

Complete search and greedy solutions

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Complete search / Brute force

Solution space

- The set of all possible solutions to a problem is called the *solution space*
- Note that this solution space will then contain all the wrong solutions too
- Iterating over the entire solution space is called a complete search or brute force solution

Iterating over solution spaces

- Iterating over different solution spaces is key to being able to brute force problems.
- For the simplest cases, like ones you may have seen already in problems, we can just nest for/while loops.

Iterating over a variable number of loops

- A common somewhat harder thing is iterating over a sequence of integers, with variable bounds
- Say we want to test every vector of n integers where each value can be from 0 to $m - 1$.
- We could do this usually with n for loops, but if n is an input this does not work
- In python we can use itertools, C++ needs something handmade

All vectors

```
int n, m; cin >> n >> m;
vector<int> counter(n, 0);
while(true) {
    process_solution(counter); // whatever the problem needs
    bool done = true;
    for(int i = 0; i < n; ++i) {
        counter[i]++;
        if(counter[i] == m) counter[i] = 0;
        else {
            done = false;
            break;
        }
    }
    if(done) { break; }
}
```

Iterating over subsets

- For subsets we could do the same where we have a `vector<bool>` and index i denotes whether we include the i -th element or not
- But for this specific case we can do something much faster
- `ints` consist of bits, so we can instead just have a number and let the i -th bit denote whether we include the i -th element or not
- This means the subsets will just be the numbers from 0 to $2^n - 1$ for n elements, which can be iterated over with a simple for loop

Bit masks

- These things are usually called bit masks
- If $A = \{1, 2, 3, 4, 5, 6\}$ and $B = \{1, 3, 5, 6\}$ then the corresponding numbers in binary would be 111111 and 110101 since the first bit is the one we write last. In decimal these are 63 and 53.
- This also gives us a whole load of useful operations that work on masks

Bit operations

Code	Meaning
0	The empty set
$(1 \ll n) - 1$	The set of the first n elements
$1 \ll k$	The set containing only the k -th element
$A \mid B$	The union of A and B
$A \& B$	The intersection of A and B
$A \sim B$	The symmetric difference of A and B
$\sim A$	The complement of A

Iterating over permutations

- Say we want to iterate over all permutations of some vector/list.
- Luckily this is built into a lot of languages:
 - `next_permutation(v.begin(), v.end())` in C++
 - `itertools.permutations` in Python

```
int n = 5; vector<int> perm(n);
for(int i = 0; i < n; ++i) perm[i] = i + 1;
do {
    for(int i = 0; i < n; ++i) cout << perm[i] << ' ';
    cout << '\n';
} while(next_permutation(perm.begin(), perm.end()));
```

Backtracking

- The methods to iterate over permutations and subsets were rather specialized
- Backtracking is a general framework to iterate over complex spaces
- Solves many classic problems like n-queens and sudoku

Backtracking

- Define some initial "empty" state and have some notion of partial or complete states
- For example in sudoku this is an empty grid, a partially filled grid and a fully numbered grid
- Then define transitions to further states
- In sudoku this would be filling in a number such that it doesn't create an immediate contradiction

Backtracking

- Now start with your empty state
- Use recursion to traverse all states by using the transitions
- If the current state is invalid, stop exploring this branch
- Process all complete states

Backtracking - pseudo code

```
state S;

void generate() {
    if(!is_valid(S)) return;

    if(is_complete(S)) print(S);

    for(each state P that S can transition to) {
        apply transition to P;
        generate();
        undo transition to P;
    }
}

S = empty state;
generate();
```

Backtracking - Subsets

- We can even replicate earlier functionality this way

```
const int n = 5; bool pick[n];

void generate(int index) {
    if(index == n) {
        for(int i = 0; i < n; ++i)
            if(pick[i]) cout << i << ' ';
        cout << '\n';
    } else {
        pick[index] = true;
        generate(index + 1); // pick element at index
        pick[index] = false;
        generate(index + 1); // don't pick element at index
    }
}

generate(0);
```

Backtracking - Permutations

```
const int n = 5; int perm[n]; bool used[n];

void generate(int index) {
    if(index == n) {
        for(int i = 0; i < n; ++i)
            cout << perm[i] + 1 << ' ';
        cout << '\n';
    } else {
        // decide what the element at index should be
        for(int i = 0; i < n; ++i) {
            if(!used[i]) {
                used[i] = true;
                perm[index] = i;
                generate(at + 1);
                used[i] = false; // remember to undo move!
            } } } }

memset(used, 0, n); generate(0);
```


Backtracking - N queens

- Another classic backtracking problem is n-queens
- We have a $n \times n$ chessboard and want to place n queens on it so no two of them can attack each other
- We could use bit tricks to iterate over all subsets of n pieces in the board, but that would be too slow
- Backtracking is much faster since we prune branches of computation early, it's almost universally good to do extra work earlier to prune branches when backtracking

Backtracking - N queens

- We go through the cells in order
- Our transition is placing a queen, or not placing a queen
- We don't place a queen if it would be able to attack another placed queen

```
const int n = 8;  
bool has_queen[n][n];  
int threatened[n][n];  
int queens_left = n;
```

```
// generate function
```

```
memset(has_queen, 0, sizeof(has_queen));  
memset(threatened, 0, sizeof(threatened));  
generate(0, 0);
```

Backtracking - N queens

```
void generate(int x, int y) {  
    if(y == n) generate(x + 1, 0); // move onto next column  
    else if(x == n) { // we are at the end  
        if(queens_left == 0) // this is a valid solution  
            print(); // exact implementation not important  
    } else {  
        if(queens_left > 0 && threatened[x][y] == 0) {  
            has_queen[x][y] = true;  
            for(auto p : queen_threaten(x, y)) // good exercise to implement this!  
                threatened[p.first][p.second]++;  
            queens_left--;  
            generate(x, y + 1);  
            has_queen[x][y] = false; // now to undo the move  
            for(auto p : queen_threaten(x, y))  
                threatened[p.first][p.second]--;  
            queens_left++;  
        }  
        generate(x, y + 1); // also have to try leaving it empty  
    }  
}
```

Greedy algorithms

Greedy algorithms

- An algorithm that always makes *locally* optimal moves is called greedy
- For some kinds of problems this will give a *globally* optimal solution as well
- Seeing when this is the case can be very tricky, and if used in the wrong context the solution will get a WA verdict

Submitting greedy solutions

- The tricky thing with these solutions are that it's often hard to know if you've made a mistake and thus get WA or if there's some hole in the greedy algorithm
- It's often easy to think of all kinds of greedy solutions, but they are very often wrong
- Generally one would like to consider complete search or dynamic programming first, but of course some problems do require greedy solutions

Coin change

- A classical example is making change. Say you want to sum up n and have only denominations of 1, 5 and 10, what's the least amount of coins you can give back?
- The greedy solution would be to just always give the biggest coin you can that's not too much. So for say 24 we'd do 10, 10, 1, 1, 1, 1.
- Is this always optimal?

Coin change

- Well, it turns out to depend on the denominations. Say we have denominations of 1, 8 and 20.
- For $n = 24$ we then give back 20, 1, 1, 1, 1 instead of the optimal 8, 8, 8.
- We will come back to this problem later when we solve the general case using dynamic programming.

Taxi assignment

- Let's consider another problem. You are managing a taxi company and today n drivers showed up and you have m cars.
- But not all drivers and cars are created equal. Car i has h_i horsepower and driver j can only handle at most g_j horsepower.
- What's the greatest number of drivers you can pair to cars such that they can handle their car?

The greedy step

- The greedy idea here is to simply pair each car to the worst driver that can still handle that car.
- Thus we start by sorting the drivers and cars and then simply linearly walk through each and pair them together.
- It might not be obvious, but this actually gives the best answer.

Implementation

```
int main() {
    int n, m; cin >> n >> m;
    vi a(n), b(m);
    for(int i = 0; i < n; ++i) cin >> a[i];
    for(int i = 0; i < m; ++i) cin >> b[i];
    sort(a.begin(), a.end());
    sort(b.begin(), b.end());
    int ans = 0;
    for(int i = 0, j = 0; i < m; ++i) {
        while(j < n && a[j] < b[i]) j++;
        if(j < n) ans++, j++;
    }
    cout << ans << '\n';
}
```

Sorting

- Greedy algorithms very often involve sorting
- More generally they often involve always picking the “extremal” option out of the local options, in some sense
- Biggest, shortest, cheapest, first, etc.

Job scheduling

- Say we have a list of jobs, each starting at some time s_j and finishing at some time f_j
- What's the largest amount of jobs we can complete if they can't overlap?

Solution

- The solution is shockingly simple, but not obviously correct
- Order the jobs by completion time f_j and then walk through them
- If you can complete a job in addition to the ones you've already picked, pick it
- The jobs you've picked by the end are the solution

Proof of correctness

- Why is this correct though? Let's prove it.
- Suppose the algorithm is not optimal. Say we pick jobs of indices i_1, i_2, \dots, i_k but a better solution picks j_1, j_2, \dots, j_l .
- Say the solutions agree on the first r jobs (possibly 0).
- Now neither i_{r+1} nor j_{r+1} clash with the jobs $i_1 = j_1, i_2 = j_2, \dots, i_r = j_r$. But because we ordered things by end time, we must have that job i_{r+1} ends no later than j_{r+1} . But then we could just as well have picked i_{r+1} . But this holds for any r , so by induction we have that i_1, \dots, i_k is no worse than j_1, \dots, j_l , which gives a contradiction.
- Thus the algorithm is optimal.