K_f} . Since always ρ_{K_f} implies ρ_f , we get that if ϕ

is an isomorphism then $\rho_f = \rho_{K_f}$.

We end this section with a discussion on certain conditions for F/M to be finite.

Lemma 16: Let M be a submonoid of F . If F is cancellative and $S_F(M) \neq F$ then F/M is infinite (and so F is infinite too).

Proof: Let $x \in F$ and let $k_1 > k_2$ be two distinct non-negative integers. Assume that $\rho_M(k_1 x) = \rho_M(k_2 x)$, then $k_1 x + m_1 = k_2 x + m_2$ for some $m_1, m_2 \in M$. Hence $k_2 x + (k_1 - k_2)x + m_1 = k_2 x + m_2$, which by cancellation implies $(k_1 - k_2)x + m_1 \in M$. Since $k_1 > k_2$ we get $k_1 - k_2 \geq 1$ and so we have $x + ((k_1 - k_2 - 1)x + m_1) \in M$ which shows that $x \in S_F(M)$. Hence if $x \notin S_F(M)$ then $\rho_M(k_1 x) \neq \rho_M(k_2 x)$ for any distinct non-negative integers k_1, k_2 , and thus F/M is infinite.

Lemma 17: Let F be cancellative and M be a submonoid of F .

If $x \in F$ but $x \notin H_F(M)$ then $\rho_M(k_1x) = \rho_M(k_2x)$

implies $|k_1 - k_2|x = \lambda$. In particular, if $k_1 \neq k_2$ and yet $\rho_M(k_1x) = \rho_M(k_2x)$,

(where $x \in F$ but $x \notin H_F(M)$,) then x is a unit of F (i.e., there is $y \in F$

such that $x + y = \lambda$).

Proof: As in the proof of Lemma 16 we get that $|k_1 - k_2|x \in N_F(M)$.

Thus $x \notin H_F(M)$ implies $|k_1 - k_2|x = \lambda$.

Corollary: Let F be cancellative and unit-free and let M be a submonoid of F . If $H_F(M) \neq F$ then F/M is infinite.

Remark: Note that since $H_F(M) \subseteq S_F(M) \subseteq F$ holds, $H_F(M) = F$ implies $S_F(M) = F$.

Lemma 18: Let F be cancellative and unit-free, M be a submonoid of F and $w \in F$; then $w^* \cap N_F(M)$ is a normal submonoid of F generated by a unique element.

Proof: Let $x, x + y \in w^*$ for $x, y \in F$, then $x = k_1w$ and $x + y = k_2w$ for some non-negative integers k_1, k_2 .

If $k_2 \geq k_1$ then let $k_2 = k_1 + k$ and we have $k_1 w + kw = k_1 w + y$ and so by cancellation we get $y = kw \in w^*$. If $k_2 < k_1$ then let $k_1 = k_2 + k$ and we have $x + y + kw = x$ and so by cancellation we get $y + kw = \lambda$. But F is unit-free and therefore we have $y = \lambda \in w^*$. Thus w^* is a normal submonoid of F . Hence $w^* \cap N_F(M)$ as an intersection of normal submonoids of F is a normal submonoid of F too.

If $w^* \cap N_F(M) = \lambda^*$ then λ is the generator of $w^* \cap N_F(M)$. If $w^* \cap N_F(M) \neq \lambda^*$ then let k_0 be the minimal positive integer k such that $kw \in (w^* \cap N_F(M))$. Clearly $(k_0 w)^* \subseteq (w^* \cap N_F(M))$ and we shall show that $(k_0 w)^* = (w^* \cap N_F(M))$.

Let $kw \in (w^* \cap N_F(M))$ and let $k = pk_0 + r$ where p, r are non-negative integers such that $0 \leq r < k_0$. Then we have $kw = p(k_0 w) + rw$ and $kw, p(k_0 w) \in (w^* \cap N_F(M))$. But $w^* \cap N_F(M)$ is normal and therefore $rw \in (w^* \cap N_F(M))$; hence, by the choice of k_0 it follows that $r = 0$ and $kw = p(k_0 w) \in (k_0 w)^*$. Thus $w^* \cap N_F(M) = (k_0 w)^*$.

As for the uniqueness of the generator of $w^* \cap N_F(M)$ we shall show that $x_1^* = x_2^*$ implies $x_1 = x_2$. From $x_1^* = x_2^*$ follows that $x_1 = k_2 x_2$ and $x_2 = k_1 x_1$ for some positive integers k_1, k_2 . Hence $x_1 = k_1 k_2 x_1$ and $x_1 = x_1 + (k_1 k_2 - 1)x_1$

which by cancellation implies $(k_1 k_2 - 1)x_1 = \lambda$ and this by the fact that F is unit-free, implies $k_1 k_2 = 1$ and thus $x_1 = x_2$.

Definition 6: Let F be cancellative and unit-free, and M be a submonoid of F . For any set $B = \{..w_i..\}$ of generators for $H_F(M)$ we associate the set $B_M = \{...\epsilon_i \dots\}$ where $\epsilon_i = k_i w_i$, for any i , is the generator of $w_i^* \cap N_F(M)$.

We denote by $[B_M]$ the set of all elements of $H_F(M)$ of the form $x = \sum_i a_i w_i$ where for any i : $0 \leq a_i < k_i$ (and $a_i \neq 0$ only for a finite set of values for i).

Lemma 19: Let M be a submonoid of F where F is cancellative and unit-free, and let B be a set of generators for $H_F(M)$. Then:

- (i) B_M is a set of elements of $N_F(M)$,
- (ii) for any $x \in H_F(M)$ there is $y \in [B_M]$ such that

$$x + B_M^* \subseteq y + B_M^*$$

(iii) $(x_1 + B_M^*) \cap (x_2 + B_M^*) \neq \emptyset$ and $x_1 \in N_F(M)$ imply

$x_2 \in N_F(M)$.

Proof: From the definition of B_M it follows directly that B_M is a set of elements of $N_F(M)$. Hence $B_M^* \subseteq N_F(M)$ and this implies (iii).

Let $x \in H_F(M)$ then $x = \sum_1^r a_i w_i$. For any i there are non-negative integers b_i and c_i such that $a_i = b_i k_i + c_i$ and $0 \leq c_i < k_i$; so $x = \sum_1^r b_i \epsilon_i + \sum_1^r c_i w_i$. Let $m = \sum_1^r b_i \epsilon_i$ and $y = \sum_1^r c_i w_i$ then $x \in B_M^*$, $y \in [B_M]$ and $x = y + m$. Hence $x + B_M^* \subseteq y + B_M^*$.

Corollary: (i) $[B_M] \cup B_M$ is a set of generators for $H_F(M)$.

(ii) $H_F(M) = \bigcup \{y + B_M^* : y \in [B_M]\}$.

(iii) $([B_M] \cap N_F(M)) \cup B_M$ is a set of generators

for $N_F(M)$.

(iv) $N_F(M) = \bigcup \{y + B_M^* : y \in ([B_M] \cap N_F(M))\}$.

In order to apply these results to factor monoids we need the following lemma.

Lemma 20: Let M_1 and M_2 be submonoids of F such that $M_1 \subseteq M_2$.

If F/M_1 is finite then F/M_2 and M_2/M_1 are finite too

(hence, $N_F(M_2)/M_1$ is also finite.)

Proof: Let $F/M_1 = \{\rho_{M_1}(x_1), \dots, \rho_{M_1}(x_k)\}$. By Lemma 14

we have that for any $x \in F$: $\rho_{M_1}(x) \subseteq \rho_{M_2}(x)$.

Hence $F = \bigcup_{i=1}^k \rho_{M_2}(x_i)$ and therefore F/M_2 contains at most k elements.

Let $\rho_1(x)$ be an element of M_2/M_1 then $\rho_1(x) \subseteq \rho_{M_1}(x) \in F/M_1$.

Let $\rho_1(x)$ and $\rho_1(y)$ be any elements of M_2/M_1 which are included in $\rho_{M_1}(z)$ for

some $z \in F$, then $x\rho_{M_1}y$ and therefore $\rho_1(x) = \rho_1(y)$. Hence M_2/M_1 contains

at most the same number of elements as F/M_2 .

By taking $M_2 = N_F(M_2)$ we get that $N_F(M_2)/M_1$ is finite.

Theorem 5: Let F be cancellative and unit-free and M be a

submonoid of F . If $H_F(M)$ is finitely generated

then $N_F(M)$ is finitely generated and $H_F(M)/M$ is finite.

Proof: Let B be a finite set of generators for $H_F(M)$, then

clearly B_M and $[B_M]$ are finite.

From the corollary of Lemma 19 it follows that $N_F(M)$ is generated by a subset

of $[B_M] \cup B_M$ and so it is finitely generated. From the same corollary follows

that $H_F(M)/B_M^*$ is finite, but $B_M^* \subseteq N_F(M)$ and so by Lemma 20 we have that $H_F(M)/N_F(M)$ is finite but $H_F(M)/N_F(M) = H_F(M)/M$ and so $H_F(M)/M$ is finite.

Combining Theorem 5 with the corollary of Lemma 17 we get a necessary and sufficient condition for F/M to be finite in the case where F is finitely generated, cancellative and unit-free, e.g., in the case where F is a finitely generated free commutative monoid.

Theorem 6: Let F be a finitely generated cancellative and unit-free commutative monoid and let M be a submonoid of F then F/M is finite iff $H_F(M) = F$.

§4 Normal submonoids of F_n

Let F_n be the free commutative monoid generated by $E = \{e_1, \dots, e_n\}$. The special case of the finitely generated submonoids of F_n is of importance to the study of commutative events since these are the submonoids of F_n which are denoted by regular expressions over E as an alphabet. For a detailed discussion on this connection the reader is referred to [1].

Lemma 21: Let M be a submonoid of F_n . There is a finitely generated free submonoid N of $N_F(M)$ which is normal in F_n and $H_{F_n}(M) = H_{F_n}(N)$.

Proof: Let R^n be the n -dimensional vector-space over the rationals; then, as one can easily verify, $H_{F_n}(M) = F_n \cap V(M)$ where $V(M)$ is the sub-vector-space spanned by M and clearly F_n is the first orthant of R^n .

From linear algebra we know that for any sub-vector-space V of R^n which has a basis in the first orthant of R^n , one can find such a basis $\{v_1, \dots, v_k\}$ with the additional property that v is a vector of V with non-negative components only iff $v = \sum_{i=1}^k r_i v_i$ where for all $1 \leq i \leq k$: $r_i \geq 0$.

Since $M \subseteq F_n$, $V(M)$ has such a basis in the first orthant of R^n say $\{v_1, \dots, v_k\}$.

For any v_i in this basis there is positive integer p_i such that $p_i v_i \in F_n$

and therefore $p_i v_i \in H_{F_n}(M)$. But this implies that $p_i q_i v_i \in N_{F_n}(M)$ for some

positive integer q_i . So let $w_i = q_i v_i$ be the first non-zero point on the

line determined by v_i which is an element of $N_{F_n}(M)$. Since $\{v_1, \dots, v_k\}$

is an independent set of vectors in R_n we get that $W = \{w_1, \dots, w_k\}$ generates

a free submonoid N of $N_{F_n}(M)$.

Let $x, x+y \in N$ for some $y \in F_n$ then clearly $y \in V(M)$ and

therefore $y \in H_{F_n}(M)$. So let $x = \sum_{i=1}^k a_i w_i$, $y = \sum_{i=1}^k r_i v_i$ and $x+y = \sum_{i=1}^k b_i w_i$

then we have

$$r_i = (b_i - a_i) k_i \geq 0 \quad \text{for all } 1 \leq i \leq k$$

which shows that $y \in N$ and therefore N is normal.

From $V(M) = V(N)$ follows $V(M) \cap F_n = V(N) \cap F_n$, that is,

$$H_{F_n}(M) = H_{F_n}(N).$$

Following some of the ideas which were discussed in the

last part of the previous section we define:

Definition 7: Let N be a normal free submonoid of F_n generated by the basis $W = \{w_1, \dots, w_k\}$.

a: We denote by $[W]_H$ the set of all elements x of F_n for which in \mathbb{R}^n we have $x = \sum_{i=1}^k r_i w_i$ where for all $1 \leq i \leq k$: r_i is rational and $0 \leq r_i < 1$.

b: We define a binary operation $\langle + \rangle$ in the first orthant of $V(N)$ with regard to W :

$$x = \sum_{i=1}^k r_i w_i \text{ and } y = \sum_{i=1}^k s_i w_i \text{ imply } x \langle + \rangle y =_{df} \sum_{i=1}^k (\max(r_i, s_i)) w_i.$$

Certain properties of $\langle + \rangle$ are summarized in the following lemma; the proof is straightforward and will not be given.

Lemma 22: (i) $\langle + \rangle$ is associative, commutative and idempotent.

(ii) $x, y \in [W]_H$ iff $x \langle + \rangle y \in [W]_H$.

Similarly to Lemma 19 we have the following theorem which establishes the relation between N and $H_{F_n}(N)$ in more detail.

Theorem 7: Let N be a normal free submonoid of F_n generated by the basis W and let $H = H_{F_n}(N)$.

Then:

- (i) $[W]_H$ is a finite set of elements of H ,
- (ii) for any $x \in H$ there is $y \in [W]_H$ such that

$$x + N \subseteq y + N,$$

- (iii) $(x+N) \cap (y+N) \neq \emptyset$ (i.e., $x \rho_N y$) for $x, y \in H$ implies:

$$(1) \quad (x+N) \cap (y+N) = (x \langle + \rangle y) + N,$$

$$(2) \quad x, y, x \langle + \rangle y \in \rho_N(x),$$

$$(3) \quad \text{if } x, y \in [W]_H \text{ then } x = y.$$

Proof: (i) From the definition of $[W]_H$ it follows that if $x \in [W]_H$ then $px \in N$ for a suitable positive integer

p and since $x \in F_n$ it follows that $x \in H$. Clearly $[W]_H$ is finite.

Let $W = \{w_1, \dots, w_k\}$. From the definition of H_F (see section 1, Df. 3) it follows that, in our case, for $x \in F_n$, $x \in M$ iff $x = \sum_{i=1}^k r_i w_i$ where for all $1 \leq i \leq k$: r_i is a non-negative rational.

(ii) Let $x \in H$ then we have $x = \sum_{i=1}^k r_i w_i$ for

non-negative rationals r_i . For any $1 \leq i < k$ let a_i be a non-negative integer

and s_i be a non-negative rational such that $r_i = a_i + s_i$ and $0 \leq s_i < 1$;

and so we have

$$x = \sum_{i=1}^k a_i w_i + \sum_{i=1}^k s_i w_i$$

Let $w = \sum_{i=1}^k a_i w_i$ and $y = \sum_{i=1}^k s_i w_i$, then we have $w \in N$ and $x = w + y$. From

$x, w \in F_n$ follows that $y \in F_n$ (in other words, F_n is a normal submonoid of

the first orthant of R^n which is a commutative monoid) and so $y \in [W]_H$ and

$x + N \subseteq y + N$.

(iii) Let $x = \sum_{i=1}^k r_i w_i$, $y = \sum_{i=1}^k s_i w_i$ and $z = \sum_{i=1}^k t_i w_i \in$

$(x+N) \cap (y+N)$ for non-negative rationals r_i , s_i and t_i . Hence we have

$$z = \sum_{i=1}^k t_i w_i = \sum_{i=1}^k r_i w_i + \sum_{i=1}^k a_i w_i = \sum_{i=1}^k s_i w_i + \sum_{i=1}^k b_i w_i,$$

or

$$z = \sum_{i=1}^k (r_i + a_i) w_i = \sum_{i=1}^k (s_i + b_i) w_i$$

for non-negative integers a_i and b_i . Since W is a linear basis of $V(N)$ we get

$$t_i = r_i + a_i = s_i + b_i \quad \text{for all } 1 \leq i \leq k,$$

which implies $t_i = \max(r_i, s_i) + \min(a_i, b_i)$

and $a_i - b_i = s_i - r_i$ for all $1 \leq i \leq k$.

Let $w = \sum_{i=1}^k (\min(a_i, b_i)) w_i$ then clearly $w \in N$ and we

have $z = (x \leftrightarrow y) + w$ which implies $(x + N) \cap (y + N) \subseteq (x \leftrightarrow y) + N$.

On the other hand we have:

$$x \leftrightarrow y = \sum_{i=1}^k r_i w_i - \sum_{\substack{s_i \geq r_i \\ r_i \geq s_i}} (s_i - r_i) w_i = x + \sum_{a_i \geq b_i} (a_i - b_i) w_i$$

and

$$x \leftrightarrow y = \sum_{i=1}^k s_i w_i + \sum_{\substack{r_i \geq s_i \\ r_i \geq s_i}} (r_i - s_i) w_i = y + \sum_{b_i \geq a_i} (b_i - a_i) w_i.$$

Hence $x \leftrightarrow y \in (x + N) \cap (y + N)$ and this concludes the proof of (iii), (1).

Furthermore, the last equalities show that $(x \leftrightarrow y) \rho_N x$ and $(x \leftrightarrow y) \rho_N y$

and since we assume $x \rho_N y$ we have proved (iii), (2).

The same equalities yield

$$x \leftrightarrow y = x + \sum_{\substack{s_i \geq r_i \\ r_i \geq s_i}} (s_i - r_i) w_i = y + \sum_{\substack{r_i \geq s_i \\ r_i \geq s_i}} (r_i - s_i) w_i,$$

and so $x, y \in [W]_H$ implies

$$0 = |r_i - s_i| < 1 \text{ for all } 1 \leq i \leq k$$

and yet $|r_i - s_i| w_i \in N$ which is possible only if $|r_i - s_i| = 0$ and therefore $x = y$.

Corollary: (i) $[W]_H \cup W$ is a set of generators for H and

therefore H is finitely generated.

(ii) $H/N = \{y + N : y \in [W]_H\}$ and so H/N is finite.

Now, by Lemma 21 and Theorem 5, Theorem 7 yields the following result:

Theorem 8: For any submonoid M of F_n , if M is normal then it is finitely generated. In particular M is a finite union of disjoint cosets of a normal free submonoid of M .

Proof: By Lemma 21 there is a normal free submonoid N of M such that $H_{F_n}(M) = H_{F_n}(N)$. By Theorem 7 we get that $H_{F_n}(M)$ is finitely generated and so by Theorem 5 we get that $N_{F_n}(M) = M$ is finitely generated.

From the relations $N \subseteq M \subseteq H_{F_n}(M) = H_{F_n}(N)$ it follows that $x \in M$ and $x p_N y$ imply $y \in N_{F_n}(M) = M$. Hence we get $M = \bigcup \{y + N : y \in [W]_H \cap M\}$ and so by Theorem 7 we get that M is a finite union of disjoint cosets of N .

Thus Theorem 8, the corollary of Theorem 7 and Lemma 9 show us that the operators N_{F_n} , H_{F_n} and S_{F_n} have in their range only finitely generated submonoids of F_n . This is implied directly from Theorem 8 "alone" since H_{F_n} and S_{F_n} have in their range only normal submonoids of F_n .

* * *

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