

Answer the questions in the boxes provided on the question sheets. If you run out of room for an answer, add a page to the end of the document.

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## More Network Flow

1. Kleinberg, Jon. *Algorithm Design* (p.416 q.6). Suppose you're a consultant for the Ergonomic Architecture Commission, and they come to you with the following problem.

They're really concerned about designing houses that are "user-friendly", and they've been having a lot of trouble with the setup of light fixtures and switches in newly designed houses. Consider, for example, a one-floor house with  $n$  light fixtures and  $n$  locations for light switches mounted in the wall. You'd like to be able to wire up one switch to control each light fixture, in such a way that a person at the switch can see the light fixture being controlled.

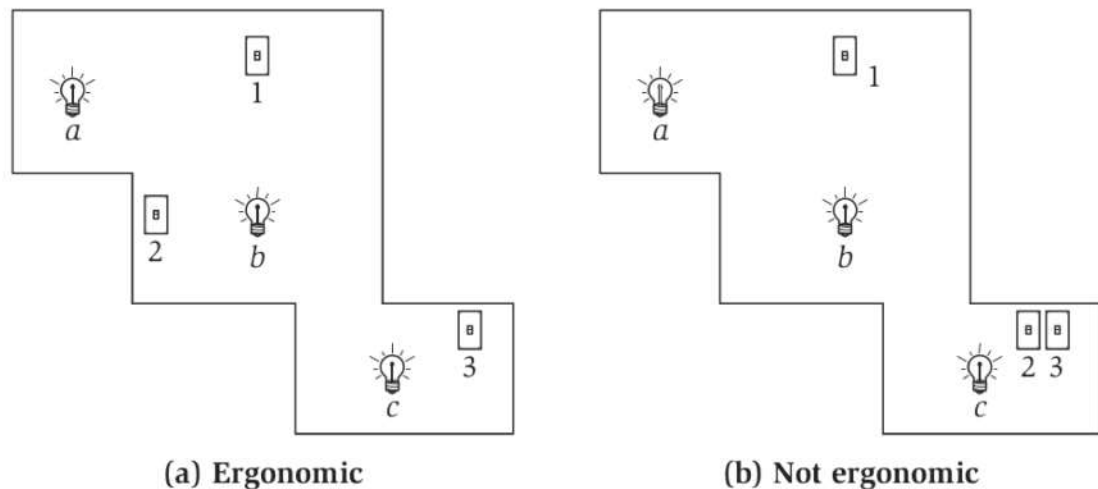


Figure 1: The floor plan in (a) is ergonomic, because we can wire switches to fixtures in such a way that each fixture is visible from the switch that controls it. (This can be done by wiring switch 1 to a, switch 2 to b, and switch 3 to c.) The floor plan in (b) is not ergonomic, because no such wiring is possible.

Sometimes this is possible and sometimes it isn't. Consider the two simple floor plans for houses in Figure 1. There are three light fixtures (labelled  $a, b, c$ ) and three switches (labelled 1, 2, 3). It is possible to wire switches to fixtures in Figure 1(a) so that every switch has a line of sight to the fixture, but this is not possible in Figure 1(b).

Let's call a floor plan, together with  $n$  light fixture locations and  $n$  switch locations, ergonomic if it's possible to wire one switch to each fixture so that every fixture is visible from the switch that controls it. A floor plan will be represented by a set of  $m$  horizontal or vertical line segments in the plane (the walls), where the  $i$ -th wall has endpoints  $(x_i, y_i), (x'_i, y'_i)$ . Each of the  $n$  switches and each of the  $n$  fixtures is given by its coordinates in the plane. A fixture is visible from a switch if the line segment joining them does not cross any of the walls.

Give an algorithm to decide if a given floor plan is ergonomic. The running time should be polynomial in  $m$  and  $n$ . You may assume that you have a subroutine with  $O(1)$  running time that takes two line segments as input and decides whether or not they cross in the plane.

**Solution:**

This problem can be represented by a bipartite matching network flow graph. The source connects to all switches with edge of capacity 1. For each switch, we can run our subroutine to find which light fixtures are possible for said switch to be wired to (this should take  $O(mn)$  time for each switch, thus  $O(mn^2)$  in total to map switches to light fixtures). Once we find which edges should exist between switches and fixtures, assign all of those edges capacity=1. Lastly, connect all light fixtures to the sink with edges of capacity 1. Find the max flow of this network flow graph. If the max-flow equals the number of light fixtures, the floor plan is ergonomic. If not, it is not ergonomic.

2. Kleinberg, Jon. *Algorithm Design* (p.426 q.20).

Your friends are involved in a large-scale atmospheric science experiment. They need to get good measurements on a set  $S$  of  $n$  different conditions in the atmosphere (such as the ozone level at various places), and they have a set of  $m$  balloons that they plan to send up to make these measurements. Each balloon can make at most two measurements. Unfortunately, not all balloons are capable of measuring all conditions, so for each balloon  $i = 1, \dots, m$ , they have a set  $S_i$  of conditions that balloon  $i$  can measure. Finally, to make the results more reliable, they plan to take each measurement from at least  $k$  different balloons. (Note that a single balloon should not measure the same condition twice.) They are having trouble figuring out which conditions to measure on which balloon.

**Example.** Suppose that  $k = 2$ , there are  $n = 4$  conditions labelled  $c_1, c_2, c_3, c_4$ , and there are  $m = 4$  balloons that can measure conditions, subject to the limitation that  $S_1 = S_2 = c_1, c_2, c_3$ , and  $S_3 = S_4 = c_1, c_3, c_4$ . Then one possible way to make sure that each condition is measured at least  $k = 2$  times is to have

- balloon 1 measure conditions  $c_1, c_2$ ,
  - balloon 2 measure conditions  $c_2, c_3$ ,
  - balloon 3 measure conditions  $c_3, c_4$ , and
  - balloon 4 measure conditions  $c_1, c_4$ .
- (a) Give a polynomial-time algorithm that takes the input to an instance of this problem (the  $n$  conditions, the sets  $S_i$  for each of the  $m$  balloons, and the parameter  $k$ ) and decides whether there is a way to measure each condition by  $k$  different balloons, while each balloon only measures at most two conditions.

**Solution:**

This can be represented by a bipartite matching network flow graph. The source connects to all balloons with edges of capacity 2, representing that each balloon can take at max 2 measurements. Then, all balloons are connected to the conditions that their set  $S_i$  says they are capable of measuring with edge of capacity 1, representing that a balloon can take only 1 measurement from each condition (that it is capable of measuring according to its  $S_i$ ). Lastly, each condition is connected to the sink with edges of capacity  $k$ , representing that my friends want each condition to be measured at least  $k$  times (by different balloons). Find the max-flow of this network flow graph. If the max-flow equals the  $m \cdot k$ , then there is a way to measure each condition by  $k$  different balloons, while each balloon only measures at most two conditions. If not, there is not.

- (b) You show your friends a solution computed by your algorithm from (a), and to your surprise they reply, “This won’t do at all—one of the conditions is only being measured by balloons from a single subcontractor.” You hadn’t heard anything about subcontractors before; it turns out there’s an extra wrinkle they forgot to mention...

Each of the balloons is produced by one of three different subcontractors involved in the experiment. A requirement of the experiment is that there be no condition for which all  $k$  measurements come from balloons produced by a single subcontractor.

Explain how to modify your polynomial-time algorithm for part (a) into a new algorithm that decides whether there exists a solution satisfying all the conditions from (a), plus the new requirement about subcontractors.

**Solution:**

Scrap the edges between the balloons and conditions and add an intermediate level of nodes in the graph between the balloons and conditions columns. This level will represent the subcontractors. Add edges from the balloons to their respective subcontractors with capacities 2 (still representing that each balloon can take max 2 measurements). Then, add edges from each subcontractor to each condition with capacity  $k-1$ , representing that one subcontractor cannot be the sole measurer of a single condition.

3. Kleinberg, Jon. *Algorithm Design* (p.442, q.41).

Suppose you're managing a collection of  $k$  processors and must schedule a sequence of  $m$  jobs over  $n$  time steps.

The jobs have the following characteristics. Each job  $j$  has an arrival time  $a_j$  when it is first available for processing, a length  $\ell_j$  which indicates how much processing time it needs, and a deadline  $d_j$  by which it must be finished. (We'll assume  $0 < \ell_j \leq d_j - a_j$ .) Each job can be run on any of the processors, but only on one at a time; it can also be preempted and resumed from where it left off (possibly after a delay) on another processor.

Moreover, the collection of processors is not entirely static either: You have an overall pool of  $k$  possible processors; but for each processor  $i$ , there is an interval of time  $[t_i, t'_i]$  during which it is available; it is unavailable at all other times.

Given all this data about job requirements and processor availability, you'd like to decide whether the jobs can all be completed or not. Give a polynomial-time (in  $k$ ,  $m$ , and  $n$ ) algorithm that either produces a schedule completing all jobs by their deadlines or reports (correctly) that no such schedule exists. You may assume that all the parameters associated with the problem are integers.

**Example.** Suppose we have two jobs  $J_1$  and  $J_2$ .  $J_1$  arrives at time 0, is due at time 4, and has length 3.  $J_2$  arrives at time 1, is due at time 3, and has length 2. We also have two processors  $P_1$  and  $P_2$ .  $P_1$  is available between times 0 and 4;  $P_2$  is available between times 2 and 3. In this case, there is a schedule that gets both jobs done.

- At time 0, we start job  $J_1$  on processor  $P_1$ .
- At time 1, we preempt  $J_1$  to start  $J_2$  on  $P_1$ .
- At time 2, we resume  $J_1$  on  $P_2$ . ( $J_2$  continues processing on  $P_1$ .)
- At time 3,  $J_2$  completes by its deadline.  $P_2$  ceases to be available, so we move  $J_1$  back to  $P_1$  to finish its remaining one unit of processing there.
- At time 4,  $J_1$  completes its processing on  $P_1$ . Notice that there is no solution that does not involve preemption and moving of jobs.

**Solution:**

This problem can be represented by a network flow graph. This one will be an augmentation to a bipartite matching graph. The source will be connected to all jobs with edges of capacity  $\ell_j$ . Each job will be connected to all of the processors that have intervals of time big enough to handle the length of the specified job, with edges of capacity  $\ell_j$ . Then, there will be a third layer of nodes (not bipartite, I know) representing the time steps, where they are all connected to all of the processors with edges of capacity 1. Then, the time steps are connected to the sink with edges of capacities of infinity. The max-flow function will represent which jobs are executed on which processors for which time steps. You can perform BFS on the residual graph from the sink to find which jobs are on which processors at which time steps.

4. Kleinberg, Jon. *Algorithm Design* (p.444, q.45).

Consider the following definition. We are given a set of  $n$  countries that are engaged in trade with one another. For each country  $i$ , we have the value  $s_i$  of its budget surplus; this number may be positive or negative, with a negative number indicating a deficit. For each pair of countries  $i, j$ , we have the total value  $e_{ij}$  of all exports from  $i$  to  $j$ ; this number is always nonnegative. We say that a subset  $S$  of the countries is *free-standing* if the sum of the budget surpluses of the countries in  $S$ , minus the total value of all exports from countries in  $S$  to countries not in  $S$ , is nonnegative. Give a polynomial-time algorithm that takes this data for a set of  $n$  countries and decides whether it contains a nonempty free-standing subset that is not equal to the full set.

**Solution:**

This problem can be represented by a network flow graph. From the source to each country with a positive  $s_i$  is an edge of capacity  $s_i$ . There are two edges between each country representing the exports  $e_{ij}$  from one to another. All countries with negative  $s_i$  are connected to the sink with edges of capacity  $\text{abs}(s_i)$ . Find the min-cut of this network flow graph. The countries in set  $A$  are the countries in subset  $S$ , such that the sum of their budget surpluses minus the total value of all exports from countries in  $S$  to countries not in  $S$  is nonnegative.

5. Implement an algorithm to determine the maximum matching in a bipartite graph and if that matching is perfect (all nodes are matched) in either C, C++, C#, Java, Python, or Rust. Be efficient and use your max-flow implementation from the previous week.

The input will start with an positive integer, giving the number of instances that follow. For each instance, there will be 3 positive integers  $m$ ,  $n$ , and  $q$ . Numbers  $m$  and  $n$  are the number of nodes in node set  $A$  and node set  $B$ . Number  $q$  is the number of edges in the bipartite graph. For each edge, there will be 2 more positive integers  $i$ , and  $j$  representing an edge between node  $1 \leq i \leq m$  in  $A$  and node  $1 \leq j \leq n$  in  $B$ .

A sample input is the following:

```
3
2 2 4
1 1
1 2
2 1
2 2
2 3 4
2 3
2 1
1 2
2 2
5 5 10
1 1
1 3
2 1
2 2
2 3
2 4
3 4
4 4
5 4
5 5
```

The sample input has 3 instances.

For each instance, your program should output the size of the maximum matching, followed by a space, followed by an  $N$  if the matching is not perfect and a  $Y$  if the matching is perfect. Each output line should be terminated by a newline. The correct output to the sample input would be:

```
2 Y
2 N
4 N
```