Algorithms: A Brief Introduction

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Introduction to Discrete Mathematics
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Real World	**Computing World**
Objects	Data Structures, ADTs, Classes
Relations	Relations and functions
Actions	Operations

Problems are specified by (1) a formulation and (2) a query.

Formulation is a set of objects and a set of relations between them

Query is the information one is trying to extract from the formulation, the question to answer.

Algorithms[1] are methods or procedures that solve instances of a problem

[1] "Algorithm" is a distortion of *al-Khwarizmi*, a Persian mathematician

Definition

An **algorithm** is a sequences of unambiguous instructions for solving a problem. Algorithms must be

- Finite – must eventually *terminate*.
- Complete – *always* gives a solution when there is one.
- Correct (sound) – *always* gives a "correct" solution.

For an algorithm to be an acceptable solution to a problem, it must also be *effective*. That is, it must give a solution in a "reasonable" amount of time.

There can be many algorithms for the same problem.

There are many broad categories of Algorithms: Randomized algorithms, Monte-Carlo algorithms, Approximation algorithms, Parallel algorithms, et al.

Usually, algorithms are studied corresponding to relevant data structures. Some general *styles* of algorithms include

1. Brute Force (enumerative techniques, exhaustive search)
2. Divide & Conquer
3. Transform & Conquer (reformulation)
4. Greedy Techniques

Pseudo-code

Algorithms are usually presented using some form of *pseudo-code*. Good pseudo-code is a balance between clarity and detail.

Bad pseudo-code gives too many details or is too implementation specific (i.e. actual `C++` or Java code or giving every step of a sub-process).

Good pseudo-code abstracts the algorithm, makes good use of mathematical notation and is easy to read.

Good Pseudo-code

Example

Intersection

INPUT : Two sets of integers, A and B

OUTPUT : A set of integers C such that $C = A \cap B$

```
C ← ∅
IF |A| > |B| THEN
    swap(A, B)
END
FOR every x ∈ A DO
    IF x ∈ B THEN
        C ← C ∪ {x}
    END
END
output C
```

Latex notation: \leftarrow.

Designing An Algorithm

A general approach to designing algorithms is as follows.

1. Understand the problem, assess its difficulty
2. Choose an approach (e.g., exact/approximate, deterministic/probabilistic)
3. (Choose appropriate data structures)
4. Choose a strategy
5. Prove termination
6. Prove correctness
7. Prove completeness
8. Evaluate complexity
9. Implement and test it.
10. Compare to other known approaches *and* algorithms.

MAX

When designing an algorithm, we usually give a formal statement about the problem we wish to solve.

Problem

Given a set $A = \{a_1, a_2, \ldots, a_n\}$ integers.
Output the index i of the maximum integer a_i.

A straightforward idea is to simply store an initial maximum, say a_1 then compare it to every other integer, and update the stored maximum if a new maximum is ever found.

MAX

Pseudo-code

MAX

INPUT : A set $A = \{a_1, a_2, \ldots, a_n\}$ of integers.

OUTPUT : An index i such that $a_i = \max\{a_1, a_2, \ldots, a_n\}$

```
index ← 1
FOR i = 2, ..., n DO
    IF a_i > a_index THEN
        index ← i
    END
END
output i
```

This is a simple enough algorithm that you should be able to:

- Prove it correct
- Verify that it has the properties of an algorithm.
- Have some intuition as to its *cost*.

That is, how many "steps" would it take for this algorithm to complete its run? What constitutes a step? How do we measure the complexity of the step?

These questions will be answered in the next few lectures, for now let us just take a look at a couple more examples.

Other examples

Check Bubble Sort and Insertion Sort in your textbooks, which you have seen ad nauseum, in CSE155, CSE156, and will see again in CSE310.

I will be glad to discuss them with any of you if you have not seen them yet.

Greedy algorithm

Optimization

In many problems, we wish to not only find *a* solution, but to find the best or *optimal* solution.

A simple technique that works for *some* optimization problems is called the *greedy technique*.

As the name suggests, we solve a problem by being greedy—that is, choosing the best, most immediate solution (i.e. a *local* solution).

However, for some problems, this technique is not guaranteed to produce the best *globally optimal* solution.

For anyone who's had to work a service job, this is a familiar problem: we want to give change to a customer, but we want to minimize the number of total coins we give them.

Problem

Given An integer n and a set of coin denominations $(c_1, c_2, \ldots, c_r)$ with $c_1 > c_2 > \cdots > c_r$

Output A set of coins $d_1, d_2, \cdots, d_k$ such that $\sum_{i=1}^{k} d_i = n$ and k is minimized.

Example
Change-Making Algorithm

Change

Input: An integer n and a set of coin denominations $(c_1, c_2, \ldots, c_r)$ with $c_1 > c_2 > \cdots > c_r$.

Output: A set of coins $d_1, d_2, \cdots, d_k$ such that $\sum_{i=1}^{k} d_i = n$ and k is minimized.

```
C ← ∅
FOR i = 1, ..., r DO
    WHILE n ≥ c_i DO
        C ← C ∪ {c_i}
        n ← n − c_i
    END
END
output C
```

Change-Making Algorithm
Analysis

Will this algorithm *always* produce an optimal answer?

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Consider a coinage system:

- where $c_1 = 20, c_2 = 15, c_3 = 7, c_4 = 1$
- and we want to give 22 "cents" in change.

What will this algorithm produce?

Is it optimal?

Will this algorithm *always* produce an optimal answer?

Consider a coinage system:

- where $c_1 = 20, c_2 = 15, c_3 = 7, c_4 = 1$
- and we want to give 22 "cents" in change.

What will this algorithm produce?

Is it optimal?

It is *not* optimal since it would give us one c_4 and two c_1, for three coins, while the optimal is one c_2 and one c_3 for two coins.

What about the US currency system—is the algorithm correct in this case?

Yes, in fact, we can prove it by contradiction.

For simplicity, let $c_1 = 25, c_2 = 10, c_3 = 5, c_4 = 1$.

Change-Making Algorithm

Proving optimality

Proof.

Change-Making Algorithm

Proving optimality

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- Let $C = \{d_1, d_2, \ldots, d_k\}$ be the solution given by the greedy algorithm for some integer n. By way of contradiction, assume there is *another* solution $C' = \{d'_1, d'_2, \ldots, d'_l\}$ with $l < k$.

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- Consider the case of quarters. Say in C there are q quarters and in C' there are q'. If $q' > q$, the greedy algorith would have used q'.

Change-Making Algorithm

Proving optimality

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- Consider the case of quarters. Say in C there are q quarters and in C' there are q'. If $q' > q$, the greedy algorith would have used q'.
- Since the greedy algorithm uses as many quarters as possible, $n = q(25) + r$. where $r < 25$, thus if $q' < q$, then in $n = q'(25) + r'$, $r' \geq 25$ and so C' does not provide an optimal solution.

Algorithms: A Brief Introduction
CSE235
Introduction
Algorithms
Examples
Greedy algorithm

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- Finally, if $q = q'$, then we continue this argument on dimes and nickels. Eventually we reach a contradiction.
- Thus, $C = C'$ is our optimal solution.

Change-Making Algorithm
Proving optimality

Why (and where) does this proof fail in our previous counter example to the general case?

We need the following lemma:

If n is a positive integer then n cents in change using quarters, dimes, nickels, and pennies using the fewet coins possible

1. *has at most two dimes, at most one nickel, at most most four pennies, and*
2. *cannot have two dimes and a nickel.*

The amount of change in dimes, nickels, and pennies cannot exceed 24 cents.