Combinatorics

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A Taste of Algebraic Combinatorics

Problem: (St. Petersburg) Students in a school go for ice cream in groups of at least two. After $k > 1$ groups have gone, every two students have gone together exactly once. Prove that the number of students in the school is at most k.

Solution. Let there be n students. Note if some student went for ice cream only once, then everyone else has to have gone with that student, due to the constraint that every pair of student have gone together exactly once. Furthermore, since each group consists of two students, no other groups can be formed. However, $k > 1$, so this situation cannot occur. Therefore, every student went for ice cream at least twice.

Let us construct **incidence vectors** $\mathbf{v}_i \in \mathbb{R}^k, 1 \le i \le n$, representing the students. That is, the j-th component of $\mathbf{v}_i$ is 1 if student i went with the j-th group, and 0 otherwise.

The condition that every two students have gone together exactly once translates into the dot product $\mathbf{v}_i \cdot \mathbf{v}_j = 1$ for $i \ne j$. The condition that every student went for ice cream at least twice translates into $|\mathbf{v}_i|^2 \ge 2$.

We want to prove that $n \le k$. Suppose otherwise. Then $\{\mathbf{v}_1, \ldots, \mathbf{v}_n\}$ consists of at least $k + 1$ vectors in $\mathbb{R}^k$, so they must be linearly dependent. It follows that there are real numbers $\alpha_1, \ldots, \alpha_n$, not all zero, such that

$$\alpha_1 \mathbf{v}_1 + \cdots + \alpha_n \mathbf{v}_n = 0.$$

Let us square the above expression (i.e., taking the dot product with itself). We get

$$0 = \sum_{i=1}^{n} \alpha_i^2 |\mathbf{v}_i|^2 + 2\sum_{i<j} \alpha_i \alpha_j \mathbf{v}_i \cdot \mathbf{v}_j = \sum_{i=1}^{n} \alpha_i^2 |\mathbf{v}_i|^2 + 2\sum_{i<j} \alpha_i \alpha_j = \sum_{i=1}^{n} \alpha_i^2 \left(|\mathbf{v}_i|^2 - 1 \right) + \left(\sum_{i=1}^{n} \alpha_i \right)^2.$$

However, the RHS expression is positive, since $|\mathbf{v}_i|^2 \ge 2$ and some α_i is nonzero. Contradiction. □

If you know a little bit of linear algebra, try the following problem.

1. (Crux 3037) There are 2007 senators in a senate. Each senator has enemies within the senate. Prove that there is a non-empty subset K of senators such that for every senator in the senate, the number of enemies of that senator in the set K is an even number.

Poset Quickies

Definition. A *partially ordered set* (or *poset* for short) P is a set, also denoted P, together with a binary relation denoted $\le$ satisfying the following axioms:

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