

# Introduction to Probability

Lecture 12: Online Algorithms

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# Outline

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Stopping Problem 1: Dice Game

Stopping Problem 2: The Secretary Problem

A Generalisation: The Odds Algorithm (non-examinable)

The End...

## Introduction: Dice Game



### Dice Game

- We throw a fair, six-sided dice  $n$  times
- After each throw, you can either STOP or CONTINUE
- You win if you STOP at the last 6 within the  $n$  throws

What is the optimal strategy for maximising the probability of winning?

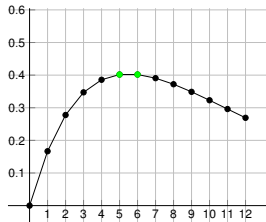
Example ( $n = 10$ )

- 3, 5, 6, 4, 2, 3, 1, 2, 6, 5  $\Rightarrow$  LOSE!  
STOP
- 3, 5, 6, 4, 2, 3, 1, 2, 6, 5  $\Rightarrow$  LOSE!  
STOP
- 3, 5, 6, 4, 2, 3, 1, 2, 6, 5  $\Rightarrow$  WIN!  
STOP

This boils down to finding a threshold from which we STOP as soon as a 6 is thrown.

## Dice Game (Solution)

$$P[\text{obtain exactly one 6 in last } k \text{ throws}] = \binom{k}{1} \cdot \frac{1}{6} \cdot \left(\frac{5}{6}\right)^{k-1} = \frac{k}{6} \cdot \left(\frac{5}{6}\right)^{k-1}$$

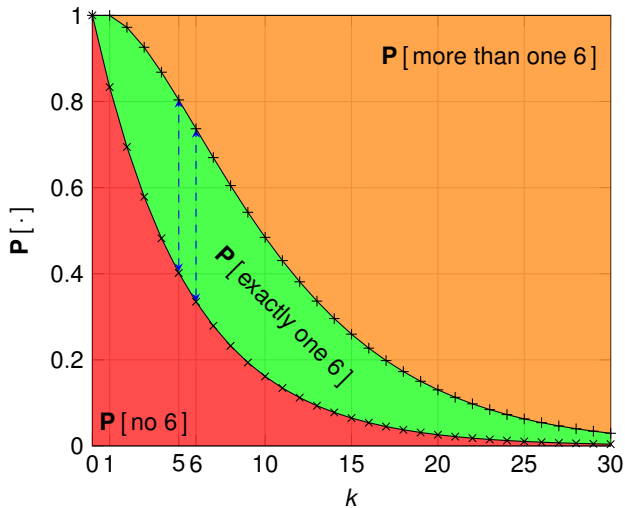


We obtain a **unimodal** distribution

- This is **maximised** for  $k = 6$  (or  $k = 5$ )  $\Rightarrow$  **best strategy**: wait until we have 6 (5) throws left, and then STOP at the first 6
- **Probability of success** is:

$$\left(\frac{5}{6}\right)^5 \approx 0.40.$$

## Illustration of the Three Possibilities



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## The Secretary Problem

### The Problem

- We are interviewing  $n$  candidates for **one job** in a sequential, **random** order
- A candidate must be accepted (STOP) or rejected **immediately** after the interview and cannot be recalled
- **Goal:** **maximise** the probability of hiring the **best** candidate

also known as **marriage problem** (Kepler 1613),  
**hiring problem** or **best choice problem**.

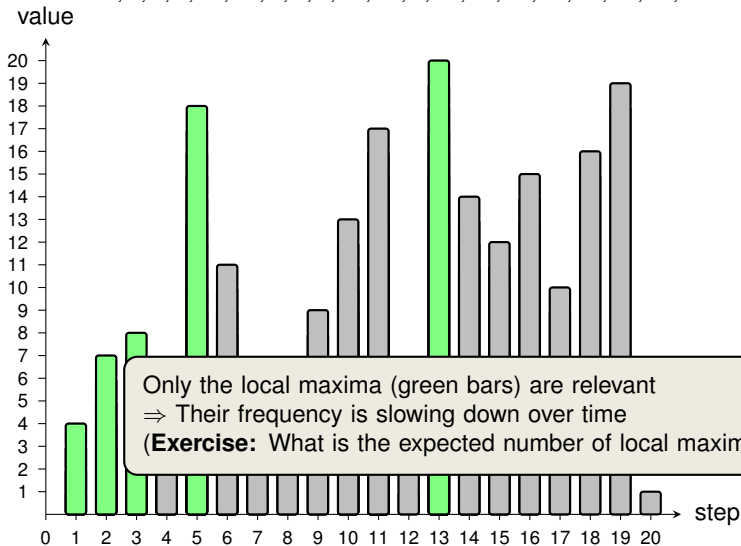
### Further Remarks

- After seeing candidate  $i$ , we only know the **relative order** among the first  $i$  candidates.
- ⇒ For our problem we may as well assume that the only information we have when interviewing candidate  $i$  is whether that candidate is best among  $\{1, \dots, i\}$  or not.

## Illustration ( $n = 20$ )

unknown permutation:

4, 7, 8, 6, 18, 11, 3, 5, 9, 13, 17, 2, 20, 14, 12, 15, 10, 16, 19, 1.



## Two Basic Strategies

### Naive Approach

- Always pick the **first** (or any other) candidate
- Probability for success is:

$$P[\text{hire best candidate}] = \frac{1}{n}.$$

A typical **exploration-exploitation** based strategy.

### Smarter Approach

- Reject the first  $n/2$  candidates, then take the first candidate that is better than the first  $n/2$  (if none is taken before, take last candidate)

How good is this approach?

## Analysis of the Refined Approach

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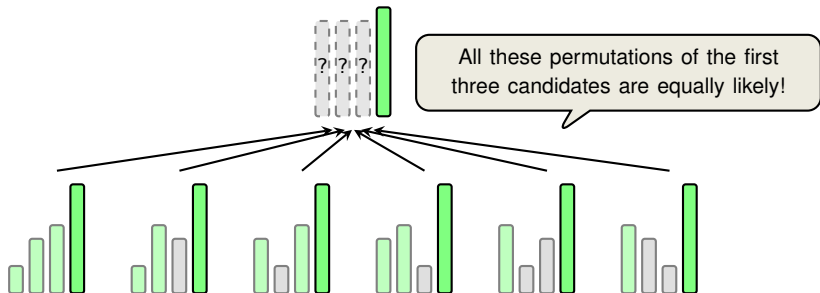
### Example 1

Find a lower bound on the success probability of the refined approach (picking the first candidate better than the first  $n/2$ ).

Answer \_\_\_\_\_

## Finding the Optimal Strategy (1/2)

- **Observation 1:** At interview  $i$ , it only matters if current candidate is best so far (i.e., no benefit in counting how many “best-so-far” candidates we had).



- **Observation 2:** If at interview  $i$ , the best strategy is to accept the candidate (if it is “best-so-far”), then the same holds for interview  $i + 1$

Optimal Strategy

- **Explore** but reject the first  $x - 1$  candidates
- **Accept** first candidate  $i \geq x$  which is better than **all candidates before**

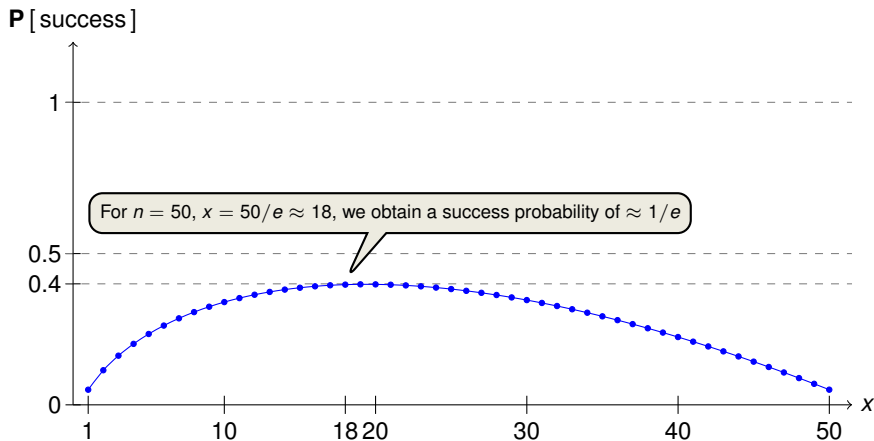
## Example 2

Find  $x$  which maximises the probability of hiring the best candidate.

Answer

## Probability for Success (Illustration)

Suppose  $n = 50$ :



## Another Variant of the Secretary Problem

“The Postdoc Variant of the Secretary Problem” (Vanderbei’80)

- same setup as in the secretary problem before
- **difference**: we want to pick the **second-best** (“the best [postdoc] is going to Harvard”)
- Success probability of the optimal strategy is:

$$\frac{0.25n^2}{n(n-1)} \xrightarrow{n \rightarrow \infty} \frac{1}{4}$$

- Thus it is **easier** to pick the best than the second-best(!)

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## Details of the Odds Algorithm

- Let  $I_1, I_2, \dots, I_n$  be a sequence of **independent** indicators and let  $p_j = \mathbf{E}[I_j]$
- Let  $r_j := \frac{p_j}{1-p_j}$  (**the odds**) and  $p_j \in (0, 1)$  for all  $j = 1, 2, \dots, n$

### Example 3

What is the probability that after trial  $k$ , there is exactly one success?

Answer

$$\mathbf{P} \left[ \sum_{j=k}^n I_j = 1 \right] = \sum_{j=k}^n p_j \cdot \prod_{k \leq j \leq n, j \neq i} (1 - p_i) = \sum_{j=k}^n r_j \cdot \left( \prod_{i=k}^n (1 - p_i) \right)$$

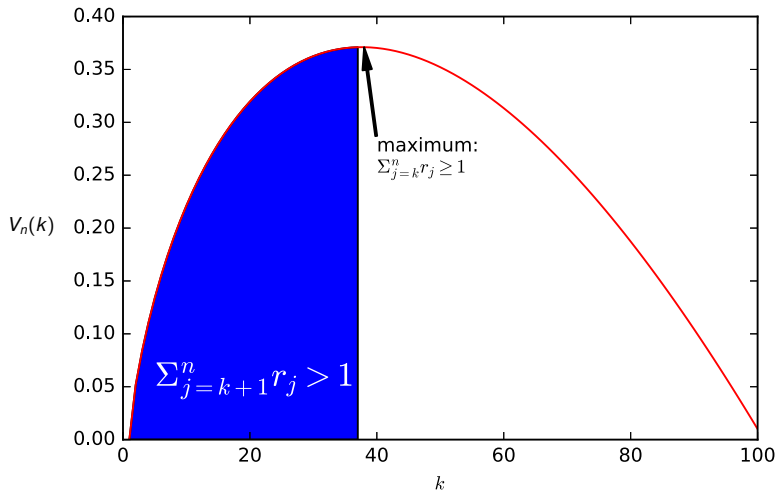
- One can prove that  $\mathbf{P} \left[ \sum_{j=k}^n I_j = 1 \right]$  is **unimodal** in  $k \Rightarrow$  there is an **ideal point** from which on we should **STOP at the first success!**

**Odds Algorithm** ("Sum the Odds to One and Stop", F. Thomas Bruss, 2000)

- Let  $k^*$  be the largest  $k$  such that  $\sum_{j=k}^n r_j \geq 1$
- Ignore** everything before the  $k^*$ -th trial, then **STOP** at the **first** success.

- The **success probability** is  $\sum_{j=k^*}^n r_j \cdot \left( \prod_{i=k^*}^n (1 - p_i) \right)$ .
- This algorithm always executes the **optimal strategy!**

## Illustration of the probability of having the last success ( $n = 100$ )



Source: Group Fibonacci

## Example 4

Use the **Odds Algorithm** to analyse the **Secretary Problem**.

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Answer

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- **Part I: Introduction to Probability**

- **Lecture 1:** Conditional probabilities and Bayes' theorem

- **Part II: Random Variables**

- **Lecture 2:** Random variables, probability mass function, expectation
- **Lecture 3:** Expectation properties, variance, discrete distributions
- **Lecture 4:** More discrete distributions: Poisson, Geometric, Negative Binomial
- **Lecture 5:** Continuous random variables
- **Lecture 6:** Marginals and Joint Distributions
- **Lecture 7:** Independence, Covariance and Correlation

- **Part III: Moments and Limit Theorems**

- **Lecture 8:** Basic Inequalities and Law of Large Numbers
- **Lecture 9:** Central Limit Theorem

- **Part IV: Applications and Statistics**

- **Lecture 10:** Estimators (Part I)
- **Lecture 11:** Estimators (Part II)
- **Lecture 12:** Online Algorithms

## List of Distributions

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### Very Important:

- Bernoulli, Binomial, Poisson
- (Continuous) Uniform, Normal, Exponential

### (Somewhat Less) Important:

- Geometric, Negative Binomial, Hypergeometric, Discrete Uniform

### Not used or not defined in this course (and thus not examinable):

- Cauchy, Gamma, bivariate Normal
- Beta

Thank you and Best Wishes for the Exam!