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# An extension of the Last-Success-Problem



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ABSTRACT

There are *n* independent Bernoulli random variables  $I_k$  with parameters  $p_k$  that are observed sequentially. We consider an extension of the last-success-problem with reward  $w_k$  if the player predicts correctly at step k that  $l_k = 1$  is the last success. We establish the optimal strategy for a payoff-function generalizing the last-success 0-1payoff by using the dynamical programming method. In particular we show that this method is intuitive and very efficient for general payoffs.

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### 1. Introduction

The Last-Success-Problem is the problem of maximizing the probability of stopping on the last success in a finite sequence of Bernoulli trials. The framework is as follows. There are n Bernoulli random variables which are observed sequentially. The problem is to find a stopping rule to maximize the probability of stopping on the last "1". We restrict ourselves here to the case in which the random variables are independent. This problem has been studied by Hill and Krengel (1992) in the context of the secretary problem and was simply and elegantly solved by Franz Thomas Bruss in Bruss (2000) with the following famous result.

**Theorem 1** (Odds-Theorem, Bruss, 2000). Let  $I_1, I_2, \ldots, I_n$  be n independent Bernoulli random variables with known n. We denote by (i = 1, ..., n)  $p_i$ , the parameter of  $I_i$ ; i.e.  $(p_i = P(I_i = 1))$ . Let  $q_i = 1 - p_i$  and  $r_i = p_i/q_i$ . We define the index

$$\mathbf{s} = \begin{cases} \max\{1 \le k \le n : \sum_{j=k}^{n} r_j \ge 1\}, & \text{if } \sum_{i=1}^{n} r_i \ge 1; \\ 1, & \text{otherwise} \end{cases}$$

To maximize the probability of stopping on the last "1" of the sequence, it is optimal to stop on the first "1" we encounter among the variables  $I_s, I_{s+1}, \ldots, I_n$ .

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The optimal win probability is given by

$$\mathcal{V}(p_1,\ldots,p_n):=\left(\prod_{j=\mathbf{s}}^n q_j\right)\left(\sum_{i=\mathbf{s}}^n r_i\right).$$

Bruss subsequently presented an addendum (Bruss, 2003) with the following result for the case in which  $\sum_{i=1}^{n} r_i \ge 1$ .

**Theorem 2.** If 
$$\sum_{j=1}^{n} \frac{p_j}{1-p_j} \ge 1$$
 then

$$\mathcal{V}(p_1,\ldots,p_n)>\frac{1}{e}.$$

The Odds-Theorem was extended by Ferguson (see Ferguson, 2011) in several ways. First, by also including an infinite number of Bernoulli variables. Second, the payoff for not stopping is allowed to be different from the payoff for stopping on a success that is not the last success. Third, the Bernoulli variables are allowed to be dependent.

In this paper, we present an extension of the Last-Success-Problem, considering a positive payoff,  $w_k$ , if the player stops on the last success and this occurs at the *k*th event. We establish the optimal strategy and the expected profit by using the dynamical programming method. In particular we show that this method is intuitive and very efficient for general payoffs.

#### 2. Threshold strategies

In this section, we shall show that, under certain conditions, the optimal strategy is a threshold strategy. Dynamic programming provides the probability of winning and the optimal strategy in a simple way. In what follows, we shall take into account the following definitions.

Definition 1. Let us define the following functions.

•  $\mathbb{E}_{\text{Stop}}(k)$  is the expected profit if we stop at the *k*th event given that  $I_k = 1$ :

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$$\mathbb{E}_{ ext{Stop}}(n) = w_n$$
  
and for  $k = n - 1, n - 2, \dots,$ 

$$\mathbb{E}_{\text{Stop}}(k) \coloneqq w_k \prod_{i=k+1}^n (1-p_i).$$

•  $\mathbb{E}_{\text{cont}}(k)$  is the expected profit after observing the *k*th event and continuing (not stopping) in order to adopt the optimal strategy later on. The dynamic program that defines it by recurrence is:

$$\mathbb{E}_{\text{cont}}(n) = 0$$

and for k = n - 1, n - 2, ..., 0

$$\mathbb{E}_{\text{cont}}(k) = p_{k+1} \cdot \max\left\{\mathbb{E}_{\text{Stop}}(k+1), \mathbb{E}_{\text{cont}}(k+1)\right\} + (1-p_{k+1}) \cdot \mathbb{E}_{\text{cont}}(k+1).$$

**Proposition 1.** With the above definitions, it is obvious that the following strategy is optimal:

 $\diamond$  Stop if  $I_k = 1$  and  $\mathbb{E}_{\text{Stop}}(k) > \mathbb{E}_{\text{cont}}(k)$  and continue otherwise.

In addition, using this strategy, the expected profit is  $\mathbb{E}_{cont}(0)$ .

**Definition 2.** We denote by the stopping set the set of indices in which the decision to stop is optimal if the corresponding event is successful. That is:

$$\Upsilon_n := \{k : \mathbb{E}_{\text{Stop}}(k) > \mathbb{E}_{\text{cont}}(k)\}$$

**Example 1.** Let us consider 9 random Bernoulli variables with the following parameters,  $p_i$ , and payoffs,  $w_i$ :

$$\{p_1 = \frac{1}{6}, p_2 = \frac{1}{10}, p_3 = \frac{1}{12}, p_4 = \frac{1}{3}, p_5 = \frac{1}{12}, p_6 = \frac{1}{10}, p_7 = \frac{1}{5}, p_8 = \frac{1}{10}, p_9 = \frac{1}{12}\}$$

 $\{w_1 = 7, w_2 = 4, w_3 = 9, w_4 = 10, w_5 = 6, w_6 = 3, w_7 = 9, w_8 = 9, w_9 = 1\}$ 

The corresponding dynamic program returns:

 $\mathsf{ExpectedProfit} = \mathbb{E}_{\texttt{cont}}(0) = \frac{6721}{2000}$ 

and the stopping set

StoppingSet =  $\{4, 5, 7, 8, 9\}$ 

**Definition 3.** If the stopping set has a single stopping island,  $\Upsilon_n = \{k : k \ge k\}$ , we shall say that the optimal strategy is a *threshold strategy* and, in this case,  $\mathbf{k} := \min \Upsilon_n$  is the *optimal threshold*. We also state that the problem is a **monotone problem**, which is not the case in the aforementioned example.

Remark. Note that, for the optimal threshold, we have that

 $\mathbf{k} = \min\{k : \mathbb{E}_{\text{Stop}}(k) > \mathbb{E}_{\text{cont}}(k)\} = 1 + \max\{k : \mathbb{E}_{\text{Stop}}(k) \le \mathbb{E}_{\text{cont}}(k)\}$ 

The following two easy results characterize monotone problems.

**Proposition 2.** The problem is monotone if and only if for all 0 < k < n

 $\mathbb{E}_{\text{Stop}}(k) > \mathbb{E}_{\text{cont}}(k) \Rightarrow \mathbb{E}_{\text{Stop}}(k+1) > \mathbb{E}_{\text{cont}}(k+1)$ 

**Proposition 3.** The problem is monotone if and only if for all  $0 < k \le n$ 

$$\mathbb{E}_{\text{Stop}}(k) - \mathbb{E}_{\text{cont}}(k)$$

change sign at the most once.

With the following result, we present a sufficient condition for the problem to be monotone. In particular, when the payment function,  $w_k$ , is non-decreasing, the problem is monotone.

**Proposition 4.** If  $w_{k+1} \ge (1 - p_{k+1})w_k$  for all  $k \in \{1, ..., n-1\}$ , then the problem is monotone.

**Proof.** If we take into account the associated dynamic program, we see that  $\mathbb{E}_{cont}(k)$  is non-increasing

$$\mathbb{E}_{\text{cont}}(k) = p_{k+1} \max \left\{ \mathbb{E}_{\text{stop}}(k+1), \mathbb{E}_{\text{cont}}(k+1) \right\} + (1-p_{k+1})\mathbb{E}_{\text{cont}}(k+1) \geq \mathbb{E}_{\text{cont}}(k+1).$$

On the other hand,  $\mathbb{E}_{\texttt{Stop}}$  is non-decreasing since

$$\frac{\mathbb{E}_{\text{Stop}}(k+1)}{\mathbb{E}_{\text{Stop}}(k)} = \frac{w_{k+1} \prod_{i=k+2}^{n} (1-p_i)}{w_k \prod_{i=k+1}^{n} (1-p_i)} = \frac{w_{k+1}}{w_k (1-p_{k+1})} \ge 1$$

As a consequence, given that  $\mathbb{E}_{Stop}$  is non-decreasing and  $\mathbb{E}_{cont}$  is non-increasing,

 $\mathbb{E}_{\text{Stop}}(k) \ge \mathbb{E}_{\text{cont}}(k) \Rightarrow \mathbb{E}_{\text{Stop}}(k+1) \ge \mathbb{E}_{\text{cont}}(k+1)$ 

and we are able to use Proposition 2.  $\Box$ 

With Proposition 2, it became evident that for the problem to be monotone, it is sufficient for  $\mathbb{E}_{\text{Stop}}(r)$  to be nondecreasing. However, this is not a necessary condition. Actually, the problem is monotone if and only if the difference  $\mathbb{E}_{\text{Stop}}(k) - \mathbb{E}_{\text{cont}}(k)$  presents one change of sign at the most. However, the verification of this statement presents difficulties as the dynamic program does not allow us to know an explicit expression of  $\mathbb{E}_{\text{cont}}(r)$ . We shall see how to overcome this difficulty below.

**Definition 4.** Let us denote by  $\overline{\mathbb{E}}_{\text{cont}}(k)$  the expected profit after observing the *k*th event and continuing in order to stop on the next success to be found.

$$\overline{\mathbb{E}}_{\text{cont}}(k) := \sum_{i=k+1}^{n} \left( \prod_{j=k+1}^{i-1} (1-p_j) \right) \cdot p_i \cdot \mathbb{E}_{\text{Stop}}(i)$$

In other words,  $\overline{\mathbb{E}}_{cont}(k)$  is the expected profit using the strategy of stopping on the first success after the *k*th event.

It is clear from the definition itself that  $\overline{\mathbb{E}}_{\text{cont}}(k) \leq \mathbb{E}_{\text{cont}}(k)$ .

**Lemma 1.** Let  $r_0$  be such that  $\mathbb{E}_{\text{stop}}(r) > \overline{\mathbb{E}}_{\text{cont}}(r)$  for every  $r > r_0$ . Then,  $\mathbb{E}_{\text{stop}}(r) > \mathbb{E}_{\text{cont}}(r)$  for every  $r > r_0$ .

**Proof.** Given  $r_0$ , let us consider the set  $S = \{r > r_0 : \mathbb{E}_{\text{Stop}}(r) \le \mathbb{E}_{\text{cont}}(r)\}$ . It is necessary to prove that  $S = \emptyset$ . Let us assume that S is nonempty and let r' be its maximum. This means that  $\mathbb{E}_{\text{Stop}}(r') \le \mathbb{E}_{\text{cont}}(r')$  and  $\mathbb{E}_{\text{Stop}}(r') > \overline{\mathbb{E}}_{\text{cont}}(r')$ , while  $\mathbb{E}_{\text{Stop}}(\mathbf{r}') > \mathbb{E}_{\text{cont}}(\mathbf{r}')$  for all  $\mathbf{r}' > r'$ ; but this is a contradiction. This is because if  $\mathbb{E}_{\text{Stop}}(\mathbf{r}') > \mathbb{E}_{\text{cont}}(\mathbf{r}')$  for all  $\mathbf{r}' > r'$ , then  $\mathbb{E}_{\text{cont}}(r') = \overline{\mathbb{E}}_{\text{cont}}(r')$ .  $\Box$ 

Using this lemma, it is possible to reformulate Propositions 2 and 3 in terms of  $\overline{\mathbb{E}}_{cont}(r)$ , which we can know explicitly.

**Proposition 5.** If for all 0 < r < n the following is true

$$\mathbb{E}_{\text{Stop}}(r) > \mathbb{E}_{\text{cont}}(r) \Rightarrow \mathbb{E}_{\text{Stop}}(r+1) > \mathbb{E}_{\text{cont}}(r+1)$$

then the problem is monotone.

**Proof.** Let  $r_0$  be the minimum of the stopping set.  $\mathbb{E}_{\text{Stop}}(r_0) > \overline{\mathbb{E}}_{\text{cont}}(r_0)$  and using the hypothesis inductively, we have that  $\mathbb{E}_{\text{Stop}}(r) > \overline{\mathbb{E}}_{\text{cont}}(r)$  for all  $r \ge r_0$ . We thus find ourselves within the conditions of Lemma 1 and hence  $\mathbb{E}_{\text{Stop}}(r) > \mathbb{E}_{\text{cont}}(r)$  for all  $r \ge r_0$ .

**Proposition 6.** The problem is monotone if and only if for all  $0 < k \le n$ 

$$\mathbb{E}_{\text{Stop}}(k) - \overline{\mathbb{E}}_{\text{cont}}(k)$$

change sign at the most once.  $\ \Box$ 

Proposition 7. If the problem is monotone and k is the optimal threshold, then

$$\begin{split} \mathbb{E}_{\text{Stop}}(r) &> \mathbb{E}_{\text{cont}}(r) \Longleftrightarrow \mathbb{E}_{\text{Stop}}(r) > \overline{\mathbb{E}}_{\text{cont}}(r) \\ \mathbb{E}_{\text{cont}}(r) &= \begin{cases} \overline{\mathbb{E}}_{\text{cont}}(r), & \text{if } r \geq \mathbf{k}; \\ \overline{\mathbb{E}}_{\text{cont}}(\mathbf{k}-1), & \text{if } r < \mathbf{k} \end{cases} \end{split}$$

#### 3. The extended Odds-Theorem

**Theorem 3.** Let  $I_1, I_2, ..., I_n$  be n independent Bernoulli random variables with parameter  $p_i$ . Let  $w_i$  be real positive numbers that represent the payments a player receives for indicating the last "1" in the variable  $I_i$ . We define the index (with auxiliary  $w_0 := 0$ )

$$\mathbf{s} = \max\left\{k: \sum_{j=k}^{n} \frac{w_j \cdot p_j}{1-p_j} \ge w_{k-1}\right\}$$

If the problem is monotone, then **s** is the optimal threshold. That is, to maximize the expected profit, it is optimal to stop on the first "1" we encounter among the variables  $I_s, \ldots, I_n$ . Furthermore, with this strategy, the expected profit is:

$$\mathbb{E} = \begin{cases} \left(\prod_{j=s}^{n} (1-p_j)\right) \sum_{i=s}^{n} \frac{w_i \cdot p_i}{1-p_i}, & \text{if } p_s < 1; \\ w_s \cdot \prod_{j=s+1}^{n} (1-p_j), & \text{if } p_s = 1. \end{cases}$$

**Proof.** Recall that the optimal threshold is

 $\mathbf{k} = 1 + \max\{k : \mathbb{E}_{\text{Stop}}(k) \le \mathbb{E}_{\text{cont}}(k)\} = \max\{k : \mathbb{E}_{\text{Stop}}(k-1) \le \mathbb{E}_{\text{cont}}(k-1)\}.$ 

We shall first assume that  $p_k < 1$  and hence  $p_k < 1$  for all  $k > \mathbf{k}$ . Bear in mind that if  $p_k = 1$  for some  $k > \mathbf{k}$ , then  $\mathbb{E}_{\text{Stop}}(\mathbf{k}) = 0$ , which would be a contradiction. We shall first prove that  $\mathbf{s} = \mathbf{k}$ .

$$\mathbf{k} = \max\{k : \mathbb{E}_{\text{Stop}}(k-1) \le \sum_{i=k}^{n} \left( \prod_{j=k}^{i-1} (1-p_j) \right) \cdot p_i \cdot \mathbb{E}_{\text{Stop}}(i) \}$$

as

$$\mathbb{E}_{\text{Stop}}(i) = w_i \prod_{t=i+1}^n (1-p_t)$$
$$\mathbf{k} = \max\left\{k : w_{k-1} \prod_{t=k}^n (1-p_t) \le \sum_{i=k}^n \left(\prod_{j=k}^{i-1} (1-p_j)\right) \cdot p_i \cdot w_i \prod_{t=i+1}^n (1-p_t)\right\}$$

$$\mathbf{k} = \max\left\{k : w_{k-1} \prod_{t=k}^{n} (1-p_t) \le \sum_{i=k}^{n} \left(\prod_{j=k}^{n} (1-p_j)\right) \cdot \frac{p_i}{1-p_i} \cdot w_i\right\}$$
$$\mathbf{k} = \max\left\{k : w_{k-1} \le \sum_{i=k}^{n} \frac{p_i}{1-p_i} \cdot w_i\right\} = \mathbf{s}$$

As to the value of the expected profit, which is in fact  $\overline{\mathbb{E}}_{cont}(s-1)$ , we have

$$\overline{\mathbb{E}}_{\text{cont}}(\mathbf{s}-1) = \sum_{i=\mathbf{s}}^{n} \left( \left( \prod_{j=\mathbf{s}}^{i-1} (1-p_j) \right) p_i \cdot \mathbb{E}_{\text{Stop}}(i) \right)$$
$$\overline{\mathbb{E}}_{\text{cont}}(\mathbf{s}-1) = \sum_{i=\mathbf{s}}^{n} \left( \left( \prod_{j=\mathbf{s}}^{i-1} (1-p_j) \right) p_i \cdot w_i \prod_{t=i+1}^{n} (1-p_t) \right)$$

and, carrying out the same operations as before, we have that

$$\mathbb{E} = \overline{\mathbb{E}}_{\texttt{cont}}(\mathbf{s} - 1) = \left(\prod_{j=\mathbf{s}}^{n} (1 - p_j)\right) \sum_{i=\mathbf{s}}^{n} \frac{w_i \cdot p_i}{1 - p_i}$$

If  $p_{\mathbf{k}} = 1$ , the proof that  $\mathbf{s} = \mathbf{k}$  is the same. As for the expected profit, bearing in mind that we shall stop at the sth variable with probability 1, then

$$\mathbb{E} = \overline{\mathbb{E}}_{\text{cont}}(\mathbf{s} - 1) = \mathbb{E}_{\text{Stop}}(\mathbf{s}) = w_{\mathbf{s}} \cdot \left(\prod_{j=\mathbf{k}+1}^{n} (1-p_j)\right). \quad \Box$$

The previous theorem has as its particular case the famous Odds-Theorem (Theorem 1) when considering  $w_i = 1$ .

#### 4. Some application examples

#### 4.1. The Best-choice Duration Problem

Let us consider the secretary problem with a payment  $w_k = (n - k + 1)$  for selecting the best secretary in the *k*th interview. Within the context of this paper, we have *n* independent Bernoulli random variables with parameters  $p_k = 1/k$  and payoffs  $w_k$ . It is not difficult (although not straightforward) to see that the problem is monotone. In this case, its proof requires using Proposition 6.

$$\mathbf{s}_{n} = \max\left\{k : \sum_{j=k}^{n} \frac{w_{j} \cdot p_{j}}{1 - p_{j}} \ge w_{k-1}\right\} = \max\left\{k : \sum_{j=k}^{n} \frac{(n - j + 1) \cdot \frac{1}{j}}{1 - \frac{1}{j}} \ge n - j + 2\right\}$$
$$\mathbf{s}_{n} = \max\left\{k : \frac{2n - 2k + 3}{n} \le \sum_{k-2}^{n-1} \frac{1}{i}\right\}$$

from which it is can easily be seen that  $\mathbf{s}_n/n$  tends to *rumour's constant*, which is the solution to the equation  $2 - 2x + \log(x) = 0$ 

$$\vartheta := -\frac{1}{2}W(-2e^{-2}) = 0.203187869....$$
 (A106533 in OEIS)

and the asymptotic expected profit is  $\mathbb{E}_n \sim n \cdot \vartheta(1 - \vartheta) = n \cdot 0.161902...$ 

**Remark.** Ferguson et al. in Ferguson et al. (1992), within the context of the Best-choice Duration Problem, consider a payoff of (n - k + 1)/n and find the above asymptotic values erroneously approximated as 0.20388... and 0.1618....

**Remark.** If we consider  $w_k := 1 - k/n$  and  $p_k = 1/k$ , the problem is equivalent to the secretary problem considering a cost of 1/n for each interview and a payment of 1 for success. The asymptotic values are the same as in the example and can be calculated in another way in Bayón et al. (2018).

#### 4.2. The Best-choice and Minimal Duration Problem

To the best of our knowledge, there is no study in the literature of this problem, which consists in considering in the secretary problem a payment for success equal to the number of interviews carried out. In the terms of this paper, we shall have *n* independent Bernoulli random variables with parameters  $p_k = 1/k$  and payoffs  $w_k = k$ . In this case, it is clear that the problem is monotone (optimal threshold strategy) as  $w_k$  is increasing.

$$\mathbf{s}_n = \max\left\{k : \sum_{j=k}^n \frac{w_j \cdot p_j}{1 - p_j} \ge w_{k-1}\right\} = \max\left\{k : \sum_{j=k}^n \frac{j \cdot \frac{1}{j}}{1 - \frac{1}{j}} \ge k - 1\right\}$$

Denoting by  $\mathbf{H}(k)$  the *k*th harmonic number, we have

$$\sum_{i=k}^{n} \frac{i\frac{1}{i}}{1-\frac{1}{i}} = 1-k+n+(\mathbf{H}(n-1)-\mathbf{H}(k-2)) = 1-k+n+\sum_{k=2}^{n-1} \frac{1}{i}$$
$$\mathbf{s}_{n} = \max\left\{k: 1-k+n+\sum_{k=2}^{n-1} \frac{1}{i} \ge k-1\right\} = \max\left\{k:\sum_{k=2}^{n-1} \frac{1}{i} \ge 2k-n-2\right\}$$

from which it can easily be seen that  $s_n/n$  tends to 1/2 and the asymptotic expected profit is

$$\mathbb{E}_n \sim \frac{n}{4}$$

#### 4.3. n Bernoulli variables with the same parameter $p_k = 1/n$ and $w_k = k$

Let us consider *n* independent Bernoulli random variables with parameters  $p_k = 1/k$  and payoffs  $w_k = k$ . The problem is monotone, as  $w_k$  is increasing.

$$\mathbf{s}_{n} = \max\left\{k : \sum_{j=k}^{n} \frac{(1-k+n) \ (k+n)}{2 \ (-1+n)} \ge k-1\right\}$$
$$\mathbf{s}_{n} = \left\lfloor \frac{3-2 \ n + \sqrt{1+8 \ n^{2}}}{2} \right\rfloor \approx \frac{3}{2} + \left(-1 + \sqrt{2}\right) \ n$$
$$\mathbb{E}_{n} \sim n \left(-1 + \sqrt{2}\right) \ e^{-2+\sqrt{2}} = n \cdot 0.230579...$$

4.4. n Bernoulli variables with the same parameter  $p_k = p$  and  $w_k = n - k + 1$ 

Let us consider *n* independent Bernoulli random variables with parameters  $p_k = p$  and payoffs  $w_k = n - k + 1$ . In this case, the problem is monotone as

$$\mathbb{E}_{\text{Stop}}(k) = (1 - k + n) \ (1 - p)^{-k + n}$$
$$\overline{\mathbb{E}}_{\text{cont}}(k) = \frac{(-1 + k - n) \ (k - n) \ (1 - p)^{-1 - k + n} p}{2}$$

and  $\mathbb{E}_{\text{Stop}}(k) - \overline{\mathbb{E}}_{\text{cont}}(k)$  change sign at the most once. Making

$$\begin{split} \Omega_n &:= \left\{ k : \sum_{j=k}^n \frac{-\left(\left(-2+k-n\right)\left(-1+k-n\right)p\right)}{2\left(-1+p\right)} \ge n-k+2 \right\} \\ \mathbf{s}_n &= \left\{ \max_{j=k}^n \Omega_n, & \text{if } \Omega_n \neq \emptyset; \\ 1, & \text{if } \Omega_n = \emptyset \\ \mathbf{s}_n &= \left\{ \begin{bmatrix} 3+n-\frac{2}{p} \end{bmatrix}, & \text{if } n > \frac{2\left(1-p\right)}{p}; \\ 1, & \text{if } n \le \frac{2\left(1-p\right)}{p} \\ \end{bmatrix} \right\} \end{split}$$

$$\mathbb{E}_{n} = \begin{cases} \frac{(1-p)^{-3+\lfloor 2/p \rfloor} p \ (-2+\lfloor 2/p \rfloor) \ (-1+\lfloor 2/p \rfloor)}{2}, & \text{if } n > \frac{2 \ (1-p)}{p}; \\ \frac{n \ (1+n) \ (1-p)^{-1+n} p}{2}, & \text{if } n \le \frac{2 \ (1-p)}{p}. \end{cases}$$

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