

Lecture 13

Lect. PhD.
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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Problem solving methods

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Overview

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- 1 Divide and conquer
- 2 Backtracking
 - Introduction
 - Generate and test
 - Backtracking
 - Recursive and iterative
- 3 Greedy
- 4 Dynamic programming
 - Longest increasing subsequence
 - Egg dropping puzzle
- 5 Dynamic programming vs. Greedy
 - This course in numbers

Problem solving methods

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- Strategies for solving more difficult problems, or general algorithms for solving certain types of problems
- A problem may be solved using more than one method - you have to select the most efficient one
- In order to apply one of the methods described here, the problem needs to satisfy certain required criteria

Divide and conquer - steps

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and conquer

Backtracking

Introduction
Generate and test

Backtracking
Recursive and iterative

Greedy

Dynamic programming

Longest increasing subsequence

Egg dropping puzzle

Dynamic programming vs. Greedy

This course in numbers

- **Divide** - divide the problem (instance) into smaller problems of the same structure
 - Divide the problem into two or more disjoint sub problems that can be resolved using the same algorithm
 - In many cases, there are more than one way of doing this
- **Conquer** - resolve the sub problems recursively
- **Combine** - combine the problems results

Remember

Typical problems for divide & Conquer

Divide and conquer - general

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

```
def divideAndConquer(data):  
    if size(data)<a:  
        #solve the problem directly  
        #base case  
        return rez  
    #decompose data into d1,d2,...,dk  
    rez_1 = divideAndConquer(d1)  
    rez_2 = divideAndConquer(d2)  
    ...  
    rez_k = divideAndConquer(dk)  
    #combine the results  
    return combine(rez_1,rez_2,...,rez_k)
```

Divide and conquer - general

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and conquer

Backtracking

Introduction
Generate and test

Backtracking
Recursive and iterative

Greedy

Dynamic programming

Longest increasing subsequence
Egg dropping puzzle

Dynamic programming vs. Greedy

This course in numbers

When can divide & conquer be applied?

- A problem P on the data set D may be solved by solving the same problem P on other data sets, d_1, d_2, \dots, d_k , of a size smaller than the size of D .

The running time for solving problems in this manner may be described using recurrences.

$$T(n) = \begin{cases} \text{solve trivial problem, } n \text{ small enough} \\ k * T(\frac{n}{k}) + \text{divide time} + \text{combine time, otherwise} \end{cases}$$

Step 1 - Divide

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and conquer

Backtracking

Introduction
Generate and test

Backtracking
Recursive and iterative

Greedy

Dynamic programming

Longest increasing subsequence
Egg dropping puzzle

Dynamic programming vs. Greedy

This course in numbers

- Simplest way: divide the data into 2 parts (*chip and conquer*): data of size 1 and data of size $n-1$
- Example: Find the maximum

```
def findMax(data):  
    '''  
        Find the greatest element in the list  
        input:  
        data - list of elements  
        Returns the maximum  
    '''  
    if len(data) == 1:  
        return data[0]  
    # Divide into 1 + (n-1) subproblems  
    max = findMax(data[1:])  
    # Combine  
    if max > data[0]:  
        return max  
    return data[0]
```

Step 1 - Divide

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic programming vs. Greedy

This course in
numbers

■ The recurrence is: $T(n) = \begin{cases} 1, n = 1 \\ T(n-1) + 1, \text{otherwise} \end{cases}$

$$T(n) = T(n-1) + 1,$$

$$T(n-1) = T(n-2) + 1,$$

$$T(n-2) = T(n-3) + 1, \text{ so}$$

$$T(n) = 1 + 1 + 1 + \dots + 1 = n, T(n) \in \theta(n)$$

Step 1 - Divide

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and conquer

Backtracking

Introduction
Generate and test

Backtracking
Recursive and iterative

Greedy

Dynamic programming

Longest increasing subsequence
Egg dropping puzzle

Dynamic programming vs. Greedy

This course in numbers

- Divide into k data of size n/k

```
def findMax(data):  
    ...  
    if len(data) == 1:  
        return data[0]  
    # Divide into 2 * n/2  
    mid = len(data) // 2  
    maxLeft = findMax(data[:mid])  
    maxRight = findMax(data[mid:])  
    # Combine  
    return max(maxLeft, maxRight)
```

Step 1 - Divide

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and conquer

Backtracking

Introduction
Generate and test

Backtracking
Recursive and iterative

Greedy

Dynamic programming

Longest increasing subsequence

Egg dropping puzzle

Dynamic programming vs. Greedy

This course in numbers

■ The recurrence is: $T(n) = \begin{cases} 1, n = 1 \\ 2 * T(\frac{n}{2}) + 1, \text{otherwise} \end{cases}$

$$T(2^k) = 2 * T(2^{k-1}) + 1$$

$$2 * T(2^{k-1}) = 2^2 * T(2^{k-2}) + 2$$

$$2^2 * T(2^{k-2}) = 2^3 * T(2^{k-3}) + 2^2$$

If we denote $n = 2^k$, then $k = \log_2 n$ and $T(n) =$

$$1 + 2^1 + 2^2 + 2^3 + \dots + 2^k = \frac{2^{k+1} - 1}{2 - 1} = 2^{k+1} - 1 = 2n \in \Theta(n)$$

Divide and conquer - Example

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and conquer

Backtracking

Introduction
Generate and test
Backtracking
Recursive and iterative

Greedy

Dynamic programming

Longest increasing subsequence
Egg dropping puzzle

Dynamic programming vs. Greedy

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- Compute x^k , where $k \geq 1$ is an integer
- Simple approach: $x^k = x * x * \dots * x$, $k-1$ multiplications.
Time complexity?
- Divide and conquer approach

$$x^k = \begin{cases} x^{\frac{k}{2}} * x^{\frac{k}{2}}, & k \text{ is even} \\ x^{\frac{k}{2}} * x^{\frac{k}{2}} * x, & k \text{ is odd} \end{cases}$$

Divide and conquer - Example

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and conquer

Backtracking

Introduction
Generate and test

Backtracking
Recursive and iterative

Greedy

Dynamic programming

Longest increasing subsequence
Egg dropping puzzle

Dynamic programming vs. Greedy

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```
def power(x, k):  
    ...  
    if k == 0:  
        return 1  
    if k == 1:  
        return x  
    # Divide  
    aux = power(x, k // 2)  
    # Conquer  
    if k % 2 == 0:  
        return aux * aux  
    else:  
        return aux * aux * x
```

Divide and conquer - applications

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- Binary-Search ($T(n) \in \theta(\log_2 n)$)
 - Divide - compute the middle of the list
 - Conquer - search on the left or for the right
 - Combine - nothing
- Quick-Sort ($T(n) \in \theta(n * \log_2 n)$)
 - Divide - partition the array into 2 subarrays
 - Conquer - sort the subarrays
 - Combine - nothing
- Merge-Sort ($T(n) \in \theta(n * \log_2 n)$)
 - Divide - divide the list into 2
 - Conquer - sort recursively the 2 list
 - Combine - merge the sorted lists

Backtracking

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

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- Applicable to search problems with more solutions
- Generates all the solutions, if they exist
- Does a depth-first search through all possibilities that can lead to a solution
- A general algorithm/technique - must be customized for each individual application.

Remember

Backtracking usually has exponential complexity

Generate and test

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction

**Generate and
test**

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

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numbers

- **Problem.** Let n be a natural number. Print all permutations of numbers $1, 2, \dots, n$.
- First solution - **generate & test** - generate all possible solutions and verify if they represent a solution

NB!

This is **not** backtracking

Generate and test - iterative

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction

Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

<pre>def perm3(): for i in range(0,3): for j in range(0,3): for k in range(0,3): #a possible solution possibleSol = [i,j,k] if i!=j and j!=k and i!=k: #is a solution print possibleSol</pre>	<pre>[0, 1, 2] [0, 2, 1] [1, 0, 2] [1, 2, 0] [2, 0, 1] [2, 1, 0]</pre>
---	--

NB!

This is **not** backtracking

Generate and test - recursive

- Generate and test recursive - using recursion to generate all the possible list (candidate solutions)

```
def generate(x, DIM):  
    if len(x) == DIM:  
        print(x)  
    if len(x) > DIM:  
        return  
    x.append(0)  
    for i in range(0, DIM):  
        x[-1] = i  
        generate(x[:], DIM)  
  
print(generate([], 3))
```

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction

Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Generate and test

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction

**Generate and
test**

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

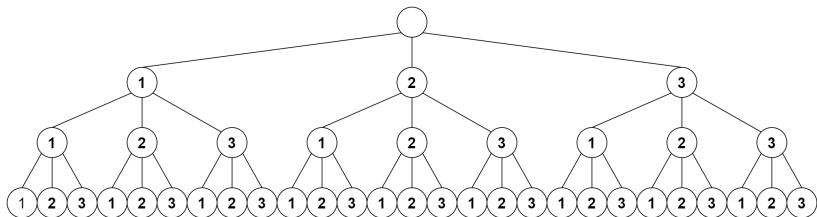
Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

■ Generate and test - all possible combinations



Generate and test

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
**Generate and
test**

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

What have we learned?

- The total number of checked arrays is 3^3 , and in the general case n^n
- First the algorithm assigns values to all components of the array possible, and only afterwards checks whether the array is a permutation
- Implementation above is not general. Only works for $n=3$

Generate and test

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- In general: if n is the depth of the tree (the number of variables in a solution) and assuming that each variable has k possible values, the number of nodes in the tree is k^n . This means that searching the entire tree leads to an exponential time complexity - $O(k^n)$

Generate and test

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
**Generate and
test**

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Possible improvements

- Do not construct a complete array in case it cannot lead to a correct solution.
- e.g - if the first component of the array is 1, then it is useless to assign other components the value 1
- Work with a potential array (a partial solution)
- When we expand the partial solution verify some conditions (conditions to continue) - so the array does not contains duplicates

Backtracking

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Test candidates - print only solutions

```
def generateAndTest(x, DIM):  
    if len(x) == DIM and isSet(x):  
        print(x)  
    if len(x) > DIM:  
        return  
    x.append(0)  
    for i in range(0, DIM):  
        x[-1] = i  
        generateAndTest(x[:], DIM)  
  
generateAndTest([], 3)
```

- We still generate all possible lists (e.g. starting with 0,0,...)
- We should not explore lists that contains duplicates (they cannot result in valid permutations)

Backtracking

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- Recursive backtracking implementation for permutations

```
def backtracking(x, DIM):  
    if len(x) == DIM:  
        print(x)  
    if len(x) > DIM: return  
    x.append(0)  
    for i in range(0, DIM):  
        x[-1] = i  
        if isSet(x):  
            # Continue only if we  
            # can reach a solution  
            backtracking(x[:], DIM)  
  
backtracking([], 4)
```

Demo

Lecture 13

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Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Backtracking

Example illustrating exponential runtimes are in
ex34_backtracking.py

Backtracking - Typical problem statements

Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- **Permutations** - Generate all permutations for a given natural number n
 - result: $x = (x_0, x_1, \dots, x_n), x_i \in (0, 1, \dots, n-1)$
 - is valid: $x_i \neq x_j$, for any $i \neq j$
- **n-Queen problem** - place n queens on a chess-like board such that no two queens are under reciprocal threat.
 - result: position of the queens on the chess board
 - is valid: no queens attack each other (not on the same row or column)
 - if $n=8$, number of combinations is over 4.5×10^9

Backtracking - Theoretical support

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Backtracking

The key to many problems that can be solved with backtracking lays in correctly and efficiently representing the elements in the search space

Backtracking - Theoretical support

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- Solutions search space: $S = S_1 \times S_2 \times \dots \times S_n$
- x is the array which represents the solutions
- $x[1..k]$ in $S_1 \times S_2 \times \dots \times S_k$ is the sub-array of solution candidates; it may or may not lead to a solution
- **consistent** - function to verify if a candidate can lead to a solution
- **solution** - function to check whether the potential array $x[1..k]$ is a solution of the problem.

Backtracking recursive

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

```
def backtrackingRec(x):  
    # Add component to candidate  
    x.append(0)  
    for i in range(0, DIM):  
        # Set current component  
        x[-1] = i  
        if consistent(x):  
            if solution(x):  
                solutionFound(x)  
            # Deal with next components  
            backtrackingRec(x[:])
```

Backtracking - recursive

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

More generally, when solution components do not have the same domain:

```
def backtrackingRec(x):  
    # Add component to candidate  
    el = first(x)  
    x.append(el)  
    while el != None:  
        # Set current component  
        x[-1] = el  
        if consistent(x):  
            if solution(x):  
                solutionFound(x)  
            # Deal with next components  
            backtrackingRec(x[:])  
        el = next(x)
```

Backtracking

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test
Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

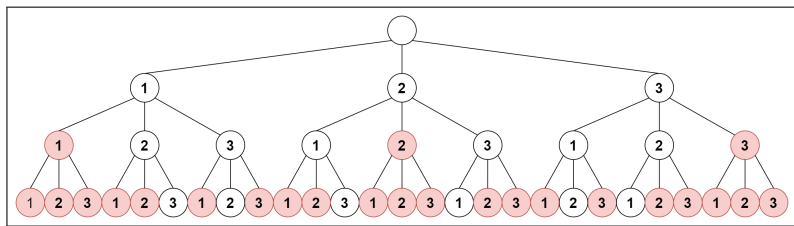
Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

The nodes explored with backtracking for the permutations of 3



Backtracking

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- How to use backtracking
- Represent the solution as a vector
$$X = (x_0, x_1, \dots, x_n) \in S_0 \times S_1 \times \dots \times S_n$$
- Define what a valid solution candidate is (conditions filter out candidates that will not conduct to a solution)
- Define condition for a candidate to be a solution

Greedy

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

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numbers

- A strategy to solve optimization problems.
- Applicable where the global optima may be found by successive selections of local optima.
- Allows solving problems without returning to previous decisions.
- Useful in solving many practical problems that require the selection of a set of elements that satisfies certain conditions (properties) and realizes an optimum.
- Disadvantages: Short-sighted and non-recoverable.

Greedy - Sample Problems

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

The knapsack problem

- A set of objects is given, characterized by usefulness and weight, and a knapsack able to support a total weight of W . We are required to place in the knapsack some of the objects, such that the total weight of the objects is not larger than the given value W , and the objects should be as useful as possible (the sum of the utility values is maximal).

The coins problem

- Let us consider that we have a sum M of money and coins (ex: 1, 5, 25) units (an unlimited number of coins). The problem is to establish a modality to pay the sum M using a minimum number of coins

Greedy - General case

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- Let us consider the given set C of candidates to the solution of a given problem P . We are required to provide a subset $B, (B \subseteq C)$ to fulfill certain conditions (called internal conditions) and to maximize (minimize) a certain objective function.

Greedy - General case

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- If a subset X fulfills the internal conditions we will say that the subset X is acceptable (possible).
- Some problems may have more acceptable solutions, and in such a case we are required to provide as good a solution as we may get, possibly even the better one, i.e. the solution that realizes the maximum (minimum) of a certain objective function.

Greedy - General case

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

In order for a problem to be solvable using the Greedy method, it should satisfy the following property:

- If B is an acceptable solution and $X \subseteq B$ then X is as well an acceptable solution.

Greedy - General case

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- The Greedy algorithm finds the solution in an incremental way, by building acceptable solutions, extended continuously. At each step, the solution is extended with the best candidate from $C - B$ at that given moment. For this reason, this method is named greedy.
- The Greedy principle (strategy) is
 - Successively incorporate elements that realize the local optimum
 - No second thoughts are allowed on already made decisions with respect to the past choices.

Greedy - General case

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Assuming that θ (the empty set) is an acceptable solution, we will construct set B by initializing B with the empty set and successively adding elements from C .

- The choice of an element from C , with the purpose of enriching the acceptable solution B , is realized with the purpose of achieving an optimum for that particular moment, and this, by itself, does not generally guarantee the global optimum.

Greedy - General case

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- If we have discovered a selection rule to help us reach the global optimum, then we may safely use the Greedy method.
- There are situations in which the completeness requirements (obtaining the optimal solution) are abandoned in order to determine an "almost" optimal solution, but in a shorter time.

Greedy - General case

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Greedy technique

- Renounces the backtracking mechanism.
- Offers a single solution (unlike backtracking, that provides all the possible solutions of a problem).
- Provides polynomial running time.

Greedy - General code

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

```
def greedy(c):  
    ''' ... '''  
  
    # The empty set is the candidate solution  
    b = []  
  
    while not solution(b) and c != []:  
        # Select best candidate (local optimum)  
        candidate = selectMostPromising(c)  
        c.remove(candidate)  
        # If the candidate is acceptable, add it  
        if acceptable(b + [candidate]):  
            b.append(candidate)  
  
    if solution(b):  
        solutionFound(b)  
    # In case no solution  
    return None
```

Greedy - General code (explanation)

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

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numbers

- **c** - The list of candidates
- **selectMostPromising()** - Function that returns the most promising candidate
- **acceptable()** - Function that decides if the candidate solution can be extended
- **solution()** - Function verifies if a candidate represents a solution

Greedy - Essential elements

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

More generally, the required elements are:

- 1 A **candidate set**, from which a solution is created.
- 2 A **selection function**, which chooses the best candidate to be added to the solution.
- 3 A **feasibility function**, that is used to determine if a candidate can be used to contribute to a solution.
- 4 An **objective function**, which assigns a value to a solution, or a partial solution.
- 5 A **solution function**, which will indicate when we have discovered a complete solution.

Greedy - The coins problem

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Divide and
conquer

Backtracking

Introduction

Generate and
test

Backtracking

Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- Let us consider that we have a sum M of money and coins (ex: 1, 5, 25) units (an unlimited number of coins). The problem is to establish a modality to pay the sum M using a minimum number of coins.

Greedy - Coins problem solution

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- **Candidate set** - the list of coin denominations (e.g. 1, 5, 10 bani).
- **Candidate solution** - a list of selected coins
- **Selection function** - choose the coin with the biggest value less than the remainder sum
- **Acceptable** - the total sum paid does not exceed the required sum
- **Solution function** - the paid sum is exactly the required sum

Demo

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Greedy

The source code for the coins problem can be found in
ex35_coins.py

Greedy - Remarks

Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

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numbers

- Before applying Greedy, it is required to prove that it provides the optimal solution. Often, the proof of applicability is non-trivial.
- Greedy leads to polynomial run time. Usually, if the cardinality of the set C of candidates is n , Greedy algorithms have $O(n^2)$ time complexity.

Greedy - Remarks

Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- There are a lot of problems that can be solved using Greedy, such as determining the shortest path between two nodes in an undirected or directed graph (Dijkstra's and Bellman-Kalaba's algorithms).
- There are problems for which Greedy algorithms do not provide optimal solution. In some cases, it is preferable to obtain a close to optimal solution in polynomial time, instead of the optimal solution in exponential time - these are known as *heuristic algorithms*.

Greedy example - Interval scheduling

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

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- You want to schedule a number of jobs on a computer
- Jobs have the same value, and are characterized by their start and finish times, namely (s_i, f_i) (the start and finish times for job "i")
- Run as many jobs as possible, making sure no two jobs overlap

Greedy example - Interval scheduling

Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

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numbers

- A Greedy implementation will directly select the next job to schedule, using some criteria
- The crucial question for solving the problem - **how to determine the correct criteria?**

Source

This example, like many others can be found in "Algorithm Design", by Kleinberg & Tardos

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Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Some ideas for selecting the next job

- **The job that starts earliest** - the idea being that you start using the computer as soon as possible
- **The shortest job** - the idea is to fit in as many jobs as possible
- **The job that overlaps the smallest number of jobs remaining** - we keep our options open
- **The job that finishes earliest** - we free up the computer as soon as possible

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Lecture 13

Lect. PhD.
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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Ideas that **don't** work:

- The job that starts earliest
- The shortest job
- The job that overlaps the smallest number of jobs remaining

Greedy example - Interval scheduling

Lecture 13

Lect. PhD.
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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

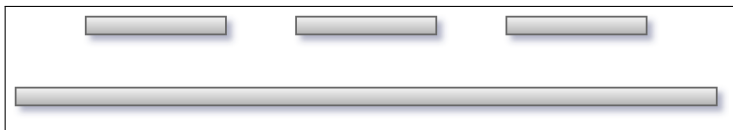
Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Ideas that **don't** work:

- The job that starts earliest



- The shortest job
- The job that overlaps the smallest number of jobs remaining

Greedy example - Interval scheduling

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

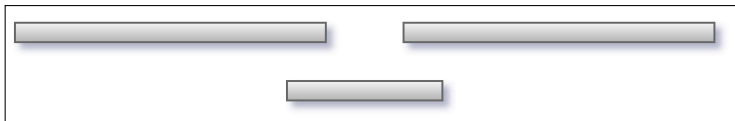
Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Ideas that **don't** work:

- The job that starts earliest
- The shortest job



- The job that overlaps the smallest number of jobs remaining

Greedy example - Interval scheduling

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

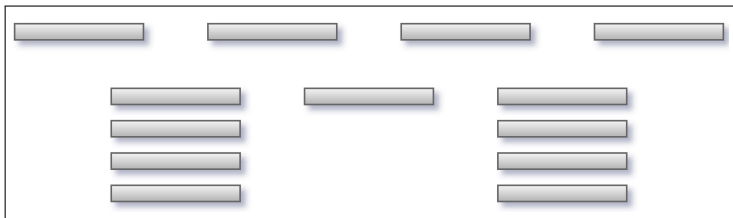
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Ideas that **don't** work:

- The job that starts earliest
- The shortest job
- The job that overlaps the smallest number of jobs remaining



Greedy example - Interval scheduling

Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

An idea that **works** - Start the job that finishes earliest

S = set of jobs

while S is not empty:

next_job = the job that has the
soonest finishing time

add next_job to solution

remove from S jobs that overlap **q**

NB!

Proving this is done using mathematical induction, but it is beyond our scope.

Further learning resources

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Further resources

[http:
//www.cs.princeton.edu/~wayne/kleinberg-tardos/](http://www.cs.princeton.edu/~wayne/kleinberg-tardos/)

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Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Applicable in solving optimality problems where:

- The solution is the result of a sequence of decisions, d_1, d_2, \dots, d_n .
- The principle of optimality holds.

Dynamic programming:

- Usually leads to polynomial run time.
- Always provides the optimal solution (unlike Greedy).
- Like divide & conquer it solves problems by combining sub solutions, but, unlike d&c, calculates only once a sub solution, by storing the intermediate results.

Dynamic programming

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

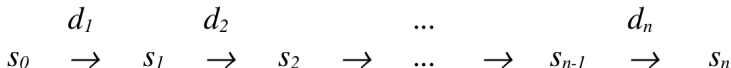
Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- We consider states $s_0, s_1, \dots, s_{n-1}, s_n$, where s_0 is the initial state, and s_n is the final state, obtained by successively applying the sequence of decisions d_1, d_2, \dots, d_n (using the decision d_i we pass from state s_{i-1} to state s_i , for $i=1, n$):



Dynamic programming

Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

The method makes use of three main concepts:

- Optimality principle
- Overlapping sub problems
- Memoization.

Dynamic programming - Optimality principle

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

If d_1, d_2, \dots, d_n is a sequence of decisions that optimally leads a system from the state s_0 to s_n , then one of the following conditions has to be satisfied:

- d_k, d_{k+1}, \dots, d_n is a sequence of decisions that optimally leads the system from state s_{k-1} to state s_n ,
 $\forall k, 1 \leq k \leq n$ (**forward variant**)
- d_1, d_2, \dots, d_k is a sequence of decisions that optimally leads the system from state s_0 to the state s_k , $\forall k, 1 \leq k \leq n$
(**backward variant**)
- $d_{k+1}, d_{k+2}, \dots, d_n$ and d_1, d_2, \dots, d_k are sequences of decisions that optimally lead the system from state s_k to state s_n and, respectively, from state s_0 to state s_k ,
 $\forall k, 1 \leq k \leq n$ (**mixed variant**)

Dynamic programming - Overlapping sub-problems, memoization

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- **Overlapping sub-problems** - A problem is said to have overlapping sub-problems if it can be broken down into sub-problems which are reused multiple times
- **Memorization** - Store the solutions to the sub-problems for later use

Dynamic programming - Requirements

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- The principle of optimality (in one of its form: forward, backward or mixed) is proven.
- The structure of the optimal solution is defined.
- Based on the principle of optimality, the value of the optimal solution is recursively defined. This means that recurrent relations, indicating the way to obtain the general optimum from partial optima, are defined.
- The value of the optimal solution is computed in a bottom-up manner, starting from the smallest cases for which the value of the solution is known.

Dynamic programming - Longest increasing subsequence

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Problem statement

Let us consider the list a_1, a_2, \dots, a_n . Determine the longest increasing subsequence $a_{i_1}, a_{i_2}, \dots, a_{i_s}$ of list a .

e.g. given sequence $[0, 8, 4, 12, 2, 10, 6, 14, 1, 9, 5, 13, 3, 11, 7, 15]$, a longest increasing subsequence is $[0, 2, 6, 9, 11, 15]$.

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Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- **Optimality principle** - verified in its forward variant.
- **Structure** of the optimal solution - we construct sequences: $L = \langle L_1, L_2, \dots, L_n \rangle$ so that for each $1 \leq i \leq n$ we have that L_i is the length of the longest increasing subsequence ending at i .
- The recursive definition for the value of the optimal solution:
 - $L_i = \max\{1 + L_j \mid A_j \leq A_i\}$, so that $A_j \leq A_i\}$, $\forall j = i - 1, n - 2, \dots, 1$

Demo

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Longest Increasing Subsequence

Examine the source code in
`ex36_longestIncreasingSubsequence.py`

Dynamic programming - Egg dropping puzzle

Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Problem statement

Suppose you have a number of n eggs and a building having k floors. Using a minimum number of drops, determine the lowest floor from which dropping an egg breaks it.

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Rules:

- All eggs are equivalent.
- An egg that survives a drop is unharmed and reusable.
- A broken egg cannot be reused.
- If an egg breaks when dropped from a given floor, it will also break when dropped from a higher floor.
- If an egg does not break when released from a given floor, it can be safely dropped from a lower floor.
- You cannot assume that dropping eggs from the first floor is safe, nor that dropping from the last floor is not.

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

**Egg dropping
puzzle**

Dynamic
programming
vs. Greedy

This course in
numbers

The problem is about finding the correct strategy to improve the worst case outcome - make sure that the **maximum** number of drops is kept to a minimum (a.k.a minimization of maximum regret).

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Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Let's start with the simplest case...

- Building has **k** floors, and we have **$n=1$** egg.

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

What do we do in the $n=1$ case?

- Drop the egg at each floor until it breaks or you've reached the top, starting from first (ground) floor.
- In this case, the maximum number of drops is equal to k , the number of floors the building has.

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Lecture 13

Lect. PhD.
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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

So, how about if we have more eggs?

- Building has k floors, but now we have $n=2$ eggs.

Discussion

How do we keep the maximum number of drops to a minimum?

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Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Possible strategies for the $n=2$ case...

- 1 The $n=1$ case was basically linear search, so we can try binary search with the first egg (drop it from the mid-level floor).
- 2 How about dropping from every 20th floor, starting from ground level?

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Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Let's try to describe the situation in a structured way...

- Imagine we drop the first egg at a given floor m .
- If it breaks, we have a maximum of $(m-1)$ drops, starting from ground.
- If it does not break, we increase by $(m-1)$ floors, as we have one less drop.
- Following the same logic, at each step we decrease the number of floors by 1.

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Lecture 13

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

So, if we have **n=2** eggs and **k=100** floors?

- We solve

$$n + (n - 1) + (n - 2) + (n - 3) + (n - 4) + \dots + 1 \geq 100$$

- Solution is between 13 and 14, which we round to **14**.
First drop is from floor 14

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Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Egg drops for **$n=2$** eggs and **$k=100$** floors...

Drop #	1	2	3	4	5	6	7	8	9	10	11	12
Floor	14	27	39	50	60	69	77	84	90	95	99	100

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Lecture 13

Lect. PhD.
Arthur Molnar

Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

Now for the general case - building has k floors, and we have n eggs.

- **Optimal substructure** - Dropping an egg from floor x might result in two cases (subproblems):
 - 1 **Egg breaks** - Problem is reduced to one with $x-1$ floors and one less eggs.
 - 2 **Egg is ok** - Problem is reduced to one with $k-x$ floors and same number of eggs.

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Lecture 13

Lect. PhD.
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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- **Overlapping subproblems** - Let's create function **eggDrop(n, k)**, where **n** is the number of eggs and **k** the number of floors.
- **eggDrop(n, k) = 1 + min{max(eggDrop(n - 1, x - 1), eggDrop(n, k - x))}**, with $1 \leq x \leq k$

Demo

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence

**Egg dropping
puzzle**

Dynamic
programming
vs. Greedy

This course in
numbers

Egg dropping puzzle

Full source code available in **ex37_eggDroppingPuzzle.py**

Dynamic programming vs. Greedy - Remarks

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Divide and
conquer

Backtracking

Introduction
Generate and
test

Backtracking
Recursive and
iterative

Greedy

Dynamic
programming

Longest
increasing
subsequence
Egg dropping
puzzle

Dynamic
programming
vs. Greedy

This course in
numbers

- Both techniques are applied in optimization problems
- Greedy is applicable to problems for which the general optimum is obtained from partial (local) optima
- Dynamic programming is applicable to problems in which the general optimum implies partial optima.

Dynamic programming vs. Greedy - An example

Lecture 13

Lect. PhD.
Arthur Molnar

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Problem statement

Let us consider the problem to determine the optimal path between two vertices i and j of a graph.

What we notice:

- The principle of optimality is verified: if the path from i to j is optimal and it passes through node x , then the paths from i to x , and from x to j are also optimal.
- Can we apply Greedy? - if the paths from i to x , and from x to j are optimal, there is no guarantee that the path from i to j that passes through x is also optimal

Dynamic programming vs. Greedy - Remarks

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- The fact that the general optimum implies partial optima, does not mean that partial optima also implies the general optimum (the example before is relevant).
- The fact that the general optimum implies partial optima is very useful, because we will search for the general optimum among the partial optima, which are stored at each moment. Anyway, the search is considerably reduced.

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A few (fun) stats...

- 503 lecture slides (including this one)¹.
- 98 images, 5500 lines of Latex source code.
- 37 examples supporting the lecture notes, 3400 lines of Python code + 1200 lines of comments.
- 2300 Python lines of code in seminars, 460 lines of comments²

¹Obligatory xkcd reference <http://xkcd.com/688/>

²Stats obtained using cloc - <https://github.com/AlDanial/cloc>