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A combinatorial problem on the semigroup of all transformations of a finite set.

by

P. v. Emde Boas

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§1. Introduction

Let T_n be the set of all mappings of a finite set consisting of n elements into itself. For convenience we take for the set on which T_n acts the set of the positive integers $\{1, 2, 3, \ldots, n\}$.

If $f \in T_n$ and if $(1)f = k_1$, $(2)f = k_2, \ldots, (n)f = k_n$ then f will be denoted by $(k_1, k_2, \ldots, k_n)$.

The product of two mappings will by definition be their composition: $(k)fg \overset{\text{Def}}{=} ((k)f)g$. Functional composition is an associative operation; hence T_n with this definition of the product is a semigroup.

If $f = (k_1, k_2, \ldots, k_n)$ and $g = (m_1, \ldots, m_n)$ then $fg = (m_{k_1}, m_{k_2}, \ldots, m_{k_n})$.

T_n contains n^n elements, for each of the n objects has n possible images.

T_n contains as a subgroup the set of all 1 - 1 mappings of $\{1, 2, 3, \ldots, n\}$ onto itself. This group will be denoted by S_n; S_n contains n! elements.

An element of T_n will be called an <u>idempotent</u> element iff $f^2 = f$. If $f \in S_n$ and f is idempotent, then f is necessarily the identity mapping $I = (1, 2, 3, \ldots, n)$. We have the following characterisation of idempotent elements:

An element $g \in T_n$ is idempotent iff there exists a set of numbers $\{a_1, a_2, \ldots, a_r\}$ $r \geq 1$ for which $(a_1)g = a_1$ $(a_2)g = a_2$ ... $(a_r)g = a_r$ and $\{1 \ldots n\}g = \{a_1, a_2, \ldots, a_r\}$.

<u>Proof</u>: If g is of this kind, then $g \mid \{1 \ldots n\}g = I \mid \{1 \ldots n\}g$, and hence $g^2 = g \circ g = g \circ I = g$.
Each idempotent has this form: If $(a)g \neq a$ and $a = (b)g$ then $(b)g^2 = (a)g \neq a = (b)g$; hence g is not idempotent.

By way of example we shall write down the complete T_2 and T_3, indicating which elements are idempotent and which are contained in the corresponding S_n.

T_2 : (1,1), (1,2),(2,1), (2,2)

(1,2) is the unity. S_2 consists of (1,2) and (2,1).

(2,1) is the only non-idempotent element of T_2.

(1,1) and (2,2) are clearly idempotent.

T_3 : S_3 consists of: (1,2,3) (identity), (1,3,2), (2,1,3), (2,3,1), (3,1,2), (3,2,1).

There are 9 non-trivial idempotents: (1,2,2), (1,2,1), (1,1,3), (1,3,3), (2,2,3), (3,2,3), (1,1,1), (2,2,2), (3,3,3).

There are 12 non-invertible non-idempotent elements:

(2,1,2), (2,1,1), (1,1,2), (2,2,1),
(3,1,3), (3,1,1), (3,3,1), (1,3,1),
(2,3,2), (3,3,2), (3,2,2), (2,3,3).

The number of idempotent elements of T_n will be denoted by V_n. We have $V_2 = 3$ $V_3 = 10$. The number V_n is given by the formula:

$$V_n = \sum_{k=1}^{n} \binom{n}{k} k^{n-k}.$$

Proof: For each $k \geq 1$ there are $\binom{n}{k}$ ways to choose a set of k numbers that are to be mapped onto themselves and for each of these ways there are k^{n-k} possibilities of mapping the other $n - k$ numbers into the set of the k chosen ones.

§2. Words on finite semigroups

This report deals with a special case of a more general problem that was dealt with in an earlier report by P.C. Baayen, D. Kruyswijk and the author [1]. I shall repeat here some definitions and theorems that will be used in the following.

A word over a semigroup H is a sequence of one or more elements of H: $w = a_1, a_2, a_3, \ldots, a_k$. Its elements are called letters.

The value of a word $w = a_1, a_2, a_3, \ldots, a_k$ is the product of its letters; it is denoted by $|w|$; $|w| = a_1 \circ a_2 \circ a_3 \circ \ldots \circ a_n$ clearly $|w| \in H$.

A subword of a word $w = a_1, a_2, \ldots, a_k$ is a word of the shape $w' = a_r, a_{r+1}, a_{r+2}, \ldots, a_{r+s}$, in which $1 \leq r \leq r + s \leq k$.

A set of subwords of a given word will be called a central word-set if the first letter of each of these subwords has the same index in the original word.

In a central word-set the words can always be ordered by increasing length. The set can then be denoted by $\{w_0, w_0w_1, w_0w_1w_2, \ldots, w_0w_1w_2\ldots w_r\}$ in which the w_j are consecutive subwords of the original word. It is clear that the word-set $\{w_1, w_1w_2, \ldots, w_1w_2\ldots w_r\}$ which is obtained through formally dividing by w_0 is central. We call this set the derived central word-set.

In [I] the following result is obtained:

Theorem: To each finite semigroup H a positive integer λ can be assigned such that any word with length λ over H contains a subword with idempotent value. Denoting the least possible λ for a fixed H with $\lambda(H)$ we have moreover: If H is a group, $\lambda(H)$ is equal to the order of the order of the group.

In this report the following theorem will be proved:

Theorem: For each n, $\lambda(T_n) = n!$.

From this theorem it follows that $\lambda(T_n) = \lambda(S_n)$. This provides us with an example of an extension of a group to a greatly larger semigroup in such a way that the maximal length of words without idempotent subwords does not increase.

§3 Proof of the Theorem

If we take a word w over T_n, then $|w|$ is a mapping. It makes sense therefore to write down an expression like $(a)\,|w| = b$; in this case we say that the word w maps the element a onto b.

We prove first that $\lambda(T_n) \leq n!$

Let w be the word $w = f_1, f_2, \ldots, f_{n!}$

We take the central word-set $C_0 = \{f_1, f_1f_2, f_1f_2f_3, \ldots, f_1f_2\ldots f_{n!}\}$ C_0 consists of n! words. If we look at the images of the element 1 under these words there are two possibilities:

I_1 : There are more than $(n - 1)!$ words in C_0 that map 1 onto 1; they form a central word-set $\{w_{11}, w_{11}w_{12}, w_{11}w_{12}w_{13}, \ldots\}$

II_1 : There are more than $(n - 1)! + 1$ words in C_0 that map 1 onto a fixed other element a_1. They form a central word-set $\{w_{10}, w_{10}w_{11}, w_{10}w_{11}w_{12}, \ldots\}$.

For let I_1 be not true. Then we have at least $n! - (n - 1)! + 1 = (n - 1)(n - 1)! + 1$ words that map 1 into $\{2, \ldots, n\}$. By the pigeonhole principle one of those elements has to serve at least $(n - 1)! + 1$ times as the image of 1.

If II_1 is true we consider the derived word-set $\{w_{11}, w_{11}w_{12}, \ldots\}$. This is a central set containing at least $(n - 1)!$ words each mapping a_1 onto a_1.

In either case the following statement O_1 is true.

O_1 : There exists an element a_1 and a central word-set C_1, containing more than $(n - 1)!$ different subwords of w, each mapping a_1 onto itself.

Suppose the following assertion O_m is true for some m, $1 \leq m \leq n - 1$:

O_m : There exists a set of m different elements $\{a_1 \ldots a_m\}$ and a central word-set C_m, containing at least $(n - m)!$ different subwords of w, under which a_1 is mapped onto a_1, a_2 is mapped onto $a_2, \ldots, a_n$ is mapped onto a_n.

Then from the following three assertions one has to be true:

I_{m+1} : There exists an element a_{m+1}, not contained in $\{a_1 \ldots a_m\}$ and a central word-set C_{m+1} containing at least $(n - m - 1)!$ words from C_m, each mapping a_{m+1} onto itself.

II_{m+1} : There exists an element b_{m+1}, not contained in $\{a_1 \ldots a_m\}$ and a central word-set C'_{m+1} containing at least $(n - m - 1)! + 1$ words from C_m, each mapping b_{m+1} onto a fixed element a_{m+1} not contained in $\{a_1, a_2, \ldots, a_m, b_{m+1}\}$.

III_{m+1} : There exists a word in C_m that maps $\{1\ 2 \ldots n\}$ onto $\{a_1\ a_2 \ldots a_m\}$.

For assume III_{m+1} not to be true. Then there exists an element x which by no word of C_m is mapped into $\{a_1 \ldots a_m\}$. There are $(n - m)!$ mappings and there are $n - m$ possible images of x (x itself being included). Then by the pigeon-hole principle either x is at least $(n - m - 1)!$ times its own image or a fixed element $y \neq x$ is at least $(n - m - 1)! + 1$ times the image of x.

In the first case we take x as the element a_{m+1} and we define C_{m+1} to be the word-set consisting of all those words in C_m mapping x onto itself. Then I_{m+1} follows. Otherwise let $b_{m+1} = x$, $a_{m+1} = y$ and let C'_{m+1} be the word-set consisting of the words in C_m mapping x onto y; now II_{m+1} follows.

If II_{m+1} is found to be true and the set C'_{m+1} contains the words $\{w_{m+1,0}, w_{m+1,0}w_{m+1,1}, w_{m+1,0}w_{m+1,1}w_{m+1,2}, \ldots\}$, we take the derived central word-set $\{w_{m+1,1}, w_{m+1,1}w_{m+1,2}, \ldots\}$, which contains at least $(n - m - 1)!$ words each mapping a_1 onto a_1, a_2 onto $a_2, \ldots, a_m$ onto a_m, and a_{m+1} onto a_{m+1}.

In this way we conclude that O_{m+1} follows if either I_{m+1} or II_{m+1} is true.

If III_{m+1} is true, however, we have arrived at a word in C_m that maps $\{1, 2 \ldots n\}$ onto $\{a_1\ a_2 \ldots a_m\}$. This word maps each element of its image onto itself and hence its value is an idempotent of T_n.

Thus we have proved: $O_m \Rightarrow [O_{m+1}$ or there exists an idempotent subword of w$]$.

Suppose we find O_n to be true. Then there exists at least one subword of w mapping each element of $\{1 \ldots n\}$ onto itself. This word has clearly the identity value and hence is idempotent. This completes the proof of the assertion $\lambda(T_n) \leq n!$

Remark: If we use the symbol A for the assumption:

A: w is a word of length n! over T_n

and if we use the symbol G to denote the assertion

G: There exists an idempotent subword of w

we have the following diagram of implications:

$$\begin{tikzcd}
 & I_1 \arrow[dr] & & I_2 \arrow[dr] & & & & I_n \arrow[dr] & & \\
A \arrow[ur, "or"] \arrow[r] & II_1 \arrow[r] & O_1 \arrow[ur, "or"] \arrow[r] \arrow[dr, "or"'] & II_2 \arrow[r] & O_2 \arrow[r, dashed] & \cdots \arrow[r, dashed] & O_{n-1} \arrow[ur, "or"] \arrow[r] \arrow[dr, "or"'] & II_n \arrow[r] & O_n \arrow[r] & G \\
 & & & III_2 \arrow[r] & G & & & III_n \arrow[r] & G &
\end{tikzcd}$$

It remains to be shown that $\lambda(T_n) \geq n!$. But this follows trivially from the fact that $S_n \subset T_n$ and that $\lambda(S_n) = n!$, as $\lambda(T_n) \geq \lambda(S_n)$. Thus the proof of our theorem has been completed.

§ 4 Additional remarks

1. In the proof of the inequality $\lambda(T_n) \geq n!$ we made use of the fact that there exists an idempotent-free subword of length n! - 1 over T_n with all its letters taken from S_n. It is not true, however, that such maximal idempotent-free words are always words over the group S_n. By way of example, consider T_3.

The word $f_1f_2f_3f_4f_5$ with $f_1 = (321)$ $f_2 = (131)$ $f_3 = (213)$ $f_4 = (321)$ $f_5 = (131)$ has no idempotent subwords.

Below I list the values of all its subwords.

$|f_1| = (321)$ $|f_1f_2| = (131)$ $|f_1f_2f_3| = (232)$ $|f_1f_2f_3f_4| = (212)$
$|f_2| = (131)$ $|f_2f_3| = (232)$ $|f_2f_3f_4| = (212)$ $|f_2f_3f_4f_5| = (313)$
$|f_3| = (213)$ $|f_3f_4| = (231)$ $|f_3f_4f_5| = (311)$
$|f_4| = (321)$ $|f_4f_5| = (131)$
$|f_5| = (131)$

$|f_1f_2f_3f_4f_5| = (313)$

2. In [1] a formula is given for the maximal value of $\lambda(H)$ for all semigroups H with n elements and V idempotents. This maximum value is denoted by $L(n,V)$. In the following tabulation the values of $L(n^n, V_n)$ and $\lambda(T_n)$ are compared for $1 \leq n \leq 5$. We observe that the maximal word length for T_n is rather short.

n	$\lvert T_n \rvert = n^n$	V_n	$L(n^n, V_n)$	$\lambda(T_n) = n!$
1	1	1	1	1
2	4	3	2	2
3	27	10	131072	6
4	256	41	approx. $7.5 \cdot 10^{34}$	24
5	3125	196	approx. $3 \cdot 10^{363}$	120

References

[1] : P.C. Baayen, P. van Emde Boas and D. Kruyswijk: A combinatorial problem on finite semigroups. Mathematical Centre report ZW 1965-006, (1965).