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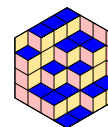


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# From Hertzsprung's problem to pattern-rewriting systems

Anders Claesson

**ABSTRACT** Drawing on a problem posed by Hertzsprung in 1887, we say that a given permutation  $\pi \in \mathcal{S}_n$  contains the Hertzsprung pattern  $\sigma \in \mathcal{S}_k$  if there is a factor  $\pi(d+1)\pi(d+2)\cdots\pi(d+k)$  of  $\pi$  such that  $\pi(d+1)-\sigma(1)=\cdots=\pi(d+k)-\sigma(k)$ . Using a combination of the Goulden–Jackson cluster method and the transfer-matrix method we determine the joint distribution of occurrences of any set of (incomparable) Hertzsprung patterns, thus substantially generalizing earlier results by Jackson et al. on the distribution of ascending and descending runs in permutations. We apply our results to the problem of counting permutations up to pattern-replacement equivalences, and using pattern-rewriting systems – a new formalism similar to the much studied string-rewriting systems – we solve a couple of open problems raised by Linton et al. in 2012.

## 1. INTRODUCTION

Severin Carl Ludvig Hertzsprung (1839–1893) was a Danish senior civil servant with a graduate degree in astronomy from the University of Copenhagen. In 1887 a letter authored by him titled “En kombinationsopgave” appeared in Tidsskrift for matematik [16]. The first paragraph reads

*At bestemme Antallet af Maader, hvorpaa Tallene 1, 2, 3, 4, . . . , n  
 kunne opstilles i Række saaledes, at Differensen mellem to ved Siden  
 af hinanden staaende Tal overalt skal være numerisk forskjellig fra 1.*

Or, translated, the problem is to determine the number of ways in which the numbers  $1, 2, 3, 4, \dots, n$  can be arranged such that the difference between two adjacent numbers is different from 1. For  $n = 4$  there are only two such arrangements, namely 2413 and 3142. An alternative interpretation is that we are asked for the number of ways  $n$  kings can be placed on an  $n$  by  $n$  chessboard, one on each row and column, so that no two attack each other. Indeed, Kaplansky [21] – who rediscovered Hertzsprung's problem in 1944 – called it the  $n$ -kings problem.

In Hertzsprung's solution – which in his own words is only slightly elegant – the problem is first generalized by defining  $u_{n,k}$  as the number of arrangements such that the numbers  $1, 2, \dots, k$  satisfy the requirement that two numbers whose difference is 1 cannot be placed next to each other. Hertzsprung derives a recurrence relation

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**KEYWORDS.** Hertzsprung's problem, cluster method, pattern, permutation, rewriting system.

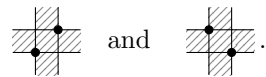
for the numbers  $u_{n,k}$  to which he guesses a solution and subsequently verifies that it indeed satisfies the recurrence. The solution to the original problem is then given by

$$u_{n,n} = n! + \sum_{k=1}^n (-1)^k \sum_{i=1}^k \binom{k-1}{i-1} \binom{n-k}{i} 2^i (n-k)!.$$

The first few numbers of this sequence are 1, 1, 0, 0, 2, 14, 90, 646, 5242, 47622, which is A002464 in the OEIS [17]. A more elegant, but less explicit, solution (see e.g. p. 737 of Flajolet and Sedgewick [12]) is obtained using generating functions:  $u_{n,n}$  is the coefficient of  $x^n$  in the expansion of

(1) 
$$\sum_{m \geq 0} m! \left( \frac{x - x^2}{1 + x} \right)^m.$$

A reader familiar with mesh patterns [7] may have noticed that Hertzsprung’s problem is to count permutations in  $\mathcal{S}_n$  that avoid the two patterns



We will use the following terminology. Let  $\pi$  be a word (e.g. a permutation written in one line notation). A word  $\beta$  is said to be a *factor* of  $\pi$  if there are words  $\alpha$  and  $\gamma$  such that  $\pi = \alpha\beta\gamma$ . If  $\alpha$  is empty we also say that  $\beta$  is a *prefix* of  $\pi$ . If, in addition,  $\gamma$  is nonempty then  $\beta$  is said to be a *proper prefix* of  $\pi$ . Similarly, if  $\gamma$  is empty we say that  $\beta$  is a *suffix* of  $\pi$ , and that  $\beta$  is a *proper suffix* if, in addition,  $\alpha$  is nonempty.

Let  $\tau \in \mathcal{S}_k$  and  $\pi \in \mathcal{S}_n$ . We call  $\tau$  a *Hertzsprung factor* of  $\pi$  if there is an integer  $c$  and a factor  $\beta = b_1b_2 \dots b_k$  of  $\pi$  such that  $\tau(i) - b_i = c$  for each  $i \in [k]$ . In this context we also say that  $\beta$  is an *occurrence* of  $\tau$  and sometimes we write  $\beta \simeq \tau$ . As an example, 213 is a Hertzsprung factor of  $\pi = 1546372$ ; indeed,  $546 \simeq 213$  is an occurrence of 213 in  $\pi$ . We similarly define *Hertzsprung prefix* and *Hertzsprung suffix*.

Another way to say that  $\tau$  is a Hertzsprung factor of  $\pi$  is that  $\tau$  appears inside  $\pi$  via a subsequence  $\beta$  which forms a consecutive set both horizontally (the positions of  $\beta$ ) and vertically (the values of  $\beta$ ). Thus,  $\tau$  is a Hertzsprung factor of  $\pi$  if  $\pi$  contains the mesh pattern  $(\tau, H_k)$ , where  $H_k$  is the mesh  $\{0, 1, \dots, k\}^2 \setminus \{0, k\}^2$ . For instance, 2341 is a Hertzsprung factor of  $\pi$  if and only if  $\pi$  contains the mesh pattern

$$(2341, H_4) = \begin{array}{|c|c|c|c|} \hline \text{shaded} & \text{shaded} & \text{shaded} & \text{shaded} \\ \hline \text{shaded} & \bullet & \text{shaded} & \text{shaded} \\ \hline \text{shaded} & \bullet & \text{shaded} & \text{shaded} \\ \hline \text{shaded} & \bullet & \text{shaded} & \text{shaded} \\ \hline \end{array}.$$

Mesh patterns of the form  $(\tau, H_k)$  will be referred to as *Hertzsprung patterns*. Since all mesh patterns in this paper will be of this form we will, by slight abuse of notation, identify the pattern  $(\tau, H_k)$  with  $\tau$ . While the Hertzsprung terminology is original with this paper, there are a number of results on these patterns under different names in the literature. Monotone Hertzsprung patterns have the longest history and are usually called (increasing or decreasing) runs in the literature [1, 20, 18, 19, 31]. Myers [26] seem to have been the first to study non-monotone Hertzsprung patterns. She calls them rigid patterns. Bóna [5] talks of permutations very tightly avoiding or containing a pattern. Let us now detail some of these results.

The identity permutation (as well as the corresponding Hertzsprung pattern) will be denoted by  $\text{id}_k = 12 \dots k$ . Its reverse will be denoted  $\overline{\text{id}}_k = k \dots 21$ . Jackson and Read [18] showed that the generating functions for respectively  $\text{id}_k$ -avoiding and

$\{\text{id}_k, \overline{\text{id}}_k\}$ -avoiding permutations are

$$\sum_{m \geq 0} m! \left( \frac{x - x^k}{1 - x^k} \right)^m \quad \text{and} \quad \sum_{m \geq 0} m! \left( \frac{x - 2x^k + x^{k+1}}{1 - x^k} \right)^m.$$

The special case  $k = 2$  in the latter formula is the generating function (1).

Some Hertzsprung patterns  $\tau \in \mathcal{S}_k$  can overlap with themselves in the sense that there is a permutation  $\sigma$  of length less than  $2k$  such that  $\tau$  is both a proper Hertzsprung prefix and a proper Hertzsprung suffix of  $\sigma$ . Myers [26] calls such patterns extendible, we will call them *self-overlapping*. The monotone patterns,  $\text{id}_k$  and  $\overline{\text{id}}_k$ , are both self-overlapping. The pattern 2143 is also self-overlapping, while 132 is not. Myers derives a formula for counting the number of permutations of  $[n]$  with a prescribed number  $m$  of occurrences of any single non-self-overlapping pattern  $\tau \in \mathcal{S}_k$ :

$$(2) \quad \sum_i (-1)^{m-i} \binom{i}{m} \binom{n - (k-1)i}{i} (n - (k-1)i)!.$$

Let  $\mathcal{S}_n(\tau)$  denote the set of permutations in  $\mathcal{S}_n$  that avoid the Hertzsprung pattern  $\tau$ . Bóna [5] showed that  $|\mathcal{S}_n(\tau)| \leq |\mathcal{S}_n(\text{id}_k)|$  for each non-self-overlapping pattern  $\tau$ . He also explains why most patterns are non-self-overlapping. Both Myers and Bóna ask if it is possible to determine  $|\mathcal{S}_n(\tau)|$  for any self-overlapping pattern  $\tau$  other than  $\text{id}_k$  and  $\overline{\text{id}}_k$ .

Let  $T$  be an *antichain* of Hertzsprung patterns. That is, every pair of distinct patterns in  $T$  are incomparable in the sense that one is not a Hertzsprung factor of the other. Let  $\mathcal{S}_n(T) = \cap_{\tau \in T} \mathcal{S}_n(\tau)$  be the set of *T-avoiding permutations* in  $\mathcal{S}_n$ . In Section 2 we show that there is a rational function  $R(x) \in \mathbb{Q}(x)$  such that

$$\sum_{n \geq 0} |\mathcal{S}_n(T)| x^n = \sum_{m \geq 0} m! R(x)^m.$$

Moreover, there is an efficient way of determining  $R(x)$  from the set  $T$ . We in fact show something stronger.

It is known [20, 19] that the number of permutations of  $[n]$  with exactly  $\ell$  occurrences of  $\text{id}_k$  is the coefficient of  $u^\ell x^n$  in

$$(3) \quad \sum_{m \geq 0} m! x^m \left( \frac{1 - ux - (1-u)x^{k-1}}{1 - ux - (1-u)x^k} \right)^m.$$

Suppose that  $T = \{\tau_1, \tau_2, \dots, \tau_k\}$  is an antichain of Hertzsprung patterns. We show that there is a rational function  $R(u_1, \dots, u_k; x)$  in  $\mathbb{Q}(u_1, \dots, u_k, x)$  such that

$$\sum_{\pi \in \mathcal{S}} u_1^{\tau_1(\pi)} u_2^{\tau_2(\pi)} \dots u_k^{\tau_k(\pi)} x^{|\pi|} = \sum_{m \geq 0} m! R(u_1, u_1, \dots, u_k; x)^m,$$

where  $\mathcal{S} = \cup_n \mathcal{S}_n$  and  $\tau_i(\pi)$  denotes the number of occurrences of  $\tau_i$  in  $\pi$ .

In Section 3 we apply the machinery developed in Section 2 to the problem of counting permutations up to certain pattern-replacement equivalences introduced by Linton, Propp, Roby and West [25]. We provide a new formalism called pattern-rewriting systems, which are similar to the much studied string-rewriting systems. Using these we solve a couple of open problems posed by Linton et al.

## 2. ENUMERATION

Let  $T$  be an antichain of Hertzsprung patterns. We will apply the Goulden–Jackson cluster method [14] to count permutations with respect to the number of occurrences of patterns in  $T$ . The context of the original formulation of this method is the free monoid over a finite set. The method has, however, been successfully adopted and

applied to permutations by Goulden and Jackson themselves and more recently by Dotsenko and Khoroshkin [10] and Elizalde and Noy [11].

A *marked permutation* is a pair  $(\pi, M)$  where  $\pi$  is a permutation and  $M$  is a subset of all occurrences in  $\pi$  of patterns from  $T$ . The members of  $M$  are called *marked occurrences* and  $\pi$  is called the *underlying permutation* of  $(\pi, M)$ . As an example, let  $T = \{123\}$ ,  $\pi = 1234567 \in \mathcal{S}_7$  and  $M = \{123, 234, 567\}$ . The marked permutation  $(\pi, M)$  is then depicted below.



Let  $(\pi, M)$  be a marked permutation such that  $|\pi| \geq 1$  and  $M$  covers  $\pi$  in the sense that each letter of  $\pi$  is in some occurrence. We say that  $\alpha, \beta \in M$  *overlap* if they have at least one letter in common. Clearly, being overlapping is a symmetric relation and we can view  $M$  as an undirected graph with edge set consisting of all  $(\alpha, \beta)$  such that  $\alpha$  and  $\beta$  overlap. If this graph is connected, then we say that  $(\pi, M)$  is a *T-cluster*, or simply a *cluster* when  $T$  is known from context. The marked permutation in the example above is not a cluster, but  $(1\ 2\ 3\ 4)$  is.

Let  $\pi$  be a permutation of  $[k]$  and let  $\sigma_1, \sigma_2, \dots, \sigma_k$  be nonempty permutations. The *inflation* (see Albert and Atkinson [2]) of  $\pi$  by  $\sigma_1, \sigma_2, \dots, \sigma_k$  is

$$\pi[\sigma_1, \sigma_2, \dots, \sigma_k] = \sigma'_1 \sigma'_2 \dots \sigma'_k,$$

where  $\sigma'_{\pi^{-1}(i)}$  is obtained from  $\sigma_{\pi^{-1}(i)}$  by adding the constant  $|\sigma_{\pi^{-1}(1)}| + |\sigma_{\pi^{-1}(2)}| + \dots + |\sigma_{\pi^{-1}(i-1)}|$  to each of its letters. An example should make this clear,

$$231[1, 213, 21] = 3\ 546\ 21.$$

Note that  $\sigma'_i$  is an occurrence of  $\sigma_i$  in  $\pi[\sigma_1, \sigma_2, \dots, \sigma_k]$  by construction. The inflation operation naturally generalizes to marked permutations. Here is a permutation with some marked occurrences of 123 and 132:

$$(4) \quad 213456[1\ 2\ 3\ 4\ 5], 1\ 2\ 3\ 5\ 4, 1, 1, 1\ 3\ 2, 1] \\ = 6\ 7\ 8\ 9\ 10\ 1\ 2\ 3\ 5\ 4\ 11\ 12\ 13\ 15\ 14\ 16.$$

It is clear that a marked permutation  $(\pi, M)$  is a cluster if and only if its underlying permutation  $\pi$  is nonempty and  $(\pi, M)$  cannot be expressed as the inflation of two or more nonempty marked permutations.

Let  $(\tau, M)$  be any nonempty marked permutation with respect to some antichain  $T$  of Hertzsprung patterns. As described above, view  $M$  as an undirected graph whose edge set is  $\{(\alpha, \beta) \in M \times M : \alpha \text{ and } \beta \text{ overlap}\}$ . Consider the connected components of this graph. For instance, with  $(\tau, M)$  as in (4) there are six connected components:

$$6\ 7\ 8\ 9\ 10, 1\ 2\ 3\ 5\ 4, 11, 12, 13\ 15\ 14, 16.$$

Note that the values in any component form a set of consecutive numbers. Construct a word by picking a single value from each component (e.g. the smallest) and let  $\pi$  be its standardization. By *standardization* we mean the result of replacing the smallest letter by 1, the next smallest letter by 2, etc. In our example we arrive at 6, 1, 11, 12, 13, 16, whose standardization is  $\pi = 213456$ . On standardizing the connected components we arrive at a list  $(\sigma_1, M_1), (\sigma_2, M_2), \dots, (\sigma_k, M_k)$  each part of which is either a *T-cluster* or the (trivially) marked permutation  $(1, \emptyset)$ . Returning to our example, we have  $\sigma_1 = 12345$ ,  $M_1 = \{123, 234, 345\}$ ,  $\sigma_2 = 12354$ ,  $M_2 = \{123, 354\}$ ,  $\sigma_3 = 1$ ,  $M_3 = \emptyset$ , etc. Note that  $(\tau, M) = \pi[(\sigma_1, M_1), \dots, (\sigma_k, M_k)]$ . Let us summarize this in a theorem.

THEOREM 2.1. *Any marked permutation, with respect to an antichain  $T$  of Hertzsprung patterns, can be uniquely written*

$$\pi[(\sigma_1, M_1), (\sigma_2, M_2), \dots, (\sigma_k, M_k)],$$

where  $\pi \in \mathcal{S}_k$  and each  $(\sigma_i, M_i)$  is either  $(1, \emptyset)$  or a  $T$ -cluster.

For each nonempty permutation  $\pi$  let there be an associated indeterminate  $u_\pi$  and let  $\mathbf{u} = (u_1, u_{12}, u_{21}, u_{123}, u_{132}, \dots)$  be the sequence of all such indeterminates. Let  $T$  be an antichain of Hertzsprung patterns. For any marked permutation  $(\pi, M)$ , define the monomial

$$\mathbf{u}_M = \prod_{\alpha \in M} u_{\text{st}(\alpha)},$$

where  $\text{st}(\alpha)$  denotes the standardization of  $\alpha$ . If  $M$  is the set of marked occurrences in (4) then  $\mathbf{u}_M = u_{123}^4 u_{132}^2$ . The *cluster generating function* associated with  $T$  is defined by

$$C(\mathbf{u}; x) = \sum_{(\pi, M)} \mathbf{u}_M x^{|\pi|},$$

where the sum is over all  $T$ -clusters. Similarly, let  $F(\mathbf{u}; x) = \sum_{(\pi, M)} \mathbf{u}_M x^{|\pi|}$ , where the sum is over *all* marked permutations. Note that the only difference between the summations defining  $C(\mathbf{u}; x)$  and  $F(\mathbf{u}; x)$  is which sets are being summed over. Further, let

$$\mathbf{u}^{T(\pi)} = \prod_{\tau \in T} u_\tau^{\tau(\pi)},$$

where  $\tau(\pi)$  denotes the number of occurrences of  $\tau$  in  $\pi$ . Then

$$\sum_{\pi \in \mathcal{S}} x^{|\pi|} (\mathbf{1} + \mathbf{u})^{T(\pi)} = \sum_{m \geq 0} m! (x + C(\mathbf{u}; x))^m.$$

Indeed, the left-hand side is the generating function  $F(\mathbf{u}; x)$  of marked permutations: for each  $\tau \in T$  and for each of the  $\tau(\pi)$  occurrences of  $\tau$  in  $\pi$  there is a choice to be made, mark it with a  $u_\tau$  or leave it unmarked. That the right-hand side equals  $F(\mathbf{u}; x)$  follows from Theorem 2.1. On replacing  $\mathbf{u}$  by  $\mathbf{u} - \mathbf{1}$  we have the following result.

THEOREM 2.2. *Let  $T$  be an antichain of Hertzsprung patterns. Then*

$$\sum_{\pi \in \mathcal{S}} \mathbf{u}^{T(\pi)} x^{|\pi|} = \sum_{m \geq 0} m! (x + C(\mathbf{u} - \mathbf{1}; x))^m.$$

In particular,

$$\sum_{n \geq 0} |\mathcal{S}_n(T)| x^n = \sum_{m \geq 0} m! (x + C(-\mathbf{1}; x))^m.$$

If  $T = \{\tau\}$  and  $\tau$  is a non-self-overlapping pattern, then the only  $T$ -cluster is  $(\tau, \{\tau\})$  and  $C(u, x) = ux^{|\tau|}$ , where  $u = u_\tau$ . Hence we arrive at the following generating function version of Myers's formula (2).

COROLLARY 2.3. *For any non-self-overlapping pattern  $\tau$ ,*

$$\sum_{\pi \in \mathcal{S}} u^{\tau(\pi)} x^{|\pi|} = \sum_{m \geq 0} m! (x + (u - 1)x^{|\tau|})^m.$$

EXAMPLE 2.4. The distribution of the number of occurrences of 132 is given by

$$\sum_{\pi \in \mathcal{S}} u^{132(\pi)} x^{|\pi|} = \sum_{m \geq 0} m! (x + (u - 1)x^3)^m.$$

Letting  $u = 0$  we get a generating function for 132-avoiding permutations:

$$\sum_{n \geq 0} |\mathcal{S}_n(132)| x^n = \sum_{m \geq 0} m! (x - x^3)^m.$$

It follows that

$$(5) \quad |\mathcal{S}_n(132)| = \sum_{i=0}^{\lfloor n/3 \rfloor} (-1)^i (n-2i)! \binom{n-2i}{i},$$

which is the case  $\tau = 132$ ,  $m = 0$  and  $k = 3$  of Myers's formula (2).

EXAMPLE 2.5. For  $T = \{123\}$  the underlying permutation of any cluster is  $\text{id}_k$  for some  $k \geq 3$ . A cluster of length  $k$  is built from clusters of length  $k-2$  or length  $k-1$  by marking the suffix  $(k-2, k-1, k)$  of  $\text{id}_k$ . Formally, if  $\mathcal{C}_k$  denotes the set of clusters whose underlying permutation is  $\text{id}_k$  then  $\mathcal{C}_2 = \emptyset$ ,  $\mathcal{C}_3 = \{(123, \{123\})\}$ , and  $\mathcal{C}_k$  consists of all clusters

$$(\text{id}_k, M \cup \{(k-2, k-1, k)\}),$$

where  $(\text{id}_{k-1}, M) \in \mathcal{C}_{k-1}$  or  $(\text{id}_{k-2}, M) \in \mathcal{C}_{k-2}$ . It follows that

$$C(u, x) = ux^3 + ux C(u, x) + ux^2 C(u, x),$$

in which  $u = u_{123}$  tracks marked factors and  $x$  tracks the length of the cluster. Thus the number of clusters of fixed length is a Fibonacci number, the generating function for clusters is  $C(u, x) = ux^3 / (1 - u(x + x^2))$ , and we have rediscovered a special case of (3):

$$\begin{aligned} \sum_{\pi \in \mathcal{S}} u^{132(\pi)} x^{|\pi|} &= \sum_{m \geq 0} m! (x + C(u-1, x))^m \\ &= \sum_{m \geq 0} m! \left( x + \frac{(u-1)x^3}{1 - (u-1)(x + x^2)} \right)^m. \end{aligned}$$

Having seen a couple of examples we now return to the general case. Let  $T$  be any antichain of Hertzsprung patterns. We will show that the cluster generating function associated with  $T$  is counting walks in a digraph and thus it is rational. This can be seen as an application of the transfer-matrix method [32].

For  $\sigma, \tau \in T$  define the set of permutations  $\mathcal{O}(\sigma, \tau)$  by stipulating that  $\pi \in \mathcal{O}(\sigma, \tau)$  if and only if

- $\sigma$  is a proper Hertzsprung prefix of  $\pi$ ,
- $\tau$  is a proper Hertzsprung suffix of  $\pi$  and
- $|\pi| < |\sigma| + |\tau|$ .

If  $\mathcal{O}(\sigma, \tau)$  is nonempty, then we say that  $\sigma$  and  $\tau$  *overlap*. In particular,  $\mathcal{O}(\tau, \tau)$  is nonempty if and only if  $\tau$  is self-overlapping. Let

$$\Omega(\sigma, \tau) = \sum_{\pi \in \mathcal{O}(\sigma, \tau)} x^{|\pi| - |\sigma|}.$$

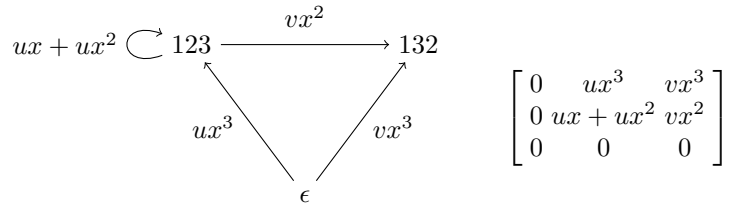
Construct an edge-weighted digraph  $D_T$  with vertices  $V = \{\epsilon\} \cup T$ , edge set  $V \times V$  and weight function  $w : V \times V \rightarrow \mathbb{Q}[\mathbf{u}, x]$  defined by

$$w(\sigma, \tau) = \begin{cases} 0 & \text{if } \tau = \epsilon, \\ u_\tau x^{|\tau|} & \text{if } \sigma = \epsilon, \\ u_\tau \Omega(\sigma, \tau) & \text{otherwise.} \end{cases}$$

EXAMPLE 2.6. Let  $T = \{123, 132\}$ . We have  $\mathcal{O}(132, 123) = \mathcal{O}(132, 132) = \emptyset$ ,

$$\mathcal{O}(123, 123) = \{1234, 12345\} \quad \text{and} \quad \mathcal{O}(123, 132) = \{12354\}.$$

For ease of notation, let  $u = u_{123}$  and  $v = u_{132}$ . The digraph  $D_T$  together with its adjacency matrix are depicted below.



Here, and in what follows, edges that are known to have weight 0 are omitted.

THEOREM 2.7. Let  $T$  be an antichain of Hertzsprung patterns. Let  $A$  be the adjacency matrix of the digraph  $D_T$  defined above. Then

$$C(\mathbf{u}; x) = \frac{1}{\det(1 - A)} \sum_{i=1}^{|T|} (-1)^i \det(1 - A : i + 1, 1),$$

where  $(B : i, j)$  denotes the matrix obtained by removing the  $i$ th row and  $j$ th column of  $B$ . In particular,  $C(\mathbf{u}; x)$  belongs to the field of rational functions  $\mathbb{Q}(x)(u_\tau : \tau \in T)$ .

*Proof.* The generating function for (weighted) directed walks in  $D_T$  starting at  $\epsilon$  and ending in any other vertex equals  $C(\mathbf{u}; x)$  by construction of  $D_T$ . Thus  $C(\mathbf{u}; x)$  is given by summing all but the first entry of the first row of

$$(1 - A)^{-1} = 1 + A + A^2 + A^3 + \cdots$$

If  $B$  is any invertible matrix, then Cramer's rule gives

$$(B^{-1})_{ij} = (-1)^{i+j} \det(B; j, i) / \det(B),$$

from which the result follows.  $\square$

By applying Theorem 2.7 to  $T = \{132\}$  and  $T = \{123\}$  we find that the cluster generating functions are respectively  $ux^3$  and  $ux^3/(1 - u(x + x^2))$ , which agree with examples 2.4 and 2.5. More generally, we have the following corollary.

COROLLARY 2.8. For any Hertzsprung pattern  $\tau$ ,

$$\sum_{\pi \in S} u^{\tau(\pi)} x^{|\pi|} = \sum_{m \geq 0} m! \left( x + \frac{(u-1)x^{|\tau|}}{1 - (u-1)\Omega(\tau, \tau)} \right)^m.$$

EXAMPLE 2.9. Hertzsprung's problem generalized to counting permutations with respect to the joint distribution of the Hertzsprung patterns 12 and 21 has the solution

$$\sum_{\pi \in S} u^{12(\pi)} v^{21(\pi)} x^{|\pi|} = \sum_{m \geq 0} m! \left( \frac{x - (u-1)(v-1)x^3}{(1+x-ux)(1+x-vx)} \right)^m.$$

More generally, the joint distribution of  $\text{id}_k$  and  $\overline{\text{id}}_\ell$  is given by

$$\sum_{m \geq 0} m! \left( x + \frac{(u-1)x^k}{1 - (u-1)([k]_x - 1)} + \frac{(v-1)x^\ell}{1 - (v-1)([\ell]_x - 1)} \right)^m,$$

where  $[k]_x = (1 - x^k)/(1 - x) = 1 + x + \dots + x^{k-1}$ . Generalizing Hertzsprung’s problem in another direction we find that the generating function for permutations avoiding all patterns in  $\mathcal{S}_3$  is

$$\begin{aligned} \sum_{m \geq 0} m! \left( \frac{-2x^6 + 3x^5 - 3x^4 - 5x^3 + x^2 + x}{x^4 + x^3 - x^2 - x - 1} \right)^m \\ = 1 + x + 2x^2 + 4x^4 + 34x^5 + 298x^6 + 2434x^7 + 21374x^8 \\ + 205300x^9 + 2161442x^{10} + 24804386x^{11} + \dots \end{aligned}$$

Theorem 2.2 together with Theorem 2.7 solves the problem of determining the distribution of a set of Hertzsprung patterns. Or, at least they solve the problem as long as the patterns are short. The weight function is defined in terms of the sets  $\mathcal{O}(\sigma, \tau)$  and those sets are a priori expensive to compute. We shall now detail why, in fact, the weight function can be efficiently computed.

The polynomials  $\Omega(\sigma, \tau)$  are akin to the correlation polynomials of Guibas and Odlyzko [15]. Consider  $\pi \in \mathcal{O}(\sigma, \tau)$ . Let  $\delta$  be the factor of  $\pi$  in which its prefix corresponding to  $\sigma$  intersects with its suffix corresponding to  $\tau$ . The permutation 978563421 is, for instance, a member of  $\mathcal{O}(53412, 563421)$  and  $\delta = 56$ . Let  $i = |\delta|$ . Note that the smallest element in  $\delta$  is either  $|\sigma| - i + 1$  or  $|\tau| - i + 1$ . Indeed, either  $\sigma$  is a (literal) prefix of  $\pi$  or  $\tau$  is a (literal) suffix of  $\pi$ . In the first case,  $\min \delta = |\sigma| - i + 1$ . In the second case,  $\min \delta = |\tau| - i + 1$ . Thus we arrive at the formula

$$\Omega(\sigma, \tau) = \sum_{i \geq 1} \chi_i(\sigma, \tau) x^{|\tau| - i},$$

where  $\chi_i(\sigma, \tau) \in \{0, 1\}$  is computed as follows. Consider the last  $i$  letters  $a_1 a_2 \dots a_i$  of  $\sigma$  and the first  $i$  letters  $b_1 b_2 \dots b_i$  of  $\tau$ . If the differences  $a_1 - b_1, a_2 - b_2, \dots, a_i - b_i$  are all equal and their common difference is  $|\sigma| - i$  or  $-(|\tau| - i)$ , then  $\chi_i(\sigma, \tau) = 1$ ; otherwise,  $\chi_i(\sigma, \tau) = 0$ . We can organize this computation in a table as in the following example.

|            |        |   |
|------------|--------|---|
| $\sigma$ : | 53412  |   |
| $\tau$ :   | 563421 | 1 |
|            | 563421 | 0 |
|            | 563421 | 1 |
|            | 563421 | 0 |

Writing  $\chi_j$  for  $\chi_j(\sigma, \tau)$  we have  $(\chi_1, \chi_2, \chi_3, \chi_4) = (0, 1, 0, 1)$  and  $\Omega(\sigma, \tau) = x^2 + x^4$ .

EXAMPLE 2.10. Penney’s game [29, 15] is a well-known coin tossing game played by two players. Player I picks a sequence of heads and tails, say  $\alpha \in \{H, T\}^k$ . Player I shows  $\alpha$  to Player II, who subsequently picks a word  $\beta \in \{H, T\}^k$ . A fair coin is tossed until either  $\alpha$  or  $\beta$  appears as a consecutive subsequence of outcomes. The player whose sequence appears first wins. Thus a winning sequence of outcomes for Player I is a word  $\omega \in \{H, T\}^n$  such that  $\alpha$  is a suffix of  $\omega$  and  $\omega$  otherwise avoids both  $\alpha$  and  $\beta$ . There is a simple formula [15, Formula (1.5)], due to Conway [13], expressing the odds that Player II will win in terms of correlation polynomials. Further, this game has the curious property of being nontransitive: Assuming  $k \geq 3$ , no matter what  $\alpha$  Player I picks, Player II can pick  $\beta$  so that his probability of winning exceeds  $1/2$ . Consider the following related question for permutations. Let  $T$  be an antichain of Hertzsprung patterns and fix a pattern  $\alpha \in T$ . How many permutations in  $\mathcal{S}_n$  avoid  $T$  except for a single occurrence of  $\alpha$  at the end of the permutation? Let us call this number  $f^\alpha(n)$ . Let  $F^\alpha(\mathbf{u}; x)$  be the generating function for marked permutations that

end in an unmarked occurrence of  $\alpha$ . Then

$$F^\alpha(\mathbf{u}; x) = C^\alpha(\mathbf{u}; x) \sum_{m \geq 1} m! (x + C(\mathbf{u}; x))^{m-1},$$

where  $C(\mathbf{u}; x)$  is the usual cluster generating function and  $C^\alpha(\mathbf{u}; x)$  is the generating function for marked permutations  $(\pi, M)$  such that the last  $k$  letters  $\gamma = \pi(n - k + 1) \dots \pi(n - 1)\pi(n)$  of  $\pi$  form an unmarked occurrence of  $\alpha$  and  $(\pi, M \cup \{\gamma\})$  is a  $T$ -cluster. By construction,

$$F^\alpha(-\mathbf{1}; x) = \sum_{n \geq 0} f^\alpha(n) x^n.$$

This formula is, however, only useful if we can efficiently compute  $C^\alpha(\mathbf{u}; x)$ . Define the digraph  $D_T^\alpha$  with vertices  $V = \{\epsilon, \hat{\alpha}\} \cup T$ , in which  $\hat{\alpha}$  is a distinct copy of  $\alpha$ , and weight function  $\hat{w} : V \times V \rightarrow \mathbb{Q}[\mathbf{u}, x]$  given by

$$\hat{w}(\sigma, \tau) = \begin{cases} w(\sigma, \tau) & \text{if } \sigma \neq \hat{\alpha} \text{ and } \tau \neq \hat{\alpha}, \\ 0 & \text{if } \sigma = \hat{\alpha}, \\ x^{|\alpha|} & \text{if } \sigma = \epsilon \text{ and } \tau = \hat{\alpha}, \\ \Omega(\sigma, \alpha) & \text{if } \sigma \notin \{\epsilon, \hat{\alpha}\} \text{ and } \tau = \hat{\alpha}. \end{cases}$$

Here,  $w$  – in the first clause – is the weight function of the digraph  $D_T$ . Let  $A$  denote the adjacency matrix of  $D_T^\alpha$ . In particular, if  $T = \{\alpha, \beta\}$  then  $V = \{\epsilon, \alpha, \beta, \hat{\alpha}\}$  and the adjacency matrix is

$$A = \begin{bmatrix} 0 & ux^{|\alpha|} & vx^{|\beta|} & x^{|\alpha|} \\ 0 & u\Omega(\alpha, \alpha) & v\Omega(\alpha, \beta) & \Omega(\alpha, \alpha) \\ 0 & u\Omega(\beta, \alpha) & v\Omega(\beta, \beta) & \Omega(\beta, \alpha) \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

Now,  $C^\alpha(\mathbf{u}; x)$  is the generating function for walks in  $D_T^\alpha$  that start at  $\epsilon$  and end in  $\hat{\alpha}$ . By the transfer-matrix method and Cramer's rule,

$$C^\alpha(\mathbf{u}; x) = (-1)^{|T|+1} \det(1 - A : |T| + 2, 1) / \det(1 - A).$$

### 3. PATTERN-REWRITING SYSTEMS

The Robinson–Schensted–Knuth (RSK) algorithm associates a permutation  $\pi \in \mathcal{S}_n$  with a pair  $(P(\pi), Q(\pi))$  of standard Young tableaux having the same shape. For  $\pi, \sigma \in \mathcal{S}_n$ , let us write  $\pi \equiv \sigma$  if  $P(\pi) = P(\sigma)$ . In particular,

$$132 \equiv 312 \quad \text{and} \quad 213 \equiv 231.$$

Knuth [22] showed that, when appropriately extended, these two elementary transformations suffice to determine whether  $\pi \equiv \sigma$ . Indeed,  $\pi \equiv \sigma$  if and only if one can be obtained from the other through a sequence of transformations of the form

$$\dots acb \dots \equiv \dots cab \dots \quad \text{and} \quad \dots bac \dots \equiv \dots bca \dots$$

where  $a < b < c$ . For instance,  $423516 \equiv 243516$ ,  $243516 \equiv 243156$  and, by transitivity,  $423516 \equiv 243156$ . A relation that is similar to Knuth's called the *forgotten equivalence* has also been studied [28].

Linton, Propp, Roby and West [25] initiated the systematic study of equivalence relations induced by pattern replacement. They considered three types of patterns:

- (i) unrestricted (classical) patterns;
- (ii) consecutive patterns (adjacent positions); and
- (iii) patterns in which both positions and values are required to be adjacent.

Knuth's equivalence as well as the forgotten equivalence belong to the second type. Patterns of the third type are Hertzsprung patterns. A number of authors have continued the work of Linton et al. For instance, Pierrot, Rossin and West [30] and Kuszmaul [23] have studied equivalences of type (ii). Kuszmaul and Zhou [24] concentrated on equivalences of type (iii). It is case (iii) that we shall also focus on.

We will approach the equivalence problem by considering the identities as unidirectional rewrite rules. We do not assume familiarity with the literature on rewriting systems and will give a brief introduction to the topic. Excellent sources for further reading are the books *Term rewriting and all that* by Baader and Nipkow [3] and *String-rewriting systems* by Book and Otto [6].

An *abstract rewriting system* is simply a set together with a binary relation. We are interested in a special kind of rewriting systems that we call pattern-rewriting systems. To stress their similarity with the well known string-rewriting systems we first introduce those systems.

Let  $\Sigma$  be a finite alphabet and let  $\Sigma^*$  denote the set of (finite) strings with letters from  $\Sigma$ . A *string-rewriting system* – also known as a Semi-Thue system –  $R$  on  $\Sigma$  is a subset of  $\Sigma^* \times \Sigma^*$ . Each pair  $(u, v)$  of  $R$  is a *rewrite rule* and is often written  $u \rightarrow v$ . The *rewrite relation*  $\rightarrow_R$  on  $\Sigma^*$  induced by  $R$  is defined as follows. For any  $w, w' \in \Sigma^*$  we have  $w \rightarrow_R w'$  if and only if there is  $x \rightarrow y$  in  $R$  such that  $w = uxv$  and  $w' = uyv$  for some  $u, v \in \Sigma^*$ .

A *pattern-rewriting system* is a subset  $R \subseteq \cup_n (\mathcal{S}_n \times \mathcal{S}_n)$ . The *rewrite relation* on  $\mathcal{S}$  induced by  $R$  is defined as follows. For any  $\pi, \pi' \in \mathcal{S}$ , we have  $\pi \rightarrow_R \pi'$  if and only if there is  $\alpha \rightarrow \beta$  in  $R$  such that we can write  $\pi = \sigma \hat{\alpha} \tau$  and  $\pi' = \sigma \hat{\beta} \tau$ , where  $\hat{\alpha} \simeq \alpha$  and  $\hat{\beta} \simeq \beta$ . As an example, if  $R = \{123 \rightarrow 132\}$ , then  $1234 \rightarrow_R 1324$  and  $1234 \rightarrow_R 1243$ . The domain of  $R$  is denoted by  $\text{dom}(R) = \{\alpha : (\alpha, \beta) \in R\}$ . The reflexive transitive closure of  $\rightarrow_R$  is denoted by  $\rightarrow_R^*$ . The equivalence closure (i.e. the reflexive symmetric transitive closure) of  $\rightarrow_R$  is denoted by  $\equiv_R$ . We omit the subscript  $R$  from  $\rightarrow_R$ ,  $\rightarrow_R^*$  and  $\equiv_R$  when the context prevents ambiguity from being introduced. We use  $\leftarrow$  to denote the inverse of  $\rightarrow$  (the relation  $\{(\beta, \alpha) : \alpha \rightarrow \beta\}$ ). Similarly,  $\leftarrow^*$  denotes the inverse of  $\rightarrow^*$ .

We shall now introduce some definitions and basic results that apply to abstract rewriting system in general and pattern-rewriting systems in particular. An element  $x$  is said to be *in normal form* if there is no  $y$  such that  $x \rightarrow y$ . We say that  $y$  is a *normal form* of  $x$  if  $x \rightarrow^* y$  and  $y$  is in normal form. The relation  $\rightarrow$  is said to be *terminating* if there are no infinite chains  $x_0 \rightarrow x_1 \rightarrow x_2 \rightarrow \dots$ . If  $\rightarrow$  is terminating then every element has a normal form. A relation  $\rightarrow$  is *confluent* if, for all  $x$ ,

$$y_1 \leftarrow^* x \rightarrow^* y_2 \implies \exists z. y_1 \rightarrow^* z \leftarrow^* y_2.$$

The relation  $\rightarrow_R$  with  $R = \{123 \rightarrow 132\}$  from the previous example is not confluent. Indeed,  $1324 \leftarrow 1234 \rightarrow 1243$  in which both 1324 and 1243 are in normal form. The relation induced by  $\{132 \rightarrow 123\}$  is, however, confluent (see Example 3.6 below).

It can be shown that being confluent is equivalent to satisfying

$$x \equiv y \iff \exists z. x \rightarrow^* z \leftarrow^* y.$$

This is known as the *Church–Rosser* property and it provides a test for equivalence. If we assume that  $\rightarrow$  is confluent (or, equivalently, satisfies the Church–Rosser property) and that  $\rightarrow$  is terminating, then every element  $x$  has a unique normal form which we will write  $x \downarrow$ . Under these assumptions we arrive at a practical test for equivalence.

LEMMA 3.1 ([3]). *If  $\rightarrow$  is terminating and confluent, then  $x \equiv y \iff x \downarrow = y \downarrow$ .*

COROLLARY 3.2. *If  $R$  is a terminating and confluent pattern-rewriting system, then the set of  $\text{dom}(R)$ -avoiding permutations in  $\mathcal{S}_n$  is a complete set of representatives for  $\mathcal{S}_n/\equiv$ , the set of equivalence classes of  $\equiv$ .*

For a particular relation, our job is thus reduced to proving that it terminates and that it is confluent. Let us start by discussing strategies for proving confluence. A relation  $\rightarrow$  is *locally confluent* if

$$y_1 \leftarrow x \rightarrow y_2 \implies \exists z. y_1 \xrightarrow{*} z \xleftarrow{*} y_2.$$

Newman's lemma [3, 27] establishes that any locally confluent and terminating relation is confluent. This is an improvement, but to test a pattern-rewriting system for local confluence we must a priori still consider all permutations  $\pi \in \mathcal{S}$  and all pairs  $\pi \rightarrow \sigma$  and  $\pi \rightarrow \tau$ . Note, however, that if  $\alpha_1 \rightarrow \beta_1$  and  $\alpha_2 \rightarrow \beta_2$  are rules in  $R$  and  $\pi = \pi_1 \hat{\alpha}_1 \pi_2 \hat{\alpha}_2 \pi_3$  where  $\hat{\alpha}_1 \simeq \alpha_1$  and  $\hat{\alpha}_2 \simeq \alpha_2$ , then

$$\begin{array}{ccc} & \pi_1 \hat{\alpha}_1 \pi_2 \hat{\alpha}_2 \pi_3 & \\ \swarrow & & \searrow \\ \pi_1 \hat{\beta}_1 \pi_2 \hat{\alpha}_2 \pi_3 & & \pi_1 \hat{\alpha}_1 \pi_2 \hat{\beta}_2 \pi_3 \\ \searrow & & \swarrow \\ & \pi_1 \hat{\beta}_1 \pi_2 \hat{\beta}_2 \pi_3 & \end{array}$$

in which  $\hat{\beta}_1 \simeq \beta_1$  and  $\hat{\beta}_2 \simeq \beta_2$ . Thus, to prove local confluence, we can restrict attention to permutations of the form  $\pi = \pi_1 \gamma \pi_2$  and pairs of rules  $(\alpha_1 \rightarrow \beta_1, \alpha_2 \rightarrow \beta_2)$  in  $R \times R$  such that  $\alpha_1$  is a proper Hertzprung prefix of  $\gamma$ ,  $\alpha_2$  is a proper Hertzprung suffix of  $\gamma$  and  $|\gamma| < |\alpha_1| + |\alpha_2|$ . The situation is summarized in the following lemma.

LEMMA 3.3. *Let  $R$  be a terminating pattern-rewriting system. Let*

$$\mathcal{O}(R) = \bigcup_{(\alpha_1, \alpha_2)} \mathcal{O}(\alpha_1, \alpha_2),$$

*where the union is over all pairs  $(\alpha_1, \alpha_2) \in \text{dom}(R) \times \text{dom}(R)$ . If, for all  $\pi \in \mathcal{O}(R)$ ,*

$$\rho_1 \leftarrow \pi \rightarrow \rho_2 \implies \exists \sigma. \rho_1 \xrightarrow{*} \sigma \xleftarrow{*} \rho_2,$$

*then  $\rightarrow$  is confluent.*

As a corollary to Lemma 3.3, confluence of a finite and terminating pattern-rewriting system is decidable.

A relation  $\rightarrow$  is called *globally finite* if for each element  $x$  there are finitely many elements  $y$  such that  $x \xrightarrow{+} y$ , where  $\xrightarrow{+}$  denotes the transitive closure of  $\rightarrow$ . A relation  $\rightarrow$  is called *acyclic* if there is no element  $x$  such that  $x \xrightarrow{+} x$ . It is well known that any acyclic and globally finite relation is terminating. Let  $R$  be a pattern-rewriting system. Since each rule in  $R$  preserves the length of a permutation, it is clear that  $\rightarrow_R$  is globally finite. Thus to prove that  $\rightarrow_R$  terminates it suffices to prove that that it is acyclic. Let us call  $f : \mathcal{S} \rightarrow \mathbb{N}$  an *increasing statistic* with respect to  $R$  if  $\pi \rightarrow_R \sigma$  implies  $f(\pi) < f(\sigma)$ . Clearly, if there exists such a function  $f$  then  $\rightarrow_R$  is acyclic.

LEMMA 3.4. *Let  $R$  be a pattern-rewriting system. If there exists an increasing statistic with respect to  $R$ , then  $\rightarrow_R$  is terminating.*

Having established the general framework we will now turn to applications. A summary of the cases we shall consider can be found in Table 1; EQ2 through EQ6 were introduced by Linton et al. [25] and in the case of Hertzprung patterns they left the enumeration of equivalence classes as open problems. Kuszmaul and Zhou [24]

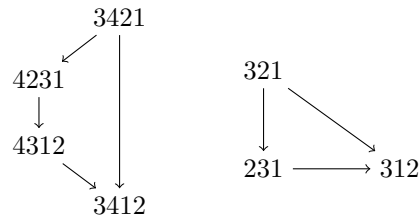
have characterized the equivalence classes induced by the three separate relations  $123 \equiv 132$ ,  $123 \equiv 321$  and  $123 \equiv 132 \equiv 321$ . These are referred to as EQ2, EQ3 and EQ4 in Table 1. Kuszmaul and Zhou provided explicit formulas for the number of equivalence classes modulo EQ2 and EQ3 and noted that the formula is the same in both cases. Indeed, it is formula (5), which is a special case of Myers’s formula (2). For each of EQ1 through EQ7 we compute generating functions for the number of equivalence classes in  $\mathcal{S}_n$ . In particular we solve the two remaining open problems, EQ5 and EQ6, posed by Linton et al. The generating function for EQ7 is also new. Our approach is quite general and could be applied to other pattern-replacement equivalences of the Hertzsprung type. The reason for choosing EQ1–EQ6 is that those equivalences have a history, and that we need to limit the scope of our investigation. We choose EQ7 for two reasons. It is a natural generalization of Stanley’s equivalence (EQ1) and it illustrates that large systems are within reach of our methods.

|     | Equivalences                                                                     | Rules                                                                                                                                                                                                                                           | OEIS    | Reference            |
|-----|----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------|----------------------|
| EQ1 | $12 \equiv 21$                                                                   | $21 \rightarrow 12$<br>$231 \rightarrow 312$                                                                                                                                                                                                    | A013999 | Stanley [33]         |
| EQ2 | $123 \equiv 132$                                                                 | $132 \rightarrow 123$                                                                                                                                                                                                                           | A212580 | Kuszmaul & Zhou [24] |
| EQ3 | $123 \equiv 321$                                                                 | $321 \rightarrow 123$<br>$2341 \rightarrow 4123$                                                                                                                                                                                                | A212580 | Kuszmaul & Zhou [24] |
| EQ4 | $123 \equiv 132$<br>$\equiv 213$                                                 | $132 \rightarrow 123$<br>$213 \rightarrow 123$                                                                                                                                                                                                  | A212581 | Kuszmaul & Zhou [24] |
| EQ5 | $123 \equiv 132$<br>$\equiv 321$                                                 | $132 \rightarrow 123$<br>$321 \rightarrow 123$<br>$2341 \rightarrow 4123$                                                                                                                                                                       | A212432 | Example 3.9          |
| EQ6 | $123 \equiv 132$<br>$\equiv 213$<br>$\equiv 321$                                 | $132 \rightarrow 123$<br>$213 \rightarrow 123$<br>$321 \rightarrow 123$<br>$2341 \rightarrow 4123$                                                                                                                                              | A212433 | Example 3.10         |
| EQ7 | $123 \equiv 132$<br>$\equiv 213$<br>$\equiv 231$<br>$\equiv 312$<br>$\equiv 321$ | $132 \rightarrow 123$<br>$213 \rightarrow 123$<br>$231 \rightarrow 123$<br>$312 \rightarrow 123$<br>$321 \rightarrow 123$<br>$2341 \rightarrow 4123$<br>$34512 \rightarrow 45123$<br>$54123 \rightarrow 45123$<br>$6745123 \rightarrow 7456123$ |         | Example 3.11         |

TABLE 1. Equivalences and corresponding pattern-rewriting systems

For reference, numerical data on the number of equivalence classes modulo each of EQ2 through EQ7 is given in Table 2 of the appendix.

EXAMPLE 3.5 (EQ1). Stanley [33] considered the equivalence relation on  $\mathcal{S}_n$  generated by the interchange of any two adjacent elements  $\pi(i)$  and  $\pi(i+1)$  such that  $|\pi(i) - \pi(i+1)| = 1$ . In our terminology it is the equivalence  $12 \equiv 21$ . As an example, for  $n = 3$  there are two equivalence classes,  $\{123, 132, 213\}$  and  $\{231, 312, 321\}$ . Let us express Stanley's equivalence relation using a rewrite system. Consider  $R = \{21 \rightarrow 12\}$ . Note that  $231 \leftarrow 321 \rightarrow 312$  in which both 231 and 312 are in normal form. Hence this system is not confluent. We can however make it into a confluent system by adding a rule, namely  $231 \rightarrow 312$ . In other words, we redefine  $R$  by setting  $R = \{21 \rightarrow 12, 231 \rightarrow 312\}$ . Since 231 and 312 are equivalent under  $12 \equiv 21$ , the equivalence relation  $\equiv_R$  induced by  $R$  still coincides with that of Stanley. To see that the rewrite rule induced by  $R$  terminates consider the following permutation statistic. Let  $\Sigma_{12}(\pi)$  be the sum of positions of occurrences of the Hertzsprung pattern 12. In other words,  $\Sigma_{12}(\pi)$  is the sum of all  $i \in [n-1]$  such that  $\pi(i+1) = \pi(i) + 1$ . Clearly,  $\Sigma_{12}$  is increasing with respect to  $R$  and hence  $\rightarrow_R$  terminates. To show confluence we will use Lemma 3.3. We have  $\mathcal{O}(21, 21) = \{321\}$ ,  $\mathcal{O}(21, 231) = \mathcal{O}(231, 231) = \emptyset$ ,  $\mathcal{O}(231, 21) = \{3421\}$  and hence  $\mathcal{O}(R) = \{321, 3421\}$ . Confluence thus follows from the two diagrams below.



By Corollary 3.2, each equivalence class under  $12 \equiv 21$  contains exactly one permutation avoiding  $\{21, 231\}$ . Hence the generating function for the number of equivalence classes can be computed using Theorem 2.2 together with Theorem 2.7.

Stanley defines a permutation  $\pi = a_1 a_2 \cdots a_n \in \mathcal{S}_n$  as *salient* if we never have  $a_i = a_{i+1} + 1$  ( $1 \leq i \leq n-1$ ) or  $a_i = a_{i+1} + 2 = a_{i+2} + 1$  ( $1 \leq i \leq n-2$ ). In terms of Hertzsprung patterns,  $\pi$  is salient if and only if it is  $\{21, 312\}$ -avoiding. Stanley shows that each equivalence class under  $12 \equiv 21$  contains exactly one salient permutation. On account of the preceding paragraph, this implies that the two sets  $\{21, 231\}$  and  $\{21, 312\}$  are Wilf-equivalent (their sets of avoiders are equipotent).

Stanley counts the salient permutations by a direct inclusion-exclusion argument. The resulting generating function is

$$\sum_{m \geq 0} m! (x(1-x))^m.$$

We, of course, obtain the same answer. In fact, Theorems 2.2 and 2.7 show that the joint distribution of 21 and 231 is the same as the joint distribution of 21 and 312. In both cases the cluster generating function is  $x^2(vx+u)/(1-ux)$ , where  $u = u_{21}$  and  $v = u_{231}$  or  $v = u_{312}$ .

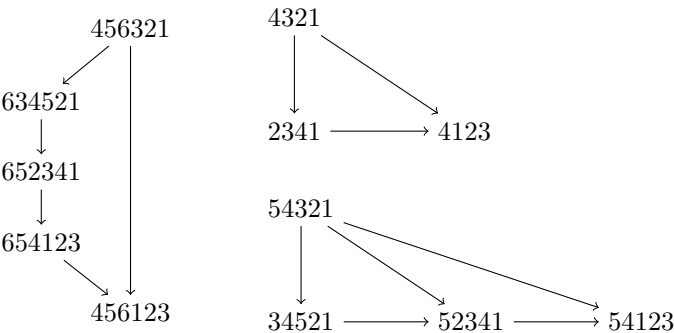
EXAMPLE 3.6 (EQ2). Consider the pattern-rewriting system  $R = \{132 \rightarrow 123\}$ . As usual, let  $\rightarrow$  also denote the rewrite relation induced by  $R$ . The equivalence closure of  $\rightarrow$  is equal to the equivalence relation induced by  $123 \equiv 132$ . Note that  $\rightarrow$  is terminating. Indeed, the number of occurrences of 123 is an increasing statistic ( $\Sigma_{12}$  is also an increasing statistic). Moreover, since  $\mathcal{O}(132, 132)$  is empty,  $\rightarrow$  is trivially

confluent. By Corollary 3.2, the number of equivalence classes is  $|\mathcal{S}_n(132)|$  for which we derived a formula in Example 2.4.

EXAMPLE 3.7 (EQ3). The relation induced by  $123 \equiv 321$  is the equivalence closure of the rewrite relation  $\rightarrow$  induced by  $R = \{321 \rightarrow 123, 2341 \rightarrow 4123\}$ . This relation is terminating since  $\Sigma_{123}$ , the sum of positions of occurrences of 123, is an increasing statistic. We shall show that it is confluent as well. The relation induced by  $\{321 \rightarrow 123\}$  is not confluent, that is why we include the rule  $2341 \rightarrow 4123$ . We have  $\mathcal{O}(321, 2341) = \mathcal{O}(2341, 2341) = \emptyset$ ,

$$\mathcal{O}(321, 321) = \{4321, 54321\} \quad \text{and} \quad \mathcal{O}(2341, 321) = \{456321\}.$$

Confluence thus follows from Lemma 3.3 and the three diagrams below.



Linton et al. [25] noted that the number of equivalence classes under  $123 \equiv 132$  and  $123 \equiv 321$  appears to be the same. This was later proved by Kuszmaul and Zhou [24]. The  $\{321, 2341\}$ -cluster generating function is

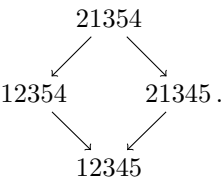
$$\frac{u_{321}u_{2341}x^5 - u_{2341}x^4 - u_{321}x^3}{u_{321}x^2 + u_{321}x - 1}.$$

Recall that the generating function for 132-clusters is  $u_{132}x^3$ . While these generating functions are quite different, on specializing  $u_{2341}$ ,  $u_{321}$  and  $u_{132}$  to  $-1$  we get  $-x^3$  in both instances, resulting in an alternative proof of the observation made by Linton et al. In particular, the two sets of patterns  $\{132\}$  and  $\{321, 2341\}$  are Wilf-equivalent. Finding a combinatorial proof of this fact remains an open problem.

EXAMPLE 3.8 (EQ4). Let  $R = \{132 \rightarrow 123, 213 \rightarrow 123\}$ . Its equivalence closure coincides with the equivalence relation induced by  $123 \equiv 132 \equiv 213$ . That  $\rightarrow$  terminates follows from  $\Sigma_{123}$  being an increasing statistic. Note that

$$\mathcal{O}(R) = \mathcal{O}(132, 213) \cup \mathcal{O}(213, 132) = \{1324, 21354\}.$$

Using either  $132 \rightarrow 123$  or  $213 \rightarrow 123$  we have  $1324 \rightarrow 1234$  in which 1234 is in normal form. The diagram for 21354 is rather simple too:



Thus, by Corollary 3.2, the number of equivalence classes under  $123 \equiv 132 \equiv 213$  is the same as the number of permutations of  $[n]$  that avoid 132 and 213, and the corresponding generating function is

$$\sum_{n \geq 0} |\mathcal{S}_n(132, 213)| x^n = \sum_{m \geq 0} m! \left( \frac{(1+x)^2(1-x)x}{x^2+x+1} \right)^m.$$

The coefficient of  $x^n$  is given by Kuzmaul and Zhou's formula [24, Theorem 2.32]

$$\sum_{i=0}^{\lfloor n/3 \rfloor} (-2)^i \binom{n-2i}{i} (n-2i)!$$

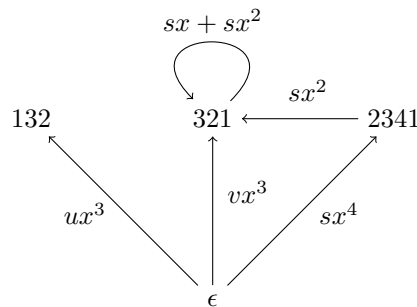
EXAMPLE 3.9 (EQ5). Consider the pattern-rewriting system

$$R = \{132 \rightarrow 123, 321 \rightarrow 123, 2341 \rightarrow 4123\}.$$

The equivalence closure of  $\rightarrow$  is induced by  $123 \equiv 132 \equiv 321$ . There is no overlap of the pattern 132 with 123 or 2341. Hence

$$\mathcal{O}(R) = \mathcal{O}(321, 321) \cup \mathcal{O}(2341, 321) = \{4321, 54321, 456321\}$$

and the proofs of confluence and termination are the same as in Example 3.7 (EQ3). Thus the number of equivalence classes under  $\equiv$  equals the number of permutations avoiding the patterns in  $\text{dom}(R) = \{132, 321, 2341\}$ . To count such permutations we construct the corresponding digraph. Letting  $u = u_{132}$ ,  $v = u_{321}$  and  $s = u_{2341}$  it is depicted below.



The cluster generating function is

$$C(u, v, s; x) = \frac{(uv + vs)x^5 + (uv - s)x^4 - (u + v)x^3}{vx^2 + vx - 1}$$

and on applying Theorem 2.2 we find that

$$\sum_{n \geq 0} |\mathcal{S}_n(132, 321, 2341)| x^n = \sum_{m \geq 0} m! (x(1 - 2x^2))^m.$$

EXAMPLE 3.10 (EQ6). Consider the pattern-rewriting system

$$R = \{132 \rightarrow 123, 213 \rightarrow 123, 321 \rightarrow 123, 2341 \rightarrow 4123\}.$$

Its equivalence closure coincides with the equivalence relation induced by  $123 \equiv 132 \equiv 213 \equiv 321$ . That  $\rightarrow$  terminates follows from  $\Sigma_{123}$  being an increasing statistic with respect to  $R$ . Note that  $\mathcal{O}(R) = \{1324, 4321, 21354, 54321, 456321\}$ . In Example 3.7 (EQ3) we have seen diagrams for 4321, 54321 and 456321. This leaves 1324 and 21354, but we have seen diagrams for those permutations in Example 3.8 (EQ4). As before, we use Theorem 2.7 to compute the cluster generating function. In the

end we find that the generating function for the number of equivalence classes under  $123 \equiv 132 \equiv 213 \equiv 321$  is

$$\sum_{n \geq 0} |\mathcal{S}_n(132, 213, 321, 2341)| x^n = \sum_{m \geq 0} m! \left( \frac{-x^5 - 2x^4 - 2x^3 + x^2 + x}{x^2 + x + 1} \right)^m.$$

EXAMPLE 3.11 (EQ7). As detailed in Example 3.5 (EQ1), Stanley characterized and counted the equivalence classes induced by  $12 \equiv 21$ . In other words, the equivalences induced by considering all permutations in  $\mathcal{S}_2$  as equivalent. We shall consider the corresponding problem for  $\mathcal{S}_3$ . That is, the equivalence induced by

$$123 \equiv 132 \equiv 213 \equiv 231 \equiv 312 \equiv 321.$$

Let  $R$  consist of the rules  $\alpha \rightarrow 123$ , for  $\alpha \in \mathcal{S}_3 \setminus \{123\}$ , together with the following four rules that are needed to make the relation confluent:

$$2341 \rightarrow 4123, \quad 34512 \rightarrow 45123, \quad 54123 \rightarrow 45123, \quad 6745123 \rightarrow 7456123.$$

One can check that  $\Sigma_{12}$  is an increasing statistic and hence  $\rightarrow$  terminates. Confluence follows from verifying local confluence for each permutation in  $\mathcal{O}(R)$ , which is the union of the sets

$$\begin{aligned} \mathcal{O}(123, 213) &= \{1324\}, \quad \mathcal{O}(213, 132) = \{21354\}, \quad \mathcal{O}(231, 312) = \{45312\}, \\ \mathcal{O}(231, 321) &= \{45321\}, \quad \mathcal{O}(231, 54123) = \{6754123\}, \quad \mathcal{O}(312, 231) = \{4231\}, \\ \mathcal{O}(312, 6745123) &= \{86745123\}, \quad \mathcal{O}(321, 312) = \{54312\}, \\ \mathcal{O}(321, 321) &= \{4321, 54321\}, \quad \mathcal{O}(321, 54123) = \{654123, 7654123\} \\ \mathcal{O}(2341, 312) &= \{456312\}, \quad \mathcal{O}(2341, 321) = \{456321\}, \\ \mathcal{O}(2341, 54123) &= \{67854123\}, \quad \mathcal{O}(34512, 231) = \{456231\}, \\ \mathcal{O}(34512, 6745123) &= \{89106745123\}, \quad \mathcal{O}(54123, 2341) = \{652341\}, \\ \mathcal{O}(54123, 34512) &= \{7634512\}, \quad \mathcal{O}(6745123, 2341) = \{78562341\}, \\ \mathcal{O}(6745123, 34512) &= \{896734512\}. \end{aligned}$$

We omit the details. Thus, the two cardinalities  $|\mathcal{S}_n/\equiv|$  and  $|\mathcal{S}_n(\text{dom}(R))|$  are equal. The adjacency matrix of  $D_T$  (with  $T = \text{dom}(R)$ ) is

$$\begin{bmatrix} 0 & u_0x^3 & u_1x^3 & u_2x^3 & u_3x^3 & u_4x^3 & u_5x^4 & u_6x^5 & u_7x^5 & u_8x^7 \\ 0 & 0 & u_1x & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & u_0x^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & u_3x^2 & u_4x^2 & 0 & 0 & u_7x^4 & 0 \\ 0 & 0 & 0 & u_2x & 0 & 0 & 0 & 0 & 0 & u_8x^5 \\ 0 & 0 & 0 & 0 & u_3x^2 & u_4x^2 + u_4x & 0 & 0 & u_7x^4 + u_7x^3 & 0 \\ 0 & 0 & 0 & 0 & u_3x^2 & u_4x^2 & 0 & 0 & u_7x^4 & 0 \\ 0 & 0 & 0 & u_2x & 0 & 0 & 0 & 0 & 0 & u_8x^5 \\ 0 & 0 & 0 & 0 & 0 & 0 & u_5x & u_6x^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & u_5x & u_6x^2 & 0 & 0 \end{bmatrix}$$

and the corresponding generating function is

$$\sum_{m \geq 0} m! \left( \frac{-x^5 - 3x^4 - 4x^3 + x^2 + x}{x^2 + x + 1} \right)^m.$$

QUESTIONS, CONJECTURES AND REMARKS

Consider two Hertzsprung patterns  $\sigma, \tau \in \mathcal{S}_k$  as equivalent if  $|\mathcal{S}_n(\sigma)| = |\mathcal{S}_n(\tau)|$  for all  $n \geq 0$ . How many equivalence classes are there? In other words, what is the number of Wilf-classes? By Corollary 2.8 it is the same as the number of distinct “autocorrelation polynomials”  $\Omega(\sigma, \sigma)$  with  $\sigma \in \mathcal{S}_k$ . For  $k = 1, 2, \dots, 7$  we find

$$\begin{aligned} &\{0\} \\ &\{x\} \\ &\{0, x^2 + x\} \\ &\{0, x^2, x^3, x^3 + x^2 + x\} \\ &\{0, x^3, x^4, x^4 + x^3 + x^2 + x\} \\ &\{0, x^3, x^4, x^4 + x^2, x^5, x^5 + x^4, x^5 + x^4 + x^3 + x^2 + x\} \\ &\{0, x^4, x^5, x^6, x^6 + x^3, x^6 + x^5, x^6 + x^5 + x^4 + x^3 + x^2 + x\} \end{aligned}$$

and the sequence for the number of Wilf-classes starts

$$1, 1, 2, 4, 4, 7, 7, 11, 12, 18, 17, 25, 27, 38, 38 \quad (k = 1, 2, \dots, 15).$$

For  $k \geq 3$  these numbers coincide with those of sequence A304178 in the OEIS, which leads us to the conjecture below. For a palindrome  $w = c_1 \dots c_n \in \{0, 1\}^n$  let  $P(w) = \{i \in [n] : c_1 \dots c_i \text{ is a palindrome}\}$  be the set of palindrome prefix lengths of  $w$ ; e.g.  $P(0100010) = \{1, 3, 7\}$ .

CONJECTURE 3.12. Let  $a_k = |\{\Omega(\sigma, \sigma) : \sigma \in \mathcal{S}_k\}|$  be the number of Wilf-classes of Hertzsprung patterns of length  $k$ . Let  $b_k$  be the number of distinct sets  $P(w)$  for palindromes  $w \in \{0, 1\}^k$ . Then  $a_k = b_{k+1}$  for  $k \geq 3$ .

Recall that Bóna [5] showed that  $|\mathcal{S}_n(\tau)| \leq |\mathcal{S}_n(\text{id}_k)|$  for each non-self-overlapping pattern  $\tau \in \mathcal{S}_k$ . Data collected using Corollary 2.8 suggest that the inequality holds regardless of whether  $\tau$  is self-overlapping or not.

CONJECTURE 3.13. We have  $|\mathcal{S}_n(\tau)| \leq |\mathcal{S}_n(\text{id}_k)|$  for all Hertzsprung patterns  $\tau \in \mathcal{S}_k$  and all natural numbers  $n$ .

In view of Theorem 2.2 it is natural to ask if there are nontrivial mesh-patterns  $p$  other than the Hertzsprung patterns for which there is a rational function  $R(x)$  such that  $\sum_{n \geq 0} |\mathcal{S}(p)|x^n = \sum_{m \geq 0} m!R(x)^m$ ? It appears that the answer is yes.

CONJECTURE 3.14. We have

$$\sum_{n \geq 0} |\mathcal{S}_n(p)|x^n = \sum_{m \geq 0} m! \left( \frac{x}{1+x^2} \right)^m, \quad \text{where } p = \begin{array}{|c|c|c|} \hline \text{shaded} & \bullet & \text{shaded} \\ \hline \text{shaded} & & \text{shaded} \\ \hline \text{shaded} & \bullet & \text{shaded} \\ \hline \end{array}.$$

This conjecture is based on computing the numbers  $|\mathcal{S}_n(p)|$  for  $n \leq 14$ . They are 1, 1, 2, 5, 20, 103, 630, 4475, 36232, 329341, 3320890, 36787889, 444125628, 5803850515, and 81625106990. At the time of writing this sequence is not in the OEIS [17]. If the conjecture is true then there is, however, a close connection with a sequence in the OEIS, namely A177249. It is defined by letting  $a_n$  be number of permutations of  $[n]$  whose disjoint cycle decompositions have no adjacent transpositions, that is, no cycles of the form  $(i, i+1)$ . Let  $F(x) = \sum_{n \geq 0} |\mathcal{S}_n(p)|x^n$  be the sought series and let  $A(x) = \sum_{n \geq 0} a_n x^n$ . Brualdi and Deutsch [8] have shown that  $(1+x^2)A(x) = F(x)$ . Our conjecture is thus equivalent to  $|\mathcal{S}_n(p)| = a_n + a_{n-2}$  for  $n \geq 2$ . Alternatively, one may note that the compositional inverse of  $x/(1+x^2)$  is  $xC(x^2)$ , where  $C(x)$  is the

generating function for the Catalan numbers. Thus, our conjecture is also equivalent to  $[x^n]F(xC(x^2)) = n!$ , which could lead to a novel decomposition of permutations.

As defined, pattern-rewriting systems are limited to transforming Hertzsprung patterns. This is an artificial limitation though. Let  $\mathcal{M}_k = \mathcal{P}([0, k] \times [0, k])$  be the set of  $(k + 1) \times (k + 1)$  meshes. Define a *pattern-rewriting system* as a set of rules  $R \subseteq \bigcup_{k \geq 0} (\mathcal{S}_k \times \mathcal{M}_k \times \mathcal{S}_k)$ . Each rule  $(\alpha, M, \beta)$  is extended to  $\mathcal{S} = \bigcup_n \mathcal{S}_n$  by allowing that any occurrence of the mesh pattern  $(\alpha, M)$  is rewritten as an occurrence of  $\beta$ . In particular, this encompasses the three types of equivalences studied by Linton et al.,  $M = \emptyset$ ,  $M = [1, k - 1] \times [0, k]$  and  $M = H_k$ .

Using Lemma 3.3 we are able to automate the proof of confluence for any finite and terminating pattern-rewriting system. Our current strategy to prove that a pattern-rewriting system terminates requires us to manually come up with an increasing statistic. This was easy for the small systems that we have considered but may not be easy in general. Can there be a mechanical test? Or is this property undecidable? It is known that termination of string-rewriting systems is undecidable, even assuming that the system is length-preserving [9].

The starting point of this article was Hertzsprung's problem and we have implicitly considered it the simplest nontrivial instance of a larger class of problems. There is arguably a simpler, yet nontrivial, instance though: permutations avoiding the single Hertzsprung pattern 12. The study of the corresponding counting sequence appears to have started with Euler. We have

$$\sum_{\pi \in \mathcal{S}} u^{12(\pi)} x^{|\pi|} = \sum_{m \geq 0} m! \left( \frac{x}{1 - (u - 1)x} \right)^m.$$

One may also note that any permutation  $\pi$  can be uniquely written as an inflation

$$\pi = \sigma[\text{id}_{k_1}, \text{id}_{k_2}, \dots, \text{id}_{k_m}],$$

where  $\sigma$  avoids the Hertzsprung pattern 12. Allowing ourselves to use the terminology of  $L$ -species [4] this amounts to the isomorphism  $S' = F' \cdot E$ , where  $E$ ,  $S$  and  $F$  are the  $L$ -species of sets, permutations and 12-avoiding permutations, respectively. Indeed, suppose  $n \geq 1$  and write  $\pi \in \mathcal{S}_n$  as  $\pi = \sigma[\text{id}_{k_1}, \text{id}_{k_2}, \dots, \text{id}_{k_m}] = \pi_1 \pi_2 \cdots \pi_m$ . Let  $\hat{\sigma}$  be the permutation obtained by taking the first element of each  $\pi_i$  and let the set  $A$  consist of all the remaining elements. Then  $\pi \mapsto (\hat{\sigma}, A)$  is the sought isomorphism. Clearly  $\hat{\sigma} \simeq \sigma$  and  $12(\pi) = |A|$ . For instance,

$$3142[12, 1, 1234, 12] = 451678923 \mapsto (4162, \{3, 5, 7, 8, 9\}).$$

Since  $S(x) = (1 - x)^{-1}$  and  $E(x) = e^x$  it follows from  $S'(x) = F'(x)E(x)$  that  $F'(x) = e^{-x}/(1 - x)^2$ . Replacing the species  $E$  with the  $\mathbb{Z}[u]$ -weighted species  $E_u$  in which each set  $A$  has weight  $u^{|A|}$  and, similarly, replacing the species  $S$  with  $S_w$  where the weight function is  $w(\pi) = u^{12(\pi)}$ , we have  $S'_w = F' \cdot E_u$  and hence

$$\sum_{n \geq 0} \left( \sum_{\pi \in \mathcal{S}_n} u^{12(\pi)} \right) \frac{x^n}{n!} = 1 + \int_0^x \frac{e^{(u-1)t}}{(1-t)^2} dt.$$

Even simple Hertzsprung patterns have interesting properties!

## APPENDIX

Table 2 gives the number of equivalence classes modulo EQ2–EQ7 for  $1 \leq n \leq 20$ .

|    | EQ2 & EQ3 (A212580) | EQ4 (A212581)       | EQ5 (A212432)       |
|----|---------------------|---------------------|---------------------|
| 1  | 1                   | 1                   | 1                   |
| 2  | 2                   | 2                   | 2                   |
| 3  | 5                   | 4                   | 4                   |
| 4  | 20                  | 17                  | 16                  |
| 5  | 102                 | 89                  | 84                  |
| 6  | 626                 | 556                 | 536                 |
| 7  | 4458                | 4011                | 3912                |
| 8  | 36144               | 32843               | 32256               |
| 9  | 328794              | 301210              | 297072              |
| 10 | 3316944             | 3059625             | 3026112             |
| 11 | 36755520            | 34104275            | 33798720            |
| 12 | 443828184           | 413919214           | 410826624           |
| 13 | 5800823880          | 5434093341          | 5399704320          |
| 14 | 81591320880         | 76734218273         | 76317546240         |
| 15 | 1228888215960       | 1159776006262       | 1154312486400       |
| 16 | 19733475278880      | 18681894258591      | 18604815528960      |
| 17 | 336551479543440     | 319512224705645     | 318348065548800     |
| 18 | 6075437671458000    | 5782488507020050    | 5763746405053440    |
| 19 | 115733952138747600  | 110407313135273127  | 110086912964367360  |
| 20 | 2320138519554562560 | 2218005876646727423 | 2212209395234979840 |
|    | EQ6 (A212433)       | EQ7                 |                     |
| 1  | 1                   | 1                   |                     |
| 2  | 2                   | 2                   |                     |
| 3  | 3                   | 1                   |                     |
| 4  | 13                  | 6                   |                     |
| 5  | 71                  | 40                  |                     |
| 6  | 470                 | 330                 |                     |
| 7  | 3497                | 2664                |                     |
| 8  | 29203               | 23258               |                     |
| 9  | 271500              | 222154              |                     |
| 10 | 2786711             | 2326410             |                     |
| 11 | 31322803            | 26568950            |                     |
| 12 | 382794114           | 328995136           |                     |
| 13 | 5054810585          | 4392819522          |                     |
| 14 | 71735226535         | 62935547966         |                     |
| 15 | 1088920362030       | 963253101304        |                     |
| 16 | 17607174571553      | 15688298164890      |                     |
| 17 | 302143065676513     | 270944692450742     |                     |
| 18 | 5484510055766118    | 4946387077324072    |                     |
| 19 | 104999034898520903  | 95184319122508074   |                     |
| 20 | 2114467256458136473 | 1925732716758497918 |                     |

TABLE 2. Enumeration of equivalence classes EQ2–EQ7

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