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Enumeration of m-endomorphisms

Louis Rubin and Brian Rushton

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An m-endomorphism on a free semigroup is an endomorphism that sends every generator to a word of length $\le m$. Two m-endomorphisms are combinatorially equivalent if they are conjugate under an automorphism of the semigroup. In this paper, we specialize an argument of N. G. de Bruijn to produce a formula for the number of combinatorial equivalence classes of m-endomorphisms on a rank-n semigroup. From this formula, we derive several little-known integer sequences.

1. Introduction

Let D be a nonempty set of symbols, and let D^+ be the set of all finite strings of one or more elements of D. That is, $D^+ = \{d_1 \cdots d_k : k \in \mathbb{N}, d_i \in D\}$. Paired with the operation of string concatenation, D^+ forms the *free semigroup* on D. If $d_1, \ldots, d_k \in D$, then we refer to the natural number k as the *length* of the string $d_1 \cdots d_k$. Denote the length of $W \in D^+$ by $|W|$.

By a *semigroup endomorphism* (or, simply, an *endomorphism*) on D^+, we mean a mapping $\phi : D^+ \to D^+$ satisfying $\phi(W_1 W_2) = \phi(W_1)\phi(W_2)$ for all $W_1, W_2 \in D^+$. Note that if ϕ is an endomorphism on D^+ and $d_1, \ldots, d_k \in D$, then $\phi(d_1 \cdots d_k) = \phi(d_1) \cdots \phi(d_k)$; this shows that an endomorphism on D^+ is determined by its action on the elements of D. On the other hand, any mapping $f : D \to D^+$ extends uniquely to the endomorphism $\phi_f : D^+ \to D^+$ defined by $\phi_f(d_1 \cdots d_k) = f(d_1) \cdots f(d_k)$, and it is straightforward to verify that ϕ_f is an automorphism (that is, a bijective endomorphism) precisely when f is a bijection on D.

Example 1. Let $D = \{a, b\}$, and let $f : D \to D^+$ be defined by $f(a) = ab$ and $f(b) = a$. Then, for example,

$$\phi_f(ababa) = f(a) f(b) f(a) f(b) f(a) = abaabaab.$$

Let $\mathrm{End}(D^+)$ be the collection of all endomorphisms on D^+, and let $m \in \mathbb{N}$. Then $\phi \in \mathrm{End}(D^+)$ is called an *m-endomorphism* if and only if $|\phi(d)| \le m$ for

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all $d \in D$. Note that the mapping ϕ_f from Example 1 is an m-endomorphism for all $m \geq 2$. Now let Γ be the set of all m-endomorphisms on D^+. That is,

$$\Gamma = \{\phi \in \mathrm{End}(D^+) : \phi(D) \subseteq R\},$$

where $R = \{W \in D^+ : |W| \leq m\}$. Consider the set Ω consisting of all mappings $f : D \to R$. Then we may write

$$\Gamma = \{\phi_f : f \in \Omega\}.$$

We can put the set Γ into one-to-one correspondence with Ω by sending each m-endomorphism to its restriction to D. Moreover, if $|D| = n \in \mathbb{N}$, then the size of these sets is easily evaluated in view of the fact that $|R| = \sum_{i=1}^{m} n^i$. In particular, if $n > 1$, then $|R| = (n^{m+1} - n)/(n-1)$, and

$$|\Gamma| = |\Omega| = \left(\frac{n^{m+1} - n}{n-1}\right)^n.$$

However, in this paper we are interested in counting the number of *classes* of m-endomorphisms under a particular equivalence relation. To motivate our definition of equivalence on Γ, we define a relation $\sim$ on Ω as follows:

$$f_1 \sim f_2 \iff \text{there exists a bijection } g : D \to D \text{ such that } f_2 \circ g = \phi_g \circ f_1.$$

As an exercise, the reader may wish to verify that $\sim$ satisfies the reflexive, symmetric, and transitive properties required of any equivalence relation. In Section 1.1, however, it will be shown that $\sim$ is a specific instance of a well-known equivalence relation induced by a group acting on a nonempty set.

Example 2. Let f be as in Example 1 (with $D = \{a, b\}$). Consider the bijection $g : D \to D$ defined by $g(a) = b$ and $g(b) = a$. Now let $f_1 : D \to D^+$ be given by $f_1(a) = b$ and $f_1(b) = ba$. Then

$$(f_1 \circ g)(a) = f_1(g(a)) = f_1(b) = ba = g(a)g(b) = \phi_g(ab) = \phi_g(f(a)) = (\phi_g \circ f)(a),$$
$$(f_1 \circ g)(b) = f_1(g(b)) = f_1(a) = b = g(a) = \phi_g(a) = \phi_g(f(b)) = (\phi_g \circ f)(b),$$

which shows that $f \sim f_1$.

Remark 3. Perhaps a more intuitive illustration of $\sim$ is as follows. If we let f and f_1 be as in Example 2, then the respective graphs of f and f_1 are $\{(a, ab), (b, a)\}$ and $\{(a, b), (b, ba)\}$. But the graph of f_1 can be obtained by applying the bijection g to each element of D that appears in the graph of f. In other words,

$$\big\{\big(g(a), g(a)g(b)\big), \big(g(b), g(a)\big)\big\} = \{(a, b), (b, ba)\}.$$

Since the graphs of f and f_1 are "the same" up to a permutation of a and b, we wish to consider these mappings equivalent, and $\sim$ provides the desired equivalence relation.

Extending $\sim$ to an equivalence relation on Γ leads to the following definition. If $f, h \in \Omega$, then ϕ_f is *combinatorially equivalent* to ϕ_h if and only if there exists a bijection $g : D \to D$ such that $\phi_h \circ \phi_g = \phi_g \circ \phi_f$. To state precisely the aim of this paper: given a set of symbols D with $|D| = n$, we wish to produce a formula for the number of equivalence classes in Γ under the relation of combinatorial equivalence. To this end, we shall specialize an argument of N. G. de Bruijn [1972] (namely, that used for his Theorem 1) to produce a formula for the number of classes in Ω under the relation $\sim$. But it is easy to check that for all $f, h \in \Omega$, we have $f \sim h$ if and only if ϕ_f is combinatorially equivalent to ϕ_h. Hence, there is a well-defined correspondence given by

$$[f] \leftrightarrow [\phi_f]$$

between the equivalence classes in Ω and those in Γ, and it follows that our formula will also provide the number of m-endomorphisms on D^+ up to combinatorial equivalence. Moreover, once this formula is obtained, we can fix one of the variables n, m and let the other run through the natural numbers in order to derive integer sequences, many of which appear to be little-known.

1.1. ***Group actions.*** For the reader's convenience, we review group actions. The following material (through Proposition 4) is paraphrased from [Malik et al. 1997]. Let G be a group and S a nonempty set. A *left action* of G on S is a function

$$\cdot : G \times S \to S, \quad (g, s) \mapsto g \cdot s,$$

such that, for all $g_1, g_2 \in G$ and for all $s \in S$,

(1) $(g_1 g_2) \cdot s = g_1 \cdot (g_2 \cdot s)$, where $g_1 g_2$ denotes the product of g_1, g_2 in G, and

(2) $e \cdot s = s$, where e is the identity element of G.

A left action induces the well-known equivalence relation E on the set S given by

$$(a, b) \in E \quad \Longleftrightarrow \quad g \cdot a = b \quad \text{for some } g \in G$$

for all $a, b \in S$. We refer to the equivalence classes under this relation as the *orbits* of G on S. The following result (known as Burnside's lemma) gives an expression for the number of these, provided that G and S are finite.

Proposition 4 [Malik et al. 1997]. *Let S be a finite, nonempty set, and suppose there is a left action of a finite group G on S. Then the number of orbits of G on S is*

$$\frac{1}{|G|} \sum_{g \in G} \bigl|\{s \in S : g \cdot s = s\}\bigr|.$$

Thus, the number of orbits of G on S equals the average number of elements of S that are "fixed" by an element of G. We now show that the relation $\sim$ from Section 1 is a specific instance of the relation E described above. To see this, let D

be a finite nonempty set, and let $\mathrm{Sym}(D)$ denote the symmetric group on D (i.e., the group of all bijections on D). Then $\mathrm{Sym}(D)$ acts on the set Ω according to the rule

$$g \cdot f = \phi_g \circ f \circ g^{-1}$$

for all $g \in \mathrm{Sym}(D)$, $f \in \Omega$. (One can easily verify that $\cdot$ defined in this way is indeed a left action.) Now, for any $f_1, f_2 \in \Omega$, we have

$$\begin{aligned} f_1 \sim f_2 &\iff f_2 \circ g = \phi_g \circ f_1 \quad \text{for some } g \in \mathrm{Sym}(D) \\ &\iff f_2 = \phi_g \circ f_1 \circ g^{-1} \quad \text{for some } g \in \mathrm{Sym}(D) \\ &\iff g \cdot f_1 = f_2 \quad \text{for some } g \in \mathrm{Sym}(D) \\ &\iff (f_1, f_2) \in E. \end{aligned}$$

It follows that the equivalence classes in Ω under the relation $\sim$ are just the orbits of $\mathrm{Sym}(D)$ on Ω. Enumerating the elements of $\mathrm{Sym}(D)$ by $g_1, \dots, g_{n!}$, we find the number of orbits to be

$$\frac{1}{n!} \sum_{r=1}^{n!} |\{f \in \Omega : f \circ g_r = \phi_{g_r} \circ f\}|. \tag{1}$$

For any permutation g of a finite set, and for each natural number j, let $c(g, j)$ denote the number of cycles of length[1] j occurring in the cycle decomposition of g. (This notation comes from [de Bruijn 1972].) The quantities $c(g, j)$ will play a role in the evaluation of $|\{f \in \Omega : f \circ g_r = \phi_{g_r} \circ f\}|$, which occurs in the next section. Our evaluation is a modification of de Bruijn's counting argument [1964, § 5.12].

2. Main results

We now produce a formula for the number of equivalence classes in Ω under the relation $\sim$. Let D be a finite set, and suppose that $g \in \mathrm{Sym}(D)$ is the product of disjoint cycles of lengths $k_1, k_2, \dots, k_\ell$, where $k_1 \le k_2 \le \cdots \le k_\ell$. Then the sequence $k_1, k_2, \dots, k_\ell$ is called the *cycle type* of g. For example, if $D = \{a, b, c, d, e\}$, then the permutation $g = (a)(b, c)(d, e)$ has cycle type $1, 2, 2$. The following lemma will be useful.

Lemma 5. *Let D be a finite set, and let $g \in \mathrm{Sym}(D)$ have cycle type $k_1, k_2, \dots, k_\ell$. For each $1 \le i \le \ell$, select a single $d_i \in D$ from the cycle corresponding to k_i. (Thus, k_i is the smallest natural number such that $g^{k_i}(d_i) = d_i$.) Now suppose that $f \in \Omega$. Then $f \circ g = \phi_g \circ f$ if and only if for each $1 \le i \le \ell$,*

(1) *$(f \circ g^j)(d_i) = (\phi_g^j \circ f)(d_i)$ for all $j \in \mathbb{N}$,*
(2) *$f(d_i)$ is of the form $d'_1 \cdots d'_{k \le m}$, where $d'_1, \dots, d'_k \in D$ each belong to a cycle in g whose length divides k_i.*

[1]There should be no confusion between the notions of "string length" and "cycle length".

Proof. First assume that $f \circ g = \phi_g \circ f$. Then condition (1) follows from an inductive argument. But $f(d_i) = f(g^{k_i}(d_i)) = \phi_g^{k_i}(f(d_i))$. Write $f(d_i) = d'_1 \cdots d'_k$, where $d'_1, \ldots, d'_k \in D$ and $k \leq m$. Then

$$d'_1 \cdots d'_k = \phi_g^{k_i}(d'_1 \cdots d'_k) = g^{k_i}(d'_1) \cdots g^{k_i}(d'_k).$$

In particular, for each $1 \leq t \leq k$, we have $d'_t = g^{k_i}(d'_t)$. This implies that

$$\big(d'_t, g(d'_t), g^2(d'_t), \ldots, g^{k_i-1}(d'_t)\big)$$

is a cycle whose length divides k_i. The conclusion follows.

Conversely, suppose that condition (1) holds. (Condition (2) is superfluous here.) Let $d \in D$. Then there exist $i, j \in \mathbb{N}$ such that $d = g^j(d_i)$. Now,

$$\begin{aligned} f(g(d)) &= f(g(g^j(d_i))) = f(g^{1+j}(d_i)) \\ &= \phi_g^{1+j}(f(d_i)) = \phi_g(\phi_g^j(f(d_i))) = \phi_g(f(g^j(d_i))) = \phi_g(f(d)). \end{aligned}$$

Therefore, $f \circ g = \phi_g \circ f$, so the proof is complete. □

Once again, suppose that $|D| = n$, and label the elements of $\mathrm{Sym}(D)$ by $g_1, \ldots, g_{n!}$. For each $1 \leq r \leq n!$, we can find the number of $f \in \Omega$ satisfying

$$f \circ g_r = \phi_{g_r} \circ f. \tag{2}$$

Suppose that g_r has cycle type $k_{r1}, k_{r2}, \ldots, k_{r\ell_r}$. For each $1 \leq i \leq \ell_r$, select a single element $d_{ri} \in D$ from the cycle corresponding to k_{ri}. Then Lemma 5 implies that any $f \in \Omega$ satisfying (2) is determined by its values on each d_{ri}. Hence, to find the number of f satisfying (2), we need only count the number of possible images of d_{ri} under such an f, and then take the product over all i. But the m or fewer elements of D comprising the string $f(d_{ri})$ must each belong to a cycle in the decomposition of g_r whose length divides k_{ri}. For each $1 \leq k \leq m$, there are

$$\Big(\sum_{j \mid k_{ri}} jc(g_r, j)\Big)^k$$

choices of $f(d_{ri})$ such that $|f(d_{ri})| = k$. Hence, there are

$$\sum_{k=1}^{m}\Big(\sum_{j \mid k_{ri}} jc(g_r, j)\Big)^k$$

total choices of $f(d_{ri})$. Taking the product over all i, it follows that the number of f satisfying (2) is

$$\prod_{i=1}^{\ell_r}\bigg(\sum_{k=1}^{m}\Big(\sum_{j \mid k_{ri}} jc(g_r, j)\Big)^k\bigg). \tag{3}$$

Thus, we've evaluated $|\{f\in\Omega : f\circ g_r=\phi_{g_r}\circ f\}|$, and putting together (1) and (3) gives an expression for the number of equivalence classes in Ω under the relation $\sim$. Recalling that these classes are in one-to-one correspondence with the classes in Γ under the relation of combinatorial equivalence, we obtain our main result:

Theorem 6. *If $|D| = n$, then the number of m-endomorphisms on D^+, up to combinatorial equivalence, is the value of*

$$\frac{1}{n!}\sum_{r=1}^{n!}\biggl(\prod_{i=1}^{\ell_r}\biggl(\sum_{k=1}^{m}\biggl(\sum_{j\mid k_{ri}} jc(g_r, j)\biggr)^k\biggr)\biggr), \tag{4}$$

where $g_1, \dots, g_{n!}$ are the elements of $\mathrm{Sym}(D)$, *and $k_{r1}, \dots, k_{r\ell_r}$ is the cycle type of g_r.*

Example 7. Let $D = \{a, b\}$. We find the number of classes of 1-endomorphisms on D^+. The elements of $\mathrm{Sym}(D)$ (in cycle notation) are $g_1 = (a)(b)$ and $g_2 = (a, b)$. Evidently, $c(g_1, 1) = 2$, $c(g_2, 1) = 0$, and $c(g_2, 2) = 1$. Using Theorem 6, there are

$$\tfrac{1}{2}\bigl(c(g_1, 1)^2 + 2c(g_2, 2)\bigr) = \tfrac{1}{2}(2^2 + 2) = 3$$

classes of 1-endomorphisms on D^+. These are given by

$$\left\{\begin{matrix} a\to a \\ b\to b\end{matrix}\right\},\quad \left\{\begin{matrix} a\to b \\ b\to a\end{matrix}\right\}\quad\text{and}\quad \left\{\begin{matrix} a\to a \\ b\to a\end{matrix}\equiv\begin{matrix} a\to b \\ b\to b\end{matrix}\right\}.$$

We can extend the result of Example 7 by fixing $n = 2$ and letting m be arbitrary. From (4), we find that the number of classes of m-endomorphisms on D^+, where $|D| = 2$, is

$$\tfrac{1}{2}\bigl((2^{m+1}-2)^2 + (2^{m+1}-2)\bigr).$$

Running m through the natural numbers, we obtain values $3, 21, 105, 465, 1953, \dots$. This is the sequence A134057 in the On-line Encyclopedia of Integers [OEIS 1996]. However, for $n = 3$, the number of classes of m-endomorphisms becomes

$$\frac{1}{6}\biggl(\biggl(\frac{3^{m+1}-3}{2}\biggr)^3 + 3m\,\frac{3^{m+1}-3}{2} + 2\,\frac{3^{m+1}-3}{2}\biggr).$$

Letting $m = 1, 2, 3, 4, \dots$ gives values $7, 304, 9958, 288280, \dots$. This sequence appears to be little-known, and has been submitted by the authors to the OEIS.

2.1. ***An alternative formulation of Theorem 6.*** We now present a slight rewording of Theorem 6. In order to compute the number of equivalence classes of m-endomorphisms (where $|D| = n$), we need not, in practice, consider each element of $\mathrm{Sym}(D)$ individually. Rather, we need only consider the cycle types of these permutations. The following well-known result gives the number of permutations in $\mathrm{Sym}(D)$ of a given cycle type.

Proposition 8 [Dummit and Foote 2004]. *Let $|D| = n$, and let $g \in \mathrm{Sym}(D)$. Suppose that $m_1, m_2, \dots, m_s$ are the distinct integers appearing in the cycle type of g. For each $j \in \{1, 2, \dots, s\}$, abbreviate $c_j = c(g, m_j)$. Let C_g be the set of all permutations in* $\mathrm{Sym}(D)$ *whose cycle type is that of g. Then*

$$|C_g| = \frac{n!}{\prod_{j=1}^{s} c_j!\, m_j^{c_j}}. \tag{5}$$

For convenience, we shall say that $g \in \mathrm{Sym}(D)$ *fixes* the mapping $f \in \Omega$ if and only if $f \circ g = \phi_g \circ f$. Now, two bijections in $\mathrm{Sym}(D)$ with the same cycle type must fix the same number of $f \in \Omega$. Therefore, in order to derive an expression for the number of classes of m-endomorphisms on D^+, we can select a single representative in $\mathrm{Sym}(D)$ of each possible cycle type, then determine the number of $f \in \Omega$ fixed by each representative using expression (3), multiply this number by the corresponding value of (5), and then sum up over all of our representatives and divide by $n!$. But the cycle types in $\mathrm{Sym}(D)$ are precisely the *integer partitions* of n, namely, the nondecreasing sequences of natural numbers whose sum is n. If $p(n)$ denotes the number of integer partitions of n, then we may restate Theorem 6 as follows.

Corollary 9. *Let $|D| = n$, and suppose that $g_1, \dots, g_{p(n)} \in$* $\mathrm{Sym}(D)$ *have distinct cycle types. Then the number of m-endomorphisms on D^+, up to combinatorial equivalence, is the value of*

$$\frac{1}{n!} \sum_{r=1}^{p(n)} \Biggl(|C_{g_r}| \prod_{i=1}^{\ell_r} \Biggl(\sum_{k=1}^{m} \Biggl(\sum_{j \mid k_{ri}} j c(g_r, j) \Biggr)^{k} \Biggr) \Biggr), \tag{6}$$

where $k_{r1}, \dots, k_{r\ell_r}$ is the cycle type of g_r, and C_{g_r} is as in Proposition 8.

Example 10. To illustrate Corollary 9, we compute the number of classes of m-endomorphisms when $|D| = 4$. Let $D = \{a, b, c, d\}$. As previously mentioned, the cycle types in $\mathrm{Sym}(D)$ are the integer partitions of 4:

$$1+1+1+1, \quad 1+1+2, \quad 2+2, \quad 1+3, \quad 4.$$

Hence, the bijections

$$g_1 = (a)(b)(c)(d), \quad g_2 = (a)(b)(c, d), \quad g_3 = (a, b)(c, d),$$
$$g_4 = (a)(b, c, d), \quad g_5 = (a, b, c, d)$$

encompass all possible cycle types in $\mathrm{Sym}(D)$. Direct calculation using (5) yields

$$|C_{g_1}| = 1, \quad |C_{g_2}| = 6, \quad |C_{g_3}| = 3, \quad |C_{g_4}| = 8, \quad |C_{g_5}| = 6.$$

Thus, by Corollary 9, the number of classes of m-endomorphisms when $n = 4$ is

$$\tfrac{1}{24}\bigl(\Lambda_4{}^4 + 6\Lambda_2{}^2\Lambda_4 + 3\Lambda_4{}^2 + 8m\Lambda_4 + 6\Lambda_4\bigr),$$

where $\Lambda_k = (k^{m+1} - k)/(k-1)$.

	$n=1$	$n=2$	$n=3$	$n=4$
$m=1$	1	3	7	19
$m=2$	2	21	304	6,915
$m=3$	3	105	9,958	2,079,567
$m=4$	4	465	288,280	556,898,155
$m=5$	5	1,953	7,973,053	144,228,436,231
$m=6$	6	8,001	217,032,088	37,030,504,349,475

	$n=5$	$n=6$
$m=1$	47	130
$m=2$	207,258	7,773,622
$m=3$	746,331,322	409,893,967,167
$m=4$	2,406,091,382,736	19,560,646,482,079,624
$m=5$	7,567,019,254,708,782	916,131,223,607,107,471,135
$m=6$	23,677,181,825,841,420,408	42,770,482,829,102,570,213,645,988

Table 1. Values of (6) for $n, m \leq 6$.

Proceeding along the lines of Example 10, we find that there are

$$\tfrac{1}{120}\left(\Lambda_5{}^5 + 10\Lambda_3{}^3\,\Lambda_5 + 15m\Lambda_5{}^2 + 20\Lambda_2{}^2\Lambda_5 + 20\Lambda_2\Lambda_3 + 30m\,\Lambda_5 + 24\,\Lambda_5\right)$$

classes of m-endomorphisms when $n = 5$, and

$$\tfrac{1}{720}\big(\Lambda_6{}^6 + 15\Lambda_4{}^4\Lambda_6 + 45\Lambda_2{}^2\Lambda_6{}^2 + 15\Lambda_6{}^3 + 40\Lambda_3{}^3\Lambda_6 \\ + 120m\Lambda_3\Lambda_4 + 40\Lambda_6{}^2 + 90\Lambda_2{}^2\Lambda_6 + 90\Lambda_2\Lambda_6 + 144m\Lambda_6 + 120\Lambda_6\big)$$

classes of m-endomorphisms when $n = 6$. Letting m run through $\mathbb{N}$ in these cases, we again obtain sequences that are not well-known. Table 1 displays the values of (6) for $n, m \leq 6$.

Remark 11. The sequence 1, 3, 7, 19, 47, 130, ... is sequence A001372 in [OEIS 1996].

3. Two natural variations

In this section, we highlight two natural variations of Corollary 9. First, we restrict our attention to endomorphisms on D^+ that send each element of D to a string of length exactly m. We then consider m-endomorphisms of the so-called free monoid, which contains the empty string. Expressions analogous to those in Section 2 are derived in each case.

3.1. ***m-uniform endomorphisms.*** Fix $n, m \in \mathbb{N}$, and suppose that $|D| = n$. Then $\phi \in \mathrm{End}(D^+)$ is called an *m-uniform endomorphism* if and only if $|\phi(d)| = m$ for each $d \in D$. In this section, we produce a formula for the number of m-uniform endomorphisms on D^+ up to combinatorial equivalence. To begin, let $g_1, \dots, g_{p(n)} \in \mathrm{Sym}(D)$ have distinct cycle types. We now put $R = \{W \in D^+ : |W| = m\}$ and take Ω to be the set of all mappings of D into R. For each $1 \le r \le p(n)$, we ask for the number of $f \in \Omega$ satisfying

$$f \circ g_r = \phi_{g_r} \circ f.$$

Once again, if g_r has cycle type $k_{r1}, \dots, k_{r\ell_r}$, then for each $1 \le i \le \ell_r$ we select an element d_{ri} from the cycle corresponding to k_{ri}, and count the number of possible values of $f(d_{ri})$. In this case, we must have $|f(d_{ri})| = m$, where the elements of D comprising the string $f(d_{ri})$ each belong to a cycle whose length divides k_{ri}. Hence, there are

$$\Bigl(\sum_{j \mid k_{ri}} jc(g_r, j)\Bigr)^m$$

choices of $f(d_{ri})$, and multiplying over all i yields

$$\prod_{i=1}^{\ell_r}\Bigl(\sum_{j \mid k_{ri}} jc(g_r, j)\Bigr)^m$$

as the value of $|\{f \in \Omega : f \circ g_r = \phi_{g_r} \circ f\}|$. Noting that permutations in $\mathrm{Sym}(D)$ of the same cycle type fix the same number of $f \in \Omega$, we multiply by $|C_{g_r}|$, sum with respect to r, and divide by $n!$ to obtain the following.

Corollary 12. *If $|D| = n$ and $g_1, \dots, g_{p(n)} \in \mathrm{Sym}(D)$ have distinct cycle types, then the number of m-uniform endomorphisms on D^+, up to combinatorial equivalence, is the value of*

$$\frac{1}{n!}\sum_{r=1}^{p(n)}\biggl(|C_{g_r}|\prod_{i=1}^{\ell_r}\Bigl(\sum_{j \mid k_{ri}} jc(g_r, j)\Bigr)^m\biggr), \tag{7}$$

where $k_{r1}, \dots, k_{r\ell_r}$ is the cycle type of g_r, and C_{g_r} is as in Proposition 8.

When $n = 2$, the number of m-uniform endomorphisms on D^+, up to combinatorial equivalence, is

$$\tfrac{1}{2}(2^{2m} + 2^m).$$

Letting $m = 1, 2, 3, 4, \dots$ gives values $3, 10, 36, 136, \dots$. This is the sequence A007582 from [OEIS 1996]. Moreover, when $n = 3$ there are

$$\tfrac{1}{6}(3^{3m} + 3 \cdot 3^m + 2 \cdot 3^m)$$

classes of m-uniform endomorphisms, and letting m run through $\mathbb{N}$ gives the sequence $7, 129, 3303, 88641, \dots$, which is not well known. Continuing, the

	$n=1$	$n=2$	$n=3$	$n=4$
$m=1$	1	3	7	19
$m=2$	1	10	129	2,836
$m=3$	1	36	3,303	700,624
$m=4$	1	136	88,641	178,981,696
$m=5$	1	528	7,973,053	45,813,378,304
$m=6$	1	2,080	64,570,689	11,728,130,323,456

	$n=5$	$n=6$
$m=1$	47	130
$m=2$	83,061	3,076,386
$m=3$	254,521,561	141,131,630,530
$m=4$	794,756,352,216	6,581,201,266,858,896
$m=5$	2,483,530,604,092,546	307,047,288,863,992,988,160
$m=6$	7,761,021,959,623,948,401	14,325,590,271,500,876,382,987,456

Table 2. Values of (7) for $n, m \leq 6$.

expressions when $n = 4, 5, 6$ are

$$\tfrac{1}{24}\big(4^{4m} + 6\cdot 2^{2m}\cdot 4^m + 3\cdot 4^{2m} + 8\cdot 4^m + 6\cdot 4^m\big),$$

$$\tfrac{1}{120}\big(5^{5m} + 10\cdot 3^{3m}\cdot 5^m + 15\cdot 5^{2m} + 20\cdot 2^{2m}\cdot 5^m + 20\cdot 2^m\cdot 3^m + 30\cdot 5^m + 24\cdot 5^m\big),$$

$$\begin{aligned}\tfrac{1}{720}\big(&6^{6m} + 15\cdot 4^{4m}\cdot 6^m + 45\cdot 2^{2m}\cdot 6^{2m} + 15\cdot 6^{3m} + 40\cdot 3^{3m}\cdot 6^m\\ &+ 120\cdot 3^m\cdot 4^m + 40\cdot 6^{2m} + 90\cdot 2^{2m}\cdot 6^m + 90\cdot 2^m\cdot 6^m + 144\cdot 6^m + 120\cdot 6^m\big),\end{aligned}$$

respectively. Table 2 displays the values of (7) for $n, m \leq 6$.

3.2. ***The free monoid.*** If we adjoin the unique string of length 0 (denoted by ϵ) to the set D^+, then we form the set D^*. Paired with the operation of string concatenation, D^* forms the *free monoid* on D. We refer to ϵ as the *empty string*, and it serves as the identity element in D^*. That is, for any $W \in D^*$,

$$W\epsilon = W = \epsilon W.$$

We define an endomorphism on D^* to be a mapping $\phi : D^* \to D^*$ such that $\phi(W_1 W_2) = \phi(W_1)\phi(W_2)$ for all $W_1, W_2 \in D^*$.

Remark 13. Note that if ϕ is an endomorphism on D^*, then $\phi(\epsilon) = \epsilon$. This follows since for any $W \in D^*$, we have

$$\phi(W) = \phi(\epsilon W) = \phi(\epsilon)\phi(W),$$

which implies that $\phi(\epsilon)$ has length 0.

Now, an m-endomorphism on D^* is an endomorphism such that $|\phi(d)| \le m$ for all $d \in D$. Thus, an m-endomorphism on D^* can map elements of D to ϵ. To determine the number of m-endomorphisms on D^* up to combinatorial equivalence, we put $R = \{W \in D^* : |W| \le m\}$, and for each $g \in \mathrm{Sym}(D)$, we ask for the number of $f : D \to R$ that are fixed by g. Again, it suffices to count the number of possible images under such an f of a single $d \in D$ from each cycle in the decomposition of g, and then multiply over all the cycles. But there is now one additional possible value of $f(d)$: the empty string. Hence, if d belongs to a cycle of length k_i, then we have

$$1 + \sum_{k=1}^{m} \Bigl(\sum_{j \mid k_i} j c(g_r, j) \Bigr)^k = \sum_{k=0}^{m} \Bigl(\sum_{j \mid k_i} j c(g_r, j) \Bigr)^k$$

choices of $f(d)$. From this observation, we deduce the following.

Corollary 14. *Let $|D| = n$, and suppose that $g_1, \dots, g_{p(n)} \in \mathrm{Sym}(D)$ have distinct cycle types. Then the number of m-endomorphisms on D^*, up to combinatorial equivalence, is the value of*

$$\frac{1}{n!} \sum_{r=1}^{p(n)} \Biggl(|C_{g_r}| \prod_{i=1}^{\ell_r} \Biggl(\sum_{k=0}^{m} \Bigl(\sum_{j \mid k_{ri}} j c(g_r, j) \Bigr)^k \Biggr) \Biggr), \tag{8}$$

where $k_{r1}, \dots, k_{r\ell_r}$ is the cycle type of g_r, and C_{g_r} is as in Proposition 8.

When $n = 2$, the number of m-endomorphisms on D^*, up to combinatorial equivalence, is

$$\tfrac{1}{2}\bigl((2^{m+1} - 1)^2 + (2^{m+1} - 1)\bigr).$$

This is sequence A006516 from [OEIS 1996]. The corresponding expressions for $n = 3, 4, 5, 6$ are

$$\tfrac{1}{6}\bigl(\Delta_3{}^3 + 3(m+1)\,\Delta_3 + 2\,\Delta_3\bigr),$$

$$\tfrac{1}{24}\bigl(\Delta_4{}^4 + 6\Delta_2{}^2\,\Delta_4 + 3\Delta_4{}^2 + 8(m+1)\,\Delta_4 + 6\,\Delta_4\bigr),$$

$$\tfrac{1}{120}\bigl(\Delta_5{}^5 + 10\Delta_3{}^3\Delta_5 + 15(m+1)\Delta_5{}^2 + 20\Delta_2{}^2\Delta_5 + 20\Delta_2\Delta_3 + 30(m+1)\Delta_5 + 24\Delta_5\bigr),$$

$$\tfrac{1}{720}\bigl(\Delta_6{}^6 + 15\Delta_4{}^4\Delta_6 + 45\Delta_2{}^2\Delta_6{}^2 + 15\Delta_6{}^3 + 40\Delta_3{}^3\Delta_6 + 120(m+1)\Delta_3\Delta_4 \\ + 40\Delta_6{}^2 + 90\Delta_2{}^2\Delta_6 + 90\Delta_2\Delta_6 + 144(m+1)\Delta_6 + 120\Delta_6\bigr),$$

where $\Delta_k = (k^{m+1} - 1)/(k - 1)$. Once again, the sequences given by these expressions appear to be little-known. Table 3 gives the values of (8) for $n, m \le 6$.

4. (χ,ζ)-patterns

In closing, we briefly place the relation $\sim$ from Section 1 into a more general context. Let G be a finite group, and let N and M be finite nonempty sets. Suppose

	$n=1$	$n=2$	$n=3$	$n=4$
$m=1$	2	6	16	45
$m=2$	3	28	390	8,442
$m=3$	4	120	10,760	2,180,845
$m=4$	5	496	295,603	563,483,404
$m=5$	6	2,016	8,039,304	144,651,898,755
$m=6$	7	8,128	217,629,416	37,057,640,711,850

	$n=5$	$n=6$
$m=1$	121	338
$m=2$	244,910	8,967,034
$m=3$	770,763,470	419,527,164,799
$m=4$	2,421,556,983,901	19,636,295,549,860,505
$m=5$	2,370,422,688,990,078	916,720,535,022,517,503,173
$m=6$	23,683,244,198,577,149,289	42,775,066,732,111,188,868,070,978

Table 3. Values of (8) for $n, m \leq 6$.

that $\chi : G \to \mathrm{Sym}(N)$ and $\zeta : G \to \mathrm{Sym}(M)$ are group homomorphisms. Denote the set of all functions from N into M by M^N. This notation comes from de Bruijn [1972], who also introduced the equivalence relation $E_{\chi,\zeta}$ on M^N defined by

$$(f_1, f_2) \in E_{\chi,\zeta} \iff f_2 \circ \chi(\gamma) = \zeta(\gamma) \circ f_1 \quad \text{for some } \gamma \in G.$$

Example 15 [de Bruijn 1972]. Suppose that N is a set of size $n \in \mathbb{N}$, and define an equivalence relation S on the set of all mappings of N into itself by

$$(f_1, f_2) \in S \iff f_2 \circ \gamma = \gamma \circ f_1 \quad \text{for some } \gamma \in \mathrm{Sym}(N).$$

Letting $G = \mathrm{Sym}(N)$, $M = N$, and $\chi = \zeta$ be the identity homomorphism on $\mathrm{Sym}(N)$ shows that S is a special case of the relation $E_{\chi,\zeta}$. Moreover, the sequence in Remark 11 gives the number of equivalence classes under S for $n = 1, 2, 3 \ldots$. (See [de Bruijn 1972, § 3].)

The relation $E_{\chi,\zeta}$ stems from the left action of G on M^N given by

$$\gamma \cdot f = \zeta(\gamma) \circ f \circ \chi(\gamma^{-1})$$

for all $\gamma \in G$, $f \in M^N$. De Bruijn [1972] referred to the orbits of G on M^N as *(χ, ζ)-patterns*, and provided a formula for the number of these by applying Burnside's lemma, and then evaluating $|\{f \in M^N : \gamma \cdot f = f\}|$ for each $\gamma \in G$. But the relation $\sim$ on the set $\Omega = \{\text{mappings of } D \text{ into } R\}$, where $0 < |D| < \infty$ and $R = \{W \in D^+ : |W| \leq m\}$, is a special instance of the relation $E_{\chi,\zeta}$. To see this, take $N = D$, $M = R$, and $G = \mathrm{Sym}(D)$. Let χ be the identity homomorphism on $\mathrm{Sym}(D)$, and define $\zeta : G \to \mathrm{Sym}(R)$ by

$$\zeta(g) = \phi_g|_R$$

for all $g \in \mathrm{Sym}(D)$. Then for any $g, g' \in \mathrm{Sym}(D)$,

$$\zeta(g \circ g') = \phi_{g \circ g'}|_R = (\phi_g \circ \phi_{g'})|_R = \phi_g|_R \circ \phi_{g'}|_R = \zeta(g) \circ \zeta(g'),$$

so ζ is a group homomorphism. Now, for any $f_1, f_2 \in \Omega$, we have

$$\begin{aligned} f_1 \sim f_2 &\iff f_2 \circ g = \phi_g \circ f_1 = \phi_g|_R \circ f_1 \quad \text{for some } g \in \mathrm{Sym}(D) \\ &\iff f_2 \circ \chi(g) = \zeta(g) \circ f_1 \quad \text{for some } g \in \mathrm{Sym}(D) \\ &\iff (f_1, f_2) \in E_{\chi,\zeta}. \end{aligned}$$

It follows that the equivalence classes in Ω under the relation $\sim$ are (χ, ζ)-patterns for χ, ζ chosen as above. In particular, our Theorem 6 is a special case of de Bruijn's formula.

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