# Dyck paths with catastrophes modulo the positions of a given pattern

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# Abstract

For any pattern p of length at most 2, we provide generating functions and asymptotic approximations for the number of p-equivalence classes of Dyck paths with catastrophes, where two paths of the same length are p-equivalent whenever the positions of the occurrences of the pattern pare the same.

# 1 Introduction and notation

A Dyck path with catastrophes is a lattice path in the first quadrant of the xy-plane that starts at the origin, ends on the x-axis, and is made of up-steps U = (1, 1), downsteps D = (1, -1), and catastrophe steps  $C_k = (1, -k)$ ,  $k \ge 2$ , so that catastrophe steps always end on the x-axis. Depending on the context, we can use the symbol Cto design a catastrophe step, and by convenience we use  $C_1 = D$ . We let  $\mathcal{E}$  denote the set of all Dyck paths with catastrophes, and  $\mathcal{D}$  be the set of Dyck paths, i.e. the paths in  $\mathcal{E}$  that do not contain any catastrophe steps  $C_k$ ,  $k \ge 2$ . The length |P| of a path P is the number of its steps. The empty path is denoted by  $\epsilon$ . See Figure 1 for an example of a Dyck path with catastrophes of length 14. A pattern consists of consecutive steps in a path. We will say that an occurrence of a pattern (or for short a pattern) is at position  $i \ge 1$  in a path whenever the first step of the pattern appears at the *i*-th step of the path, the second step at the (i + 1)-st step, and so on. The *height* of an occurrence of a pattern is the minimal ordinate reached by its points. For instance, the Dyck path with catastrophes  $P = UUC_2UUUDUDUDUC_2UD$  contains three occurrences of the pattern UU at positions 1, 4 and 5, and the heights of these occurrences are respectively 0, 0 and 1.

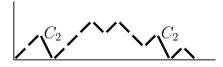


Figure 1: Dyck path with catastrophes  $UUC_2UUUDUDUDUC_2UD$ .

The concept of a Dyck path with catastrophes was first introduced by Krinik et al. in [9] in the context of queuing theory. These paths correspond to the evolution of a queue by allowing some resets modeled by a catastrophe step  $C_k$ ,  $k \ge 2$ . Then, Banderier and Wallner [1] provided enumerative results and limit laws of these objects. They showed how any non empty path  $P \in \mathcal{E}$  can be decomposed either as  $P = U\alpha D\beta$ , or  $P = U\alpha_1 U\alpha_2 \dots U\alpha_k C_k\beta$  for some  $k \ge 2$ , where  $\alpha, \alpha_1, \alpha_2, \dots, \alpha_k$  are Dyck paths in  $\mathcal{D}$  and  $\beta \in \mathcal{E}$ . They deduced a functional equation for the generating function  $E(x) = \sum_{n \ge 0} e_n x^n$  where  $e_n$  is the number of paths of length n in  $\mathcal{E}$ , with the solution

$$E(x) = \frac{2x - 1 + \sqrt{1 - 4x^2}}{x - 1 + (1 + x)\sqrt{1 - 4x^2}}.$$

The sequence  $(e_n)_{n\geq 0}$  corresponds to A224747 in the On-line Encyclopedia of Integer Sequences (OEIS) [12], and the first values for  $n \geq 0$  are 1, 0, 1, 3, 5, 12, 23, 52, 105, 232, 480. More recently, Baril and Kirgizov [4] exhibited a one-to-one correspondence between Dyck paths with catastrophes of length n and Dyck paths of length 2navoiding UUU and DUD at height at least one, and where every occurrence of UDon the x-axis appears before (but not necessarily contiguous with) an occurrence of UUU.

On the other hand, in [2–6, 10] the authors investigated equivalence relations on the sets of Dyck paths, Motzkin paths, skew Dyck paths, Lukasiewicz paths, and Ballot paths where two paths of the same length are equivalent whenever they coincide on all occurrences of a given pattern. The main goal of this study consists in extending these studies for Dyck paths with catastrophes by considering the analogous equivalence relation on  $\mathcal{E}$ .

**Definition 1.1** Two Dyck paths of the same length and with catastrophes are p-equivalent whenever they have the same positions of the occurrences of the pattern p.

For instance, the path  $UUDUUC_3$  is U-equivalent to  $UUC_2UUC_2$  since the occurrences of U appear at the same positions in the two paths.

Then, one may naturally split the set  $\mathcal{E}$  into *p*-equivalence classes, which are constructed so that paths P and Q in  $\mathcal{E}$  belong to the same *p*-equivalence class if, and only if, they are *p*-equivalent.

In this paper, we provide ordinary generating functions (o.g.f. for short) for the number of *p*-equivalence classes in  $\mathcal{E}$  with respect to the length whenever *p* is a pattern of length at most two. Our method consists in providing one-to-one correspondences between equivalence classes and certain subsets of  $\mathcal{E}$  (called subsets of *representative elements*) and enumerating them using algebraic techniques. Remark that only one pattern of size 2, namely DD, gives a non-rational generating function. For this pattern, the construction of a set of representative elements and its enumeration are quite intricate and handled in the last subsection of the paper. We refer to Table 1 for an overview of our results.

Pattern	OEIS [12]	Sequences for $a_n, 2 \leq n \leq 10$ , and formulæ	Theorem	O.g.f.
U	Shift of A037952	$ \begin{array}{c} 1, 1, 3, 4, 10, 15, 35, 56, 126, \dots \\ \binom{n-1}{\lfloor \frac{n-2}{2} \rfloor} \end{array} $	Thm 2.2	Algebraic
D	New	$ \begin{array}{c} 1, 1, 3, 5, 11, 21, 42, 84, 162, \dots \\ \left\{ \begin{pmatrix} n \\ \frac{n-3}{2} \end{pmatrix} & \text{if } n \text{ is odd,} \\ \left( \frac{n}{\frac{n-4}{2}} \right) + \left( \frac{n}{2} \right) / \left( \frac{n}{2} + 1 \right) & \text{otherwise} \\ \end{array} \right. \\ 1, 1, 2, 3, 5, 8, 13, 21, 34, \dots $	Thm 2.4	
С	A212804	1, 1, 2, 3, 5, 8, 13, 21, 34, $\begin{cases} c_n = c_{n-1} + c_{n-2}, \\ c_0 = 1, c_1 = 0 \\ 1, 1, 3, 4, 8, 13, 24, 41, 75, \dots \end{cases}$	Thm 2.6	
UU	A347493	$\begin{cases} f_n = f_{n-1} + f_{n-2} + f_{n-4}, \\ f_0 = 1, f_1 = 0, f_2 = 1, f_3 = 1 \end{cases}$	Thm 3.2	
UD	A215004	1, 1, 3, 5, 10, 17, 30, 50, 84, $\begin{cases} g_n = 2g_{n-1} + g_{n-2} - 3g_{n-3} + g_{n-5}, \\ g_1 = 0, g_0 = g_2 = g_3 = 1, g_4 = 3 \end{cases}$	Thm 3.4	
UC	New	$\begin{cases} 1, 1, 2, 4, 5, 9, 15, 24, 40, \dots \\ i_n = 2i_{n-1} - i_{n-2} + i_{n-3} - i_{n-4} + i_{n-5} - i_{n-6} + i_{n-7}, \\ i_0 = 1, i_1 = 0, i_2 = 1, i_3 = 1, i_4 = 2, i_5 = 4, i_6 = 5 \end{cases}$	Thm 3.6	Rational
DC	New	$ \begin{array}{c} 1,1,1,2,2,4,6,9,14,\ldots \\ \\ j_n=2j_{n-1}-j_{n-2}+j_{n-5}-j_{n-6}+j_{n-7},\\ \\ j_0=1,j_1=0,j_2=j_3=j_4=1,j_5=2,j_6=2\\ \hline 1,1,1,2,3,5,8,13,21,\ldots \end{array} $	Thm 3.8	
CU	Shift of A000045	$ \begin{array}{c} 1,\ 1,\ 1,\ 2,\ 3,\ 5,\ 8,\ 13,\ 21,\ \dots \\ \\ \left\{ \begin{array}{c} k_n = k_{n-1} + k_{n-2}, \\ k_0 = 1, k_1 = 0, k_2 = k_3 = k_4 = 1 \\ \hline 1,\ 1,\ 2,\ 3,\ 5,\ 8,\ 13,\ 21,\ 34,\ \dots \end{array} \right. \end{array} $	Thm 3.10	
DU	A212804	$\begin{cases} \ell_n = \ell_{n-1} + \ell_{n-2}, \\ \ell_0 = 1, \ell_1 = 0, \ell_2 = 1 \end{cases}$	Thm 3.12	
DD	New	1, 1, 2, 1, 4, 5, 11, 11, 27, General formula remains to be found	Thm 3.15	Algebraic

Table 1: Summary of results; generating functions are given in the corresponding theorems.

# 2 Patterns of length one

Our goal in this section is to provide generating functions that count p-equivalence classes with respect to the path length, whenever the pattern p is U, D, or C. For

each pattern, the method consists in constructing a set of representative elements of p-equivalence classes and enumerating them with respect to the length by giving a generating function. From this, we deduce a closed-form expression (that depends on the length) or a recurrence relation for the number of corresponding p-equivalence classes.

# 2.1 Pattern U

Let us define the set  $\mathcal{A}$  consisting of the union of the set  $\mathcal{D}$  of Dyck paths with the set  $\mathcal{D}'$  of paths in  $\mathcal{E}$  having only one catastrophe  $C_k, k \ge 2$ , located at the end of the path. We will prove that there is a one-to-one correspondence between  $\mathcal{A}$  and the *U*-equivalence classes of  $\mathcal{E}$ , and we enumerate them by providing a generating function that counts  $\mathcal{A}$  with respect to the length.

**Theorem 2.1** There is a bijection between  $\mathcal{A}$  and the set of U-equivalence classes of  $\mathcal{E}$ .

*Proof.* First, we prove that for every  $P \in \mathcal{E}$  there is  $Q \in \mathcal{A}$  such that P and Q belong to the same U-equivalence class. If we have  $P \in \mathcal{D}$ , then we choose  $Q = P \in \mathcal{A}$ . Otherwise, we decompose  $P = \alpha_1 C_{k_1} \alpha_2 C_{k_2} \dots \alpha_r C_{k_r} \alpha_{r+1}$  where  $r \ge 1$ ,  $k_i \ge 2$  for  $1 \le i \le r$  and all  $\alpha_i$  do not contain any catastrophe steps. If  $\alpha_{r+1}$  is empty, then we set  $Q = \alpha_1 D \alpha_2 D \dots \alpha_r C_k$  where  $k = (k_1 - 1) + (k_2 - 1) + \dots + (k_{r-1} - 1) + k_r =$  $\sum_{i=1}^r k_i - (r-1) \ge 2r - (r-1) \ge 2$ . If  $\alpha_{r+1}$  is not empty, it can be written  $\alpha' D$ , and we set  $Q = \alpha_1 D \alpha_2 D \dots \alpha_r D \alpha' C_k$  where  $k = k_1 - 1 + k_2 - 1 + k_{r-1} - 1 + k_r - 1 + 1 =$  $\sum_{i=1}^r k_i - r + 1 \ge 2r - r + 1 \ge 2$ . In these last two cases, we have  $Q \in \mathcal{A}$  so that Pand Q belong to the same U-equivalence class.

Now, let us prove that if P and Q are two paths of the same length in  $\mathcal{A}$  lying in the same U-equivalence class, then P = Q. According to the decomposition of a Dyck path with catastrophes (see the Introduction), we write either  $P = \alpha$ or  $P = \alpha U \alpha_1 U \alpha_2 \dots U \alpha_k C_k$  (respectively  $Q = \alpha'$  or  $Q = \alpha' U \alpha'_1 U \alpha'_2 \dots U \alpha'_\ell C_\ell$ ) for some  $k, \ell \geq 2$  and where  $\alpha, \alpha', \alpha_i, \alpha'_i$  are some Dyck paths. Since a Dyck path is characterized by the positions of its up steps, and P and Q are in the same U-equivalence class, we necessarily have  $\alpha = \alpha', \alpha'_i = \alpha'_i$  for  $i \leq \min\{k, \ell\}$ , which implies that P = Q.

**Theorem 2.2** The o.g.f. with respect to the length for the set  $\mathcal{A}$  is given by

$$A(x) = \frac{\left(1 - \sqrt{1 - 4x^2}\right)\left(1 - x\right)}{x\left(2x - 1 + \sqrt{1 - 4x^2}\right)}.$$

The series expansion of A(x) is

$$1 + x^{2} + x^{3} + 3x^{4} + 4x^{5} + 10x^{6} + 15x^{7} + 35x^{8} + 56x^{9} + 126x^{10} + 210x^{11} + O(x^{12})$$

Proof. A path in  $\mathcal{A}$  is either a Dyck path in  $\mathcal{D}$ , or a path  $\alpha U \alpha_1 U \alpha_2 U \alpha_3 \dots U \alpha_k C_k$ where  $k \ge 2$  and  $\alpha, \alpha_1, \dots, \alpha_k$  are some Dyck paths. We deduce that  $A(x) = D(x) + D(x) \cdot \frac{x^2 D(x)^2}{1-x D(x)} \cdot x$  where  $D(x) = \frac{1-\sqrt{1-4x^2}}{2x^2}$  is the o.g.f. that counts Dyck paths with respect to the length (see [7]).

**Remark 2.1** With Theorem 2.2, it is easy to check that  $x^2 - 2x + 1 + (-2x^2 + 3x - 1)A(x) + (2x^2 - x)A(x)^2 = 0$ , and the coefficient  $a_n$  of  $x^n$  in A(x) is  $\binom{n-1}{\lfloor \frac{n-2}{2} \rfloor}$  which generates a shift of the sequence A037952 in OEIS [12]. Using a classical analysis [8,11] of dominant singularity of A(x),  $a_n$  has the asymptotic approximation  $\frac{2^n}{\sqrt{2\pi n}}$ .

#### 2.2 Pattern D

Let us define the set  $\mathcal{B}$  consisting of the union of the set  $\mathcal{D}$  of Dyck paths with the set  $\mathcal{D}''$  of paths  $P \in \mathcal{E}$  having only one catastrophe.

**Theorem 2.3** There is a bijection between  $\mathcal{B}$  and the set of *D*-equivalence classes of  $\mathcal{E}$ .

*Proof.* First, we prove that for every  $P \in \mathcal{E}$  there is  $Q \in \mathcal{B}$  such that P and Q belong to the same D-equivalence class. If we have  $P \in \mathcal{D}$ , then we choose  $Q = P \in \mathcal{B}$ ; otherwise, we decompose  $P = \alpha_1 C_{k_1} \alpha_2 C_{k_2} \dots \alpha_r C_{k_r} \alpha_{r+1}$  where  $r \ge 1$ ,  $k_i \ge 2$  for  $1 \le i \le r$  and all  $\alpha_i$  do not contain any catastrophe steps. If  $\alpha_{r+1}$  is empty, then we set  $Q = \alpha_1 U \alpha_2 U \dots \alpha_r C_k$  where  $k = (k_1 + 1) + (k_2 + 1) + \dots + (k_{r-1} + 1) + k_r =$  $r - 1 + \sum_{i=1}^r k_i$ . If  $\alpha_{r+1}$  is not empty, it is necessarily a Dyck path, and we set  $Q = \alpha_1 U \alpha_2 U \dots \alpha_r C_k \alpha_{r+1}$  where  $k = k_1 + 1 + k_2 + 1 + k_{r-1} + 1 + k_r = r - 1 + \sum_{i=1}^r k_i$ . In all these cases, we have  $Q \in \mathcal{B}$  so that P and Q belong to the same D-equivalence class.

With a similar argument as for the proof of Theorem 2.1, it is easy to prove that if P and Q are two paths in  $\mathcal{B}$  lying in the same class, then P = Q.

**Theorem 2.4** The o.g.f. with respect to the length for the set  $\mathcal{B}$  is given by

$$B(x) = \frac{\left(1 - \sqrt{1 - 4x^2}\right)\left(2x^3 - 4x^2 + 1 + (2x^2 - 1)\sqrt{1 - 4x^2}\right)}{2x^4\left(2x - 1 + \sqrt{1 - 4x^2}\right)}$$

The series expansion of B(x) is

 $1 + x^{2} + x^{3} + 3x^{4} + 5x^{5} + 11x^{6} + 21x^{7} + 42x^{8} + 84x^{9} + 162x^{10} + 330x^{11} + O(x^{12}).$ 

*Proof.* A path in  $\mathcal{B}$  is either a Dyck path in  $\mathcal{D}$ , or a path of the form  $\alpha U \alpha_1 U \alpha_2 U \alpha_3 \dots U \alpha_k C_k \beta$  where  $k \ge 2$  and  $\alpha, \alpha_1, \dots, \alpha_k, \beta$  are some Dyck paths. We deduce that

B(x) satisfies the functional equation  $B(x) = D(x) + \frac{x^3 D(x)^4}{1-xD(x)}$  where  $D(x) = \frac{1-\sqrt{1-4x^2}}{2x^2}$  is the o.g.f. that counts Dyck paths with respect to the length (see [7]).  $\Box$ 

### Remark 2.2 We have

$$5x^{3} - 4x^{2} - x + 1 + (-2x^{4} - 5x^{3} + 5x^{2} + x - 1)B(x) + (2x^{5} - x^{4})B(x)^{2} = 0$$

and the coefficient  $b_n$  of  $x^n$  in B(x) is

$$b_n = \begin{cases} \binom{n}{\frac{n-3}{2}} & \text{if } n \text{ is odd} \\ \binom{n}{\frac{n-4}{2}} + \binom{n}{\frac{n}{2}} / \left(\frac{n}{2} + 1\right) & \text{otherwise.} \end{cases}$$

This last result can be easily obtained by combining already known formulæ (see A002054 and A344191 in [12]), or directly using Maple. The sequence  $b_n$  has an asymptotic approximation  $\frac{2^{n+\frac{1}{2}}}{\sqrt{\pi n}}$ .

## 2.3 Pattern C

In this section, two paths of the same length are *C*-equivalent whenever, for any  $k \ge 2$  they have the same positions of the occurrences of  $C_k$ . For instance,

# $UUDDUUC_2UUUC_3UUC_2UD$

is C-equivalent to

 $UDUDUUC_2UUUC_3UUC_2UD$ ,

but not to

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UUUDUUC_4UUUC_3UUC_2UD.
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Let  $\mathcal{C}$  be the set of paths  $P \in \mathcal{E}$  such that:

- (i)  $P = (UD)^k$  for  $k \ge 0$ , or
- (ii)  $P = (UD)^{\ell_1} U^{k_1} C_{k_1} (UD)^{\ell_2} U^{k_2} C_{k_2} \dots (UD)^{\ell_r} U^{k_r} C_{k_r} (UD)^{\ell_{r+1}}$  with  $r \ge 1, \ell_i \ge 0$ for  $1 \le i \le r+1$ , and  $k_i \ge 2$  for  $1 \le i \le r$ .

**Theorem 2.5** There is a bijection between C and the set of C-equivalence classes of  $\mathcal{E}$ .

Proof. First, we prove that for every  $P \in \mathcal{E}$  there is  $Q \in \mathcal{C}$  such that P and Q belong to the same C-equivalence class. If we have  $P \in \mathcal{D}$ , then we choose  $Q = (UD)^k \in \mathcal{C}$ with k = |P|/2. Otherwise, we decompose  $P = \alpha_1 C_{k_1} \alpha_2 C_{k_2} \dots \alpha_r C_{k_r} \alpha_{r+1}$  where  $r \ge 1$ ,  $k_i \ge 2$  for  $1 \le i \le r$  and all  $\alpha_i$  do not contain any catastrophe steps. We set  $Q = (UD)^{j_1} U^{k_1} C_{k_1} (UD)^{j_2} U^{k_2} C_{k_2} \dots (UD)^{j_r} U^{k_r} C_{k_r} (UD)^{j_{r+1}}$  where  $j_i + k_i = |\alpha_i|$ ,  $1 \le i \le r$  and  $j_{r+1} = |\alpha_{r+1}|$ . We have  $Q \in \mathcal{C}$  so that P and Q belong to the same C-equivalence class. Due to the form of Q, it is straightforward to see that if P and Q are two paths in  $\mathcal{C}$  lying in the same class, then P = Q. **Theorem 2.6** The o.g.f. with respect to the length for the set C is given by

$$C(x) = \frac{1 - x}{1 - x - x^2}$$

The series expansion of C(x) is

$$1 + x^{2} + x^{3} + 2x^{4} + 3x^{5} + 5x^{6} + 8x^{7} + 13x^{8} + 21x^{9} + 34x^{10} + 55x^{11} + O(x^{12}).$$

*Proof.* Due to the definition of the set  $\mathcal{C}$ , we obtain directly the functional equation  $C(x) = \frac{1}{1-x^2} + \frac{1}{1-x^2} \cdot \frac{C'(x)}{1-C'(x)}$  where  $C'(x) = \frac{x^3}{1-x} \cdot \frac{1}{1-x^2}$  is the o.g.f. that counts the paths of the form  $(UD)^{\ell} U^k C_k$  for  $\ell \ge 0$  and  $k \ge 2$ .

**Remark 2.3** From Theorem 2.6, we deduce that the coefficient  $c_n$  of  $x^n$  in C(x) satisfies  $c_n = c_{n-1} + c_{n-2}$  for  $n \ge 2$  with  $c_0 = 1$  and  $c_1 = 0$ , which generates the sequence A212804 in [12] (it is a variant of the well known Fibonacci sequence A000045). Using the classical method for asymptotic approximation (see [8,11]), we have

$$c_n \sim \frac{3-\sqrt{5}}{5-\sqrt{5}} \cdot \left(\frac{\sqrt{5}-1}{2}\right)^n.$$

# 3 Patterns of length two

In this section, we provide generating functions that count p-equivalence classes with respect to the length whenever the pattern p is UU, UD, UC, DC, CU, DU or DD. The techniques used are similar, although more elaborate, to those used in the previous section.

#### 3.1 Pattern UU

Let  $\mathcal{F}$  be the set of paths  $P \in \mathcal{E}$  such that:

(i) 
$$P = (UD)^k$$
 for  $k \ge 0$ , or

(ii)  $P = (UD)^{\ell_0} U^{k_1} \alpha_1 U^{k_2} \alpha_2 \dots U^{k_r} \alpha_r$  where  $r \ge 1$ ,  $\ell_0 \ge 0$ ,  $k_i \ge 2$  for  $1 \le i \le r$ , all  $\alpha_i$  for  $1 \le i \le r - 1$  are either  $(DU)^k D$  or  $(DU)^k DD$  for some  $k \ge 0$ , and  $\alpha_r$  is either  $(DU)^k C_s$  or  $(DU)^k DC_s$  for some  $k \ge 0$  and with  $s \ge 1$  is so that the path ends on the x-axis (note that s can be 1, and in this case  $C_1 = D$ ).

**Theorem 3.1** There is a bijection between  $\mathcal{F}$  and the set of UU-equivalence classes of  $\mathcal{E}$ .

*Proof.* First, we prove that for every  $P \in \mathcal{E}$  there is  $Q \in \mathcal{F}$  such that P and Q belong to the same UU-equivalence class. If P does not contain occurrences of UU, then we choose  $Q = (UD)^k \in \mathcal{F}$  where k = |P|/2. Otherwise, we decompose

 $P = \alpha_0 U^{k_1} \alpha_1 U^{k_2} \dots \alpha_{r-1} U^{k_r} \alpha_r$  where  $r \ge 1$ ,  $k_i \ge 2$  for  $1 \le i \le r$ , and such that all occurrences of UU in P belong necessarily to a run  $U^{k_i}$  for some i.

We set  $Q = (UD)^{\ell_0} U^{k_1} \beta_1 U^{k_2} \dots \beta_{r-1} U^{k_r} \beta_r$  where  $\ell_0 = |\alpha_0|$ , and for  $1 \leq i \leq r-1$ ,  $\beta_i = (DU)^{\frac{t_i-1}{2}} D$  if  $t_i = |\alpha_i|$  is odd,  $\beta_i = (DU)^{\frac{t_i-2}{2}} DD$  otherwise; finally, we set  $\beta_r = (DU)^{\frac{t_r-1}{2}} C_s$  if  $t_r = |\alpha_r|$  is odd, and otherwise,  $\beta_r = (DU)^{\frac{t_r-2}{2}} DC_s$  with  $s \geq 1$  is chosen so that Q ends on the x-axis.

We have  $Q \in \mathcal{F}$  so that P and Q belong to the same UU-equivalence class. It is straightforward to see that if P and Q are two paths in  $\mathcal{F}$  lying in the same class, then P = Q.

**Theorem 3.2** The o.g.f. with respect to the length for the set  $\mathcal{F}$  is given by

$$F(x) = \frac{x-1}{(x+1)(x^3 - x^2 + 2x - 1)}$$

The series expansion of F(x) is

$$1 + x^{2} + x^{3} + 3x^{4} + 4x^{5} + 8x^{6} + 13x^{7} + 24x^{8} + 41x^{9} + 73x^{10} + 127x^{11} + O(x^{12}).$$

*Proof.* Due to the definition of  $\mathcal{F}$ , we have  $F(x) = \frac{1}{1-x^2} + \frac{1}{1-x^2} \cdot \frac{1}{1-\frac{x^3}{(1-x)^2}} \frac{x^3}{(1-x)^2}$ . A simple calculation completes the proof.

**Remark 3.1** The coefficient  $f_n$  of  $x^n$  in F(x) satisfies  $f_n = f_{n-1} + f_{n-2} + f_{n-4}$  with  $f_0 = 1, f_1 = 0, f_2 = 1, f_3 = 1$ , which generates the sequence A347493 in [12]. An asymptotic approximation of  $f_n$  is

$$f_n \sim \frac{(a-1)(a^2-a+2)^n}{a(a+1)(-3a^2+2a-2)} \approx 0.26212 \cdot 1.75487^n,$$

where  $a = \frac{(44 + 12\sqrt{69})^{2/3} + 2(44 + 12\sqrt{69})^{1/3} - 20}{6(44 + 12\sqrt{69})^{1/3}}.$ 

## 3.2 Pattern UD

Let  $\mathcal{G}$  be the set of paths  $P \in \mathcal{E}$  such that either :

- (i)  $P = (UD)^k$  for some  $k \ge 0$ , or
- (ii)  $P = (UD)^{\ell} U^k C_k (UD)^m$  with  $\ell, m \ge 0$  and  $k \ge 2$ , or
- (iii)  $P = (UD)^{\ell_0} U^{k_1} (UD)^{\ell_1} U^{k_2} (UD)^{\ell_2} \dots U^{k_r} (UD)^{\ell_r} U^{k_{r+1}} C_s (UD)^{\ell_{r+1}}$  with  $r \ge 1$ ,  $\ell_0, \ell_{r+1} \ge 0, k_i \ge 1$  for  $1 \le i \le r, k_{r+1} \ge 0, \ell_i \ge 1$  for  $1 \le i \le r$ , and  $s \ge 1$  is so that the path ends on the x-axis (note that s can be one).

**Theorem 3.3** There is a bijection between  $\mathcal{G}$  and the set of UD-equivalence classes of  $\mathcal{E}$ .

Proof. First, we prove that for every  $P \in \mathcal{E}$  there is  $Q \in \mathcal{G}$  such that P and Q belong to the same UD-equivalence class. If P satisfies the case (i), then we obviously set Q = P. If  $P = (UD)^{\ell} \alpha (UD)^m$  with  $l, m \ge 0$  and  $\alpha$  is a nonempty path in  $\mathcal{E}$  avoiding UD, then we set  $Q = (UD)^{\ell}U^k C_k (UD)^m$ . Otherwise, we decompose  $P = (UD)^{\ell_0} \alpha_1 (UD)^{\ell_1} \alpha_2 (UD)^{\ell_2} \dots \alpha_r (UD)^{\ell_r} \alpha_{r+1}$  with all  $\alpha_i$  being non-empty partial paths avoiding UD (except  $\alpha_{r+1}$  that can be empty). If  $|\alpha_{r+1}| > 1$  then we set  $Q = (UD)^{\ell_0}U^{k_1} (UD)^{\ell_1}U^{k_2} (UD)^{\ell_2} \dots U^{k_r} (UD)^{\ell_r}U^{k_{r+1}}C_s$  where  $k_i = |\alpha_i|$  and  $k_{r+1} + 1 = |\alpha_{r+1}|$ ; otherwise, if  $|\alpha_{r+1}| = 0$  then we set  $Q = (UD)^{\ell_0}U^{k_1} (UD)^{\ell_1} \dots U^{k_r-1}C_s (UD)^{\ell_r}$  where  $k_i = |\alpha_i|$  and s is so that Q ends on the x-axis. For all these cases, we have  $Q \in \mathcal{G}$  so that P and Q belong to the same UD-equivalence class. Due to the form of a path in  $\mathcal{G}$ , if P and Q are two paths in  $\mathcal{G}$  lying in the same UD-equivalence class, the P = Q. □

**Theorem 3.4** The o.g.f. with respect to the length for the set  $\mathcal{G}$  is given by

$$G(x) = \frac{2x^3 - 2x + 1}{(1 - x^2 - x)(1 - x)^2(x + 1)}$$

The series expansion of G(x) is

$$1 + x^{2} + x^{3} + 3x^{4} + 5x^{5} + 10x^{6} + 17x^{7} + 30x^{8} + 50x^{9} + 84x^{10} + 138x^{11} + O(x^{12}).$$

*Proof.* According to the different cases in the definition of  $\mathcal{G}$ , G(x) is given by:

$$1 + \frac{x^2}{1 - x^2} + \frac{1}{1 - x^2} \frac{x^3}{1 - x} \frac{1}{1 - x^2} + \frac{1}{1 - x^2} \frac{R(x)}{1 - R(x)} \frac{x}{1 - x} \frac{1}{1 - x^2}$$

where  $R(x) = \frac{x^3}{(1-x)(1-x^2)}$  is the o.g.f. that counts the paths of the form  $U^k(UD)^\ell$  with  $k, \ell \ge 1$ .

**Remark 3.2** The coefficient  $g_n$  of  $x^n$  in G(x) satisfies  $g_n = 2g_{n-1} + g_{n-2} - 3g_{n-3} + g_{n-5}$  for n > 4 with  $g_1 = 0$ ,  $g_0 = g_2 = g_3 = 1$ ,  $g_4 = 3$ , which generates the sequence A215004 in [12]. An asymptotic approximation of  $g_n$  is

$$g_n \sim \frac{4(5-2\sqrt{5})}{5(\sqrt{5}-3)^2} \cdot \left(\frac{\sqrt{5}+1}{2}\right)^n \approx 0.72360 \cdot 1.61803^n.$$

#### 3.3 Pattern UC

In this section, two paths are UC-equivalent whenever they coincide on all their occurrences  $UC_k$  for  $k \ge 2$ . For instance,  $UUDUC_2$  and  $UDUUC_2$  are UC-equivalent, while  $UDUUC_2$  and  $UUUUC_4$  are not.

Let  $\mathcal{I}_1$  be the set of paths of length  $n \ge 0$ ,  $n \notin \{1,3\}$ , defined by either (i)  $(UD)^{\frac{n}{2}}$  if n is even, or

(*ii*)  $(UD)^{\frac{n-5}{2}}UUUDC_2$  if is *n* is odd.

Let  $\mathcal{I}$  be the set consisting of the union of  $\mathcal{I}_1$  with the set of paths of the form  $\alpha_1 U^{k_1} C_{k_1} \alpha_2 U^{k_2} C_{k_2} \ldots \alpha_r U^{k_r} C_{k_r} \alpha_{r+1}$  where  $r \ge 1$ , all values  $k_i$  are at least 2, and all  $\alpha_i$  are in  $\mathcal{I}_1$ .

**Theorem 3.5** There is a bijection between  $\mathcal{I}$  and the set of UC-equivalence classes of  $\mathcal{E}$ .

Proof. First, we prove that for every  $P \in \mathcal{E}$  there is  $Q \in \mathcal{I}$  such that P and Q belong to the same UC-equivalence class. If P does not contain any pattern UC, then we set  $Q = (UD)^{\frac{n}{2}}$  if n is even, and  $Q = (UD)^{\frac{n-5}{2}}UUUDC_2$  otherwise. If P contains  $r \ge 1$  occurrences of UC, then we decompose  $P = \alpha_1 UC\alpha_2 UC \dots \alpha_r UC\alpha_{r+1}$  where all  $\alpha_i$  are paths avoiding UC. Showing the size of every catastrophes, we obtain the decomposition  $P = \alpha_1 UC_{k_1} \alpha_2 UC_{k_2} \dots \alpha_r UC_{k_r} \alpha_{r+1}$  where  $k_i \ge 2$  for  $1 \le i \le r$ .

We set  $Q = \beta_1 U^{k_1} C_{k_1} \beta_2 U^{k_2} C_{k_2} \dots \beta_r U^{k_r} C_{k_r} \beta_{r+1}$  where all  $\beta_i$  are in  $\mathcal{I}_1$  (all  $\beta_i$  are entirely determined by the length of each  $\alpha_i$ ). We have  $Q \in \mathcal{I}$  so that P and Q belong to the same UC-equivalence class. Obviously, due to the definition of  $\mathcal{I}$ , if P and Q belong to  $\mathcal{I}$  in the same UC-equivalence class, then P = Q.  $\Box$ 

**Theorem 3.6** The o.g.f. with respect to the length for the set  $\mathcal{I}$  is given by

$$I(x) = \frac{x^5 - 2x^4 + 2x^3 - 2x^2 + 2x - 1}{x^7 - x^6 + x^5 - x^4 + x^3 - x^2 + 2x - 1}$$

The series expansion of I(x) is

 $1 + x^{2} + x^{3} + 2x^{4} + 4x^{5} + 5x^{6} + 9x^{7} + 15x^{8} + 24x^{9} + 40x^{10} + 65x^{11} + O(x^{12}).$ 

Proof. The o.g.f. for  $\mathcal{I}_1$  is  $I_1(x) = \frac{1}{1-x} - x - x^3$  and the o.g.f. for  $\mathcal{I}$  is  $I_1(x) + I_1(x) \cdot \frac{I_2(x)}{1 - I_2(x)}$ where  $I_2(x) = \frac{I_1(x)x^3}{1-x}$  is the o.g.f. of a nonempty sequence of terms of the form  $\alpha U^k C_k$ with  $\alpha \in \mathcal{I}_1$  and  $k \ge 2$ .

**Remark 3.3** The coefficient  $i_n$  of  $x^n$  in I(x) satisfies  $i_n = 2i_{n-1} - i_{n-2} + i_{n-3} - i_{n-4} + i_{n-5} - i_{n-6} + i_{n-7}$  for  $n \ge 7$  with  $i_0 = 1, i_1 = 0, i_2 = 1, i_3 = 1, i_4 = 2, i_5 = 4$ , and  $i_6 = 5$ . This sequence does not appear in [12]. An asymptotic approximation of  $i_n$  is

$$i_n \sim 0.28134 \cdot 1.64072^n$$
.

#### 3.4 Pattern DC

In this section, two paths are *DC*-equivalent whenever they coincide on all their occurrences  $DC_k$  for  $k \ge 2$ .

Let  $\mathcal{J}_1$  be the set of paths of length  $n \ge 0, n \ne 1$ , defined by either (i)  $(UD)^{\frac{n}{2}}$  if n is even, or

(*ii*)  $(UD)^{\frac{n-3}{2}}UUC_2$  if is *n* is odd.

Let  $\mathcal{J}$  be the set consisting of the union of  $\mathcal{J}_1$  with the set of paths of the form  $\alpha_1 U^{k_1+1} DC_{k_1} \alpha_2 U^{k_2+1} DC_{k_2} \dots \alpha_r U^{k_r+1} DC_{k_r} \alpha_{r+1}$  where  $r \ge 1$ , all values  $k_i$  are at least 2, and all  $\alpha_i$  are in  $\mathcal{J}_1$ .

**Theorem 3.7** There is a bijection between  $\mathcal{J}$  and the set of DC-equivalence classes of  $\mathcal{E}$ .

*Proof.* The proof is obtained *mutatis mutandis* as for Theorem 3.5.

**Theorem 3.8** The o.g.f. with respect to the length for the set  $\mathcal{J}$  is given by

$$J(x) = \frac{x^3 - 2x^2 + 2x - 1}{x^7 - x^6 + x^5 - x^2 + 2x - 1}$$

The series expansion of J(x) is

$$1 + x^{2} + x^{3} + x^{4} + 2x^{5} + 2x^{6} + 4x^{7} + 6x^{8} + 9x^{9} + 14x^{10} + 20x^{11} + O(x^{12}).$$

*Proof.* The o.g.f. for  $\mathcal{J}_1$  is  $J_1(x) = \frac{1}{1-x} - x$  and the o.g.f. for  $\mathcal{J}$  is  $J_1(x) + J_1(x) \cdot \frac{J_2(x)}{1-J_2(x)}$ where  $J_2(x) = \frac{J_1(x)x^5}{1-x}$  is the o.g.f. of a nonempty sequence of terms of the form  $\alpha U^{k+1}DC_k$  with  $\alpha \in \mathcal{J}_1$  and  $k \ge 2$ .

**Remark 3.4** The coefficient  $j_n$  of  $x^n$  in J(x) satisfies  $j_n = 2j_{n-1} - j_{n-2} + j_{n-5} - j_{n-6} + j_{n-7}$  for  $n \ge 7$  with  $j_0 = 1, j_1 = 0, j_2 = j_3 = j_4 = 1, j_5 = 2, j_6 = 2$  which is not in [12]. An asymptotic approximation of  $j_n$  is

$$j_n \sim 0.25317 \cdot 1.48698^n$$
.

#### **3.5** Pattern CU

In this section, two paths are CU-equivalent whenever they coincide on all their occurrences  $C_k U$  for  $k \ge 2$ .

Let  $\mathcal{K}_1$  be the set of paths of even length defined by  $(UD)^k$  for  $k \ge 0$ . Let  $\mathcal{K}_2$  be the set of paths of length  $n \ne 1$  defined by  $(UD)^k$ ,  $k \ge 1$ , if n is even, and

 $(UD)^k UUC_2, k \ge 0$ , if n is odd. Let  $\mathcal{K}$  be the set consisting of the union of  $\mathcal{K}_2$  with the set of paths of the form

Let  $\mathcal{K}$  be the set consisting of the union of  $\mathcal{K}_2$  with the set of paths of the form  $\beta_1 U^{k_1} C_{k_1} \beta_2 U^{k_2} C_{k_2} \dots \beta_r U^{k_r} C_{k_r} \beta_{r+1}$  where  $k_i \ge 2$  for  $1 \le i < r$ , and for  $1 \le i < r+1$ ,  $\beta_i \in \mathcal{K}_1$ , and  $\beta_{r+1}$  is a path from  $\mathcal{K}_2$ .

**Theorem 3.9** There is a bijection between  $\mathcal{K}$  and the set of CU-equivalence classes of  $\mathcal{E}$ .

Proof. First, we prove that for every  $P \in \mathcal{E}$  there is  $Q \in \mathcal{K}$  such that P and Q belong to the same CU-equivalence class. If P does not contain any pattern CU, then we set  $Q = (UD)^{\frac{n}{2}}$  whenever n = |P| is even, and we set  $Q = (UD)^{\frac{n-3}{2}}UUC_2$  otherwise; in both cases  $Q \in \mathcal{K}_2$ . If P contains  $r \ge 1$  occurrences of CU, then we decompose P = $\alpha_1 CU\alpha_2 CU \dots \alpha_r CU\alpha_{r+1}$  where all  $\alpha_i$  are paths avoiding CU. Showing the size of every catastrophe, we obtain the decomposition  $P = \alpha_1 C_{k_1} U\alpha_2 C_{k_2} U \dots \alpha_r C_{k_r} U\alpha_{r+1}$ where all  $k_i$  are at least 2. So, we set  $Q = \beta_1 U^{k_1} C_{k_1} \beta_2 U^{k_2} C_{k_2} \dots \beta_r U^{k_r} C_{k_r} \beta_{r+1}$  where  $|\alpha_1| = |\beta_1|, |\alpha_i| + 1 = |\beta_i| + k_i$  for  $1 < i < r + 1, |\alpha_{r+1}| + 1 = |\beta_{r+1}|$ , and

- for  $1 \leq i < r+1, \beta_i \in \mathcal{K}_1$ ;
- $\beta_{r+1}$  is a path from  $\mathcal{K}_2$ .

We have  $Q \in \mathcal{K}$  so that P and Q belong to the same CU-equivalence class. Obviously, due to the definition of  $\mathcal{K}$ , if P and Q belong to  $\mathcal{K}$  in the same CU-equivalence class, then P = Q.

**Theorem 3.10** The o.g.f. with respect to the length for the set  $\mathcal{K}$  is given by

$$K(x) = \frac{x^4 + x - 1}{x^2 + x - 1}.$$

The series expansion of K(x) is

 $1 + x^{2} + x^{3} + x^{4} + 2x^{5} + 3x^{6} + 5x^{7} + 8x^{8} + 13x^{9} + 21x^{10} + 34x^{11} + O(x^{12}).$ 

*Proof.* Due to the definition of  $\mathcal{K}$ , the o.g.f. K(x) is given by

$$K(x) = \frac{1}{1-x} - x + \frac{1}{1-x^2} \cdot \frac{1}{1-\frac{x^3}{(1-x)(1-x^2)}} \cdot \frac{x^3}{1-x} \cdot \frac{x^2}{1-x}.$$

**Remark 3.5** The coefficient  $k_n$  of  $x^n$  in K(x) satisfies  $k_n = k_{n-1} + k_{n-2}$  for  $n \ge 5$  with  $k_0 = 1, k_1 = 0, k_2 = k_3 = k_4 = 1$  which is a shift of the Fibonacci sequence A000045 in [12]. An asymptotic approximation of  $k_n$  is

$$k_n \sim \frac{2(\sqrt{5}-2)}{5-\sqrt{5}} \cdot \left(\frac{2}{\sqrt{5}-1}\right)^n \approx 0.17082 \cdot 1.61803^n.$$

#### **3.6 Pattern** DU

Let  $\mathcal{L}$  be set of paths  $P \in \mathcal{E}$  such that

$$P = U^{\ell_1} (DU)^{k_1} U^{\ell_2} (DU)^{k_2} \dots U^{k_r} (DU)^{k_r} U^{\ell_{r+1}} C_s$$

with  $r \ge 1$ ,  $\ell_i, k_i \ge 1$  for  $1 \le i \le r$ ,  $\ell_{r+1} \ge 0$ , and s is so that the path ends on the x-axis (note that s can be 1, and in this case  $C_1 = D$ ).

**Theorem 3.11** There is a bijection between  $\mathcal{L}$  and the set of DU-equivalence classes of  $\mathcal{E}$ .

*Proof.* First, we prove that for every  $P \in \mathcal{E}$  there is  $Q \in \mathcal{G}$  such that P and Q belong to the same DU-equivalence class. We decompose  $P = \alpha_1 (DU)^{k_1} \alpha_2 (DU)^{k_2} \alpha_3 (DU)^{k_3} \dots \alpha_r (DU)^{k_r} \alpha_{r+1}$  with all  $\alpha_i$  being non-empty paths avoiding DU, with  $r \ge 0$ , and all  $k_i$  are at least one. Then we set

$$Q = U^{\ell_1} (DU)^{k_1} U^{\ell_2} (DU)^{k_2} U^{\ell_3} (DU)^{k_3} \dots U^{\ell_r} (DU)^{k_r} U^{\ell_{r+1}-1} C_s$$

where  $\ell_i = |\alpha_i|$ , and where s is so that the path ends on the x-axis. For all these cases, we have  $Q \in \mathcal{L}$  so that P and Q belong to the same DU-equivalence class. Due to the form of a path in  $\mathcal{L}$ , if P and Q are two paths in  $\mathcal{L}$  lying in the same DU-equivalence class, then P = Q.

**Theorem 3.12** The o.g.f. with respect to the length for the set  $\mathcal{L}$  is given by

$$L(x) = \frac{1 - x}{1 - x - x^2}.$$

The series expansion of L(x) is

$$1 + x^{2} + x^{3} + 2x^{4} + 3x^{5} + 5x^{6} + 8x^{7} + 13x^{8} + 21x^{9} + 34x^{10} + 55x^{11} + O(x^{12}).$$

*Proof.* According to the definition of  $\mathcal{L}$  and handling separately the cases where r = 1 and  $r \ge 2$ , the o.g.f. L(x) is given by:

$$1 + \frac{x^2}{1 - x^2} + \frac{R(x)}{1 - R(x)} \cdot \frac{x}{1 - x}$$

where  $R(x) = \frac{x^3}{(1-x)(1-x^2)}$  is the o.g.f. that counts paths of the form  $U^{\ell}(DU)^k$  with  $k, \ell \ge 1$ .

**Remark 3.6** The coefficient  $\ell_n$  of  $x^n$  in G(x) satisfies  $\ell_n = \ell_{n-1} + \ell_{n-2}$  for  $n \ge 3$  with  $\ell_0 = 1, \ell_1 = 0, \ell_2 = 1$ , which generates the sequence A212804 in [12] (a variant of the well known Fibonacci sequence A000045). An asymptotic approximation of  $\ell_n$  is

$$\ell_n \sim \frac{(\sqrt{5}-3)}{5-\sqrt{5}} \cdot \left(\frac{2}{\sqrt{5}-1}\right)^n \approx 0.27639 \cdot 1.61803^n.$$

#### **3.7 Pattern** DD

In [2], the authors exhibited a set  $\overline{\mathcal{A}}$  (denoted  $\mathcal{A}$  in [2]) of representatives for the DD-equivalence classes of Dyck paths:  $\overline{\mathcal{A}}$  consists of Dyck paths P satisfying

**Condition** (C): P avoids UUDU and the minimal ordinate reached by every occurrence of UDU is at most one (i.e. the height of every occurrence of UDU is at most 1).

For a Dyck path P, we denote by  $\psi(P)$  the unique path in  $\overline{\mathcal{A}}$  which is DD-equivalent to P. In [2], it is shown how  $\psi(P)$  can be constructed from P after several transformations preserving the positions of all occurrences of DD. The following proposition extends this result for the set  $\mathcal{D}'$  of Dyck paths with only one catastrophe  $C_k$  at the end.

**Proposition 3.1** For any path  $P \in \mathcal{D}'$  ending with catastrophe  $C_k$ ,  $k \ge 2$ , there is a unique path in  $\mathcal{D}'$ , denoted  $\psi(P)$ , which is DD-equivalent to P, ending with catastrophe  $C_k$  (the same k as for P), and satisfying Condition (C).

*Proof.* Let Q be the Dyck path obtained from P by replacing  $C_k$  with  $D^k$ . Using [2], there is a unique path  $\psi(Q)$  in  $\overline{\mathcal{A}}$  in the class of Q. Replacing the last  $D^k$  of  $\psi(Q)$  with  $C_k$ , there is a unique Dyck path with only catastrophe  $C_k$  at the end equivalent to P.

**Lemma 3.1** Let P be a path in  $\mathcal{E}$ . If P contains at least two catastrophes, then there exists  $Q \in \mathcal{E}$  in the class of P, such that Q has only one catastrophe.

*Proof.* We obtain Q from P by replacing with U every catastrophe, except the last, and by increasing the size of the last catastrophe so that  $Q \in \mathcal{E}$ . See Figure 2 for an example with two catastrophes.

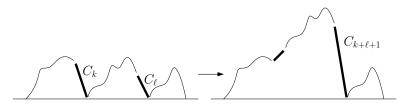


Figure 2: Example for Lemma 3.1 with two catastrophes.

Considering this previous lemma, we can focus our study on the set of Dyck paths with at most one catastrophe. Recall that  $\mathcal{D}''$  is the set of paths in  $\mathcal{E}$  having only one catastrophe (see Section 2.2).

**Lemma 3.2** Let P be a path of length n in  $\mathcal{D}''$  (i.e. P contains only one catastrophe). The size of the catastrophe and n have different parity.

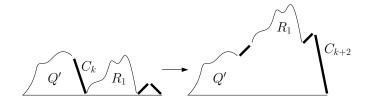
*Proof.* For any Dyck path in  $\mathcal{D}''$  having the catastrophe of size k, the number of U minus the number of D equals k, which implies that the number of U and D (which is equal to n-1) has the same parity as k.

In the following, for a given path P, a D-step will be called *isolated* if and only if it does not lie in an occurrence of DD.

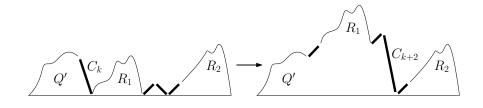
**Lemma 3.3** Let P be a path in  $\mathcal{D}''$  having its catastrophe of size  $k \ge 2$ . We have  $P = QC_kR$  where R is a Dyck path. If R contains isolated D-steps, then there is a path in  $\mathcal{D}''$ , DD-equivalent to P, with a catastrophe  $C_{k+2}$  of size k+2, and such that every D-step on the right of  $C_{k+2}$  is not isolated.

*Proof.* First, we construct  $P' = Q'C_kR'$ , where  $Q'C_k$  is the result of application of Proposition 3.1 on  $QC_k$  and R' is obtained applying  $\phi$  from [2] on R. It implies that P' and P are DD-equivalent and this construction ensures that the height of the rightmost isolated D step in P' is at most one. After this, we distinguish three cases according to the position and the height of the rightmost isolated D-step.

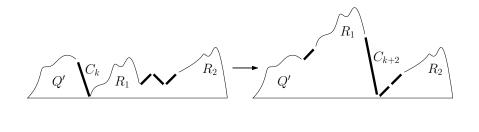
- if  $R' = R_1 UD$ , then the paths  $Q' U R_1 U C_{k+2}$  and P are equivalent;



- if  $R' = R_1 U D U R_2$  where  $U R_2$  is a Dyck path, then  $Q' U R_1 U C_{k+2} U R_2$  and P are equivalent;



- if  $R' = R_1 U D U R_2$  where  $U U R_2$  is a Dyck path then  $Q' U R_1 C_{k+2} U U R_2$  and P are equivalent.



**Lemma 3.4** Let P be a path in  $\mathcal{D}''$  satisfying Condition (C) and having its catastrophe of size  $k \ge 4$ . Then, there is a path  $Q \in \mathcal{D}''$ , equivalent to P, having its catastrophe of size k - 2, and such that  $C_k$  and  $C_{k-2}$  are in the same position in P and Q, respectively.

*Proof.* Before describing the construction of Q, it is worth noticing the following fact. There is an occurrence of UUU at height k - 3 on the left of  $C_k$  in P. Indeed, let us consider the rightmost U at height k - 3 on the left of  $C_k$ ; clearly it necessarily precedes a step U which constitutes an occurrence of UU at height k - 3. Moreover, since P avoids UUDU, the two steps UU are necessarily followed by another step U, and P can be decomposed  $P = P_1UUUP_2C_kP_3$  where  $P_1$  is a prefix of a Dyck path ending at height k - 3,  $UP_2D$  is a Dyck path and  $P_3$  is a Dyck path. We complete the proof by setting  $Q = P_1UDUP_2C_{k-2}P_3$ . See Figure 3 for an illustration of this construction. □

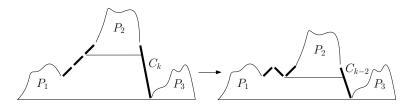


Figure 3: Illustration for Lemma 3.4.

#### 3.7.1 The case of odd length

Let  $\mathcal{A}'$  be the subset of paths in  $\overline{\mathcal{A}}$  avoiding UDU, and not ending with UD, which also is the set of paths in  $\overline{\mathcal{A}}$  without isolated *D*-steps. Let  $\mathcal{A}_2$  be the set of paths satisfying Condition (*C*) and having only one catastrophe  $C_2$  at the end.

**Proposition 3.2** A set of representatives of the DD-equivalence classes of odd length Dyck paths with catastrophes, is the set  $\mathcal{R}_1$  of paths R = AA' where  $A \in \mathcal{A}_2$  and  $A' \in \mathcal{A}'$ .

Proof. First, let us prove that for any path  $P \in \mathcal{E}$ , there is a path  $Q \in \mathcal{R}_1$  lying in the same class. We obtain Q by applying the following process: (i) we apply Lemma 3.1; (ii) we apply Lemma 3.3; (iii) we apply  $\psi$  extended to Dyck paths with only one catastrophe (see Proposition 3.1); (iv) we apply Lemma 3.4 and Proposition 3.1, and we repeat it until the size of the catastrophe reaches 2 (thanks to Lemma 3.2). In the case where UD precedes  $C_2$ , i.e.  $Q = Q_1 U D C_2 Q_2$ , we replace the path with  $Q_1 U U C_4 Q_2$  (see Fig. 4) and we apply Lemma 3.4 and Proposition 3.1.

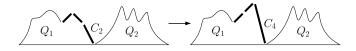


Figure 4: Illustration for Proposition 3.2.

Now, it suffices to prove that two different paths Q and Q' in  $\mathcal{R}_1$  with the same length cannot belong to the same class. Let us assume that Q and Q' lie in the same

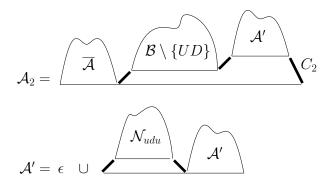
class. We decompose  $Q = RC_2S$  and  $Q' = R'C_2S'$ . Suppose that  $|S| \ge |S'|$ . Since S' does not contain isolated D-steps, S' is entirely determined by the positions of occurrences of DD, which implies that S has the form S = TS'. Since S does not contain an isolated D-step, T cannot end with UD, and since Q is DD-equivalent to Q' it cannot end with DD, which means that T is empty. So we have |S| = |S'| and then S = S'. Using Proposition 3.1 for  $RC_2$  and  $R'C_2$ , we obtain Q = Q'.

**Theorem 3.13** (The case of odd length) The o.g.f. for the number of DD-equivalence classes of odd length paths in  $\mathcal{E}$  is given by:

$$N(x) = \frac{8x^3}{(x^2 + \sqrt{1 - 3x^4 - 2x^2} + 1)^2(-x^4 + (1 + x^2)\sqrt{1 - 3x^4 - 2x^2} - 2x^2 + 1)^2}$$

We have  $N(x) = x^3 + x^5 + 5x^7 + 11x^9 + 33x^{11} + 88x^{13} + 247x^{15} + O(x^{16}).$ 

*Proof.* By Proposition 3.2, it suffices to provide the o.g.f. N(x) for  $\mathcal{A}_2 \times \mathcal{A}'$  with respect to the length. Sets  $\mathcal{A}_2$  and  $\mathcal{A}'$  are constructed as follows



where  $\mathcal{N}_{udu}$  is the set of non-empty Dyck paths avoiding UDU,  $\overline{\mathcal{A}}$  is the set of representatives for the DD-equivalence classes of Dyck paths, e.g. Dyck paths avoiding UUDU and having all UDU at height 0 or 1, and  $\mathcal{B}$  is the set of Dyck paths having all UDU on x-axis and not starting with UDU. From [2] it follows that

$$\overline{A}(x) = \frac{1 - x^2 + \sqrt{-3x^4 - 2x^2 + 1}}{1 + x^6 + x^4 - 3x^2 - (x^4 - 1)\sqrt{-3x^4 - 2x^2 + 1}},$$
$$B(x) = \frac{2 - x^2 - x^4 + x^2\sqrt{-3x^4 - 2x^2 + 1}}{1 - x^2 + \sqrt{-3x^4 - 2x^2 + 1}},$$

and from [2,13] we have  $N_{udu}(x) = (x^2 - \sqrt{-3x^4 - 2x^2 + 1} + 1)/(2x^2) - 1$ .

Finally, we compute  $N(x) = \overline{A}(x) (B(x) - x^2) A'(x) x^3 A'(x)$  where A'(x) satisfies  $A'(x) = 1 + x^2 N_{udu}(x) A'(x)$ .

#### 3.7.2 The case of even length

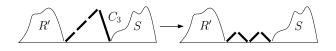
**Proposition 3.3** A set of representatives of the DD-equivalence classes of even length Dyck paths with catastrophes is the set  $\mathcal{R}_2$  defined by the union of  $\overline{\mathcal{A}}$  with the sets  $\mathcal{S}_0$  and  $\mathcal{S}_1$  defined below:

-  $S_0$  is the set of Dyck paths  $S = PDUUC_3$  where PDU is a prefix of Dyck path satisfying condition (C), and ending at height 2,

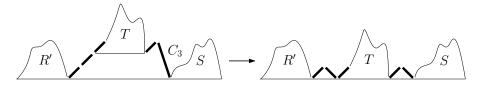
-  $S_1$  is the set of Dyck paths  $S = PDDC_3$  where P is a prefix of Dyck path satisfying condition (C), and ending at height 5.

Proof. Let P be a path in  $\mathcal{E}$ . If P does not contain any catastrophe, then using Lemma 1 from [2], there is a unique path in  $\overline{\mathcal{A}}$  equivalent to P. Now, let us assume that P contains at least one catastrophe. We obtain Q by applying the following process: (i) we apply Lemma 3.1; we apply Lemma 3.3; we apply  $\psi$  (extended to Dyck paths with only one catastrophe); we apply Lemma 3.4 followed by Proposition 3.1 until the path contains only one catastrophe  $C_3$  (thanks to Lemma 3.2). We decompose the obtained path  $Q = RC_3S$  where S is a Dyck path with no isolated D-step. With the same argument used at the beginning of the proof of Lemma 3.4, R is of the form R = R'UUUR'' where R' and UR''D are Dyck paths.

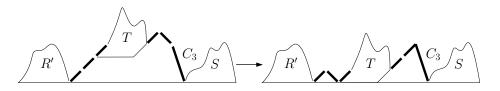
(a) if R'' is empty, i.e. R = R'UUU, we replace Q with  $R'UDUDS \in \overline{A}$ ;



(b) if R'' = TU ends with U, i.e. R = R'UUUTU, we replace Q with  $R'UDUTUDS \in \overline{\mathcal{A}}$ ;

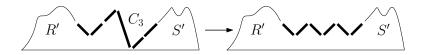


(c) if R'' = TUD ends with UD, i.e. R = R'UUUTUD, we replace Q with  $R'UDUTUUC_3S$  (see the illustration below); In the case where T ends with U, we apply the transformation (a) and we obtain a path in  $\overline{\mathcal{A}}$ ;

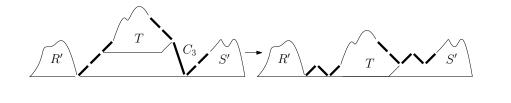


After applying all these transformations, the path is either in  $\overline{\mathcal{A}}$ , or it satisfies Condition (C) and contains only one catastrophe  $C_3$  that follows an occurrence DUUor DD. If S is empty then the path lies in  $\mathcal{R}_2$ . Otherwise, S does not contain isolated D-step and it starts necessarily with UU. In this case we set S = UUS' and make the catastrophe disappear as follows:

(d) if R ends at height 3 with DUU, we set R = R'DUU and replace Q with  $R'DUDUDUS' \in \overline{\mathcal{A}}$ ;



(e) if R ends with UUUT, where UT is a prefix of a Dyck path ending at height 1 and with DD, we set R = R'UUUT and replace Q by R'UDUTUDUS'.

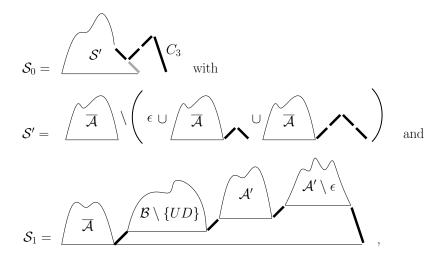


**Theorem 3.14** (The case of even length) The o.g.f. V(x) for the number of DDequivalence classes of even length paths in  $\mathcal{E}$  is given by:

$$V(x) = \frac{4(x^4 - x^2 - 1)\sqrt{-3x^4 - 2x^2 + 1} + 8x^8 + 20x^6 + 8x^4 - 4}{\left((-x^2 - 1)\sqrt{-3x^4 - 2x^2 + 1} + x^4 + 2x^2 - 1\right)\left(x^2 + \sqrt{-3x^4 - 2x^2 + 1} + 1\right)^2}.$$

We have  $V(x) = 1 + x^2 + 2x^4 + 4x^6 + 11x^8 + 27x^{10} + 73x^{12} + 194x^{14} + 529x^{16} + 1448x^{18} + O(x^{19}).$ 

*Proof.* By Proposition 3.3, it suffices to provide the o.g.f. M(x) for  $\overline{\mathcal{A}} \cup S_0 \cup S_1$  with respect to the length. Sets  $S_0$  and  $S_1$  are constructed as follows:



where  $\mathcal{A}'$  is the set of non-empty Dyck paths avoiding UDU not ending with UD,  $\overline{\mathcal{A}}$  is the set of representatives for the DD-equivalence classes of Dyck paths, e.g. Dyck paths avoiding UUDU and having all UDU at height 0 or 1, and  $\mathcal{B}$  is the set of Dyck paths having all UDU on x-axis and not starting with UDU.

Then, we have

$$S_0(x) = x^2 \cdot (\overline{A}(x) - 1 - x^2 \cdot \overline{A}(x) - x^4 \cdot \overline{A}(x))$$

and

$$S_1(x) = x^4 \cdot \overline{A}(x)(B(x) - x^2)A'(x)(A'(x) - 1)$$

which gives the claimed result after a simple calculation.

# 3.7.3 The general case

Combining Theorems 3.13 and 3.14, we deduce:

**Theorem 3.15** The o.g.f. L(x) for the number of DD-equivalence in  $\mathcal{E}$  is given by

$$\frac{\left(4x^{4}-4x^{2}-4\right)\sqrt{-3x^{4}-2x^{2}+1}+8x^{8}+20x^{6}+8x^{4}-8x^{3}-4}{\left(\left(-x^{2}-1\right)\sqrt{-3x^{4}-2x^{2}+1}+x^{4}+2x^{2}-1\right)\left(x^{2}+\sqrt{-3x^{4}-2x^{2}+1}+1\right)^{2}},$$

and it satisfies the following equation:  $x^{10} - x^9 + 4x^8 - 3x^7 + 5x^6 - 5x^5 + 2x^4 - 2x^3 + x^2 - x + 1 + (-x^{10} + x^9 - 6x^8 + 5x^7 - 9x^6 + 6x^5 - 3x^4 + 3x^3 + x - 1)L(x) + (x^{10} - x^9 + 4x^8 - 3x^7 + 5x^6 - 3x^5 + 2x^4 - x^3)L(x)^2 = 0.$ 

The first coefficients of  $x^n$ ,  $n \ge 2$ , of the series expansion of L(x) are 1, 1, 2, 1, 4, 5,  $11, 11, 27, 33, 73, 88, 194, 247, \ldots$ , and they do not correspond to a part of a sequence listed in [12].

An asymptotic approximation of these coefficients is

$$\frac{41\sqrt{2}}{2\sqrt{\pi}} \cdot \frac{\sqrt{3}^{n+1}}{n^{\frac{3}{2}}} \text{ for } n \text{ even, and}$$
$$\frac{135\sqrt{2}}{4\sqrt{\pi}} \cdot \frac{\sqrt{3}^{n}}{n^{\frac{3}{2}}} \text{ otherwise.}$$

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