The Method of Undetermined Generalization and Specialization Illustrated with Fred Galvin's Amazing Proof of the Dinitz Conjecture

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At the very beginning of our waning century, in what turned out to be the most influential mathematical address ever delivered, David Hilbert[H] said:

"If we do not succeed in solving a mathematical problem, the reason frequently consists in our failure to recognize the more general standpoint from which the problem before us appears only as a single link in a chain of related problems."

One paragraph later, he also said:

In dealing with mathematical problems, specialization plays, as I believe, a still more important part than generalization.

Alas, all this is easier said than done. How does one find the 'right' generalization and specialization?

The answer is: just go ahead and start proving the conjecture. At first, leave the exact form of the generalization and/or specialization blank, and as you go along, see what kind of generalization/specialization would be required to make the proof work out. Keep 'guessing and erasing' until you get it done, just like doing a crossword puzzle.

I will illustrate this proof strategy in terms of Fred Galvin's[G] recent brilliant proof of the Dinitz conjecture. Following a tradition that goes back to Euclid, Galvin presented his proof as a marvelous but 'static' completed edifice, just like the solution to yesterday's (or last Sunday's) puzzle, that hides all the trials and tribulations by which it was arrived. Not very useful for solving today's puzzle...

The Dinitz conjecture asserts that given n^2 arbitrary sets $A_{i,j}$ $(1 \leq i,j \leq n)$, each having n elements, then it is always possible to pick elements $a_{i,j} \in A_{i,j}$ such that $(a_{i,j})$ is a 'generalized Latin square', which means that each row and each column must have all its n entries distinct.

In other words, given a party of n boys and n girls, in which every boy must dance once with every girl, and such that each possible couple (i,j) knows how to dance (with each other[2]) only n dances, then out of the n^{n^2} ways of assigning dances to couples, there is at least one way in which each of the $2n$ individuals dances a different dance in each of his or her n performances.

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[2] These are couples' dances and the two dancers should be able to coordinate their steps, so it is possible for Abe to be able to dance the tango with Alice but not with Barbara, although Barbara may be able to dance it with other boys.

Like many people, I first heard about the Dinitz conjecture[ERT] when Jeannette Janssen[J] brilliantly applied the powerful algebraic method of Alon and Tarsi[AT] to 'almost' prove it: she proved the analogous statement for 'non-square' rectangles.

As soon as I found out about the Dinitz conjecture, I was struck by its simplicity. Like so many times before, it seemed to me that there ought to be a 'simple' proof to such a simple statement, and I spent many hours trying, in vain, to prove it.

The reason I found my inability to prove the Dinitz conjecture so frustrating is that it appears to be 'intuitively obvious'. When all the sets $A_{i,j}$ are (pairwise) disjoint, then the statement is obvious. In the other extreme, when all the sets $A_{i,j}$ coincide, then it is also obvious: we have the problem of constructing an ordinary $n \times n$ Latin square. This can be constructed by looking at the multiplication table of any group of order n, in particular, the additive group of $\{0, 1, \ldots, n-1\}$ mod n:

$$\begin{matrix} 0 & 1 & \ldots & n-2 & n-1 \\ 1 & 2 & \ldots & n-1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \\ n-1 & 0 & \ldots & n-3 & n-2 \end{matrix} \quad . \tag{L}$$

It is intuitively obvious that as there is less overlap between the sets $A_{i,j}$, there would have to be more options, which should make it even easier to construct a generalized Latin square.

The need to prove intuitively obvious statements is very common in analysis, which is why I find it such a forbidding subject. Indeed, this was one of the reasons why, shortly after my Ph.D., I decided to change fields from analysis to combinatorics, which I found much more gratifying, as there the gap between 'convincing yourself' and 'convincing the referee' is usually so much smaller.

Last spring, while I was still spending an hour a day trying to prove the Dinitz conjecture, I got an E-mail message from Herb Wilf, who forwarded an E-mail message from Richard Ehrenborg, who forwarded an E-mail message from Jeannette Janssen, who forwarded an E-mail message from Gil Kalai[K][3] which contained a lucid and concise two-and-a-half page outline of Fred Galvin's proof, that Kalai had compiled.

When I finished reading and digesting the proof, I kicked myself. I felt that I could have found it myself, had I only followed Hilbert's advice, coupled with the 'crossword methodology' alluded to above. With the very generous help of Lady Hindsight, I will now describe how I (and you!) could have, and should have, found the very same proof, *without any prior knowledge of combinatorics or graph theory.*

Hopefully, this presentation would enable you (or, better still, me!), to give an elementary proof (not using 'the class number formula for the Selmer group associated to the symmetric square representation of a modular lifting') of Wiles' theorem, and an elementary (and 'the first') proof of

[3] I am pleased to be in the same connected component as Kalai, but I wish that Gil would draw a directed edge between him and myself, especially since there already exists an edge from me to him.

the Riemann Hypothesis.[4]

The method of undetermined coefficients

Every mathematician (and electrical engineer) knows that in order to find a particular solution of a linear differential equation such as

$$y'' + y = x^2 \quad ,$$

one writes $y = Ax^2 + Bx + C$, for some *undetermined* constants A, B, C. We don't know yet what they are, but we hope that they exist, and are constants. Assuming this, we plug it into the equation, getting

$$Ax^2 + Bx + (C + 2A) = x^2 \quad .$$

Comparing the coefficients of x^2, x^1 and x^0 on both sides, leads to the system of equations $A = 1, B = 0, C + 2A = 0$, which leads to the solution $A = 1, B = 0, C = -2$. Hence $y = x^2 - 2$ is a solution of the given differential equation.

The method of undetermined parameters in proofs

In many proofs in number theory and elsewhere (e.g. [I] pp. 27-28), we take parameters, say t_0 and ρ, fiddle with them, and only at the end commit ourselves to a relation between them (for example, [I], p.28, $\rho = 1/(\log t_0 + 2)$), that produces the desired effect.

How to Generalize Dinitz's Conjecture?

There is something too narrow and 'square' about the statement of the Dinitz conjecture. A natural generalization that comes to mind is to arbitrary graphs. Calling the elements of the sets $A_{i,j}$ 'colors', the task of the Dinitz conjecture is to color each cell (i, j) by one of the colors of the set of colors $A_{i,j}$ that the cell is allowed to use, in such a way that no two cells sharing the same row, or the same column, can be colored by the same color. This immediately brings to mind graph coloring. The $n \times n$ discrete square is an undirected graph having the n^2 vertices $\{(i, j) | 1 \leq i, j \leq n\}$, and each vertex (i, j) is connected to the $2(n - 1)$ vertices $(i, j'), j' \neq j$ and $(i', j), i' \neq i$. A natural generalization would have the form

If G is any graph in a class X (that includes squares) then whenever each vertex v is assigned a set of colors A_v, and the cardinalities of the sets A_v satisfy condition $Y(G)$, then it is possible to properly color the vertices of G so that the color of each vertex v is drawn from the set A_v.

(A coloring of a graph is *proper* if two vertices joined by an edge always receive different colors.)

[4] RH is (almost) equivalent to the following elementary statement: Let a_n be the difference between the number of square-free integers between 1 and n with an even number of prime factors and the number of those with an odd number of prime factors, then for some constant A, $a_n \leq An^{9999/10000}$. This would already make you rich and famous. The full RH is equivalent to replacing the 9999/10000 by any number larger than 1/2.

For the time being, both the class X, and the condition Y, are left *blank*. All we need is that the class X contains the graphs of squares and the condition $Y(G)$ becomes 'having cardinalities $\geq n$' when G happens to be the $n \times n$ square.

Occam's Razor and Specialization

Properly coloring a graph means that for every two vertices x and y that are connected by an edge, we require that:

The colors assigned to x and y must differ.

This statement really embodies two statements:

The color of x is different from the color of y AND The color of y is different from the color of x.

What a waste! Following Occam's advice, we can drop either one of the two statements. This leads to the idea of directing the edges of our $n \times n$ square-graph and to consider the set of *directed graphs*. This class might be easier to handle, since it has more structure. For any given graph of e edges, there are 2^e ways to make it a directed graph. A proper coloring of a directed graph is assigning colors to each vertex such that whenever there is an edge from vertex x to vertex y, the color assigned to x must differ from the color assigned to y. So in order to properly color an undirected graph, all you need is to be able to color a single one of its many possible directed versions. So now we have one more free parameter at our disposal: the way to 'orient' the graph of the $n \times n$ square. Let's call this orientation Z. The proposed generalization/specialization is now:

If G is any directed graph in a class X (that includes the squares with orientation Z) then whenever each vertex v is assigned a set of colors A_v, and the cardinalities of the sets A_v satisfy condition $Y(G)$, then it is possible to properly color the vertices of G so that the color of each vertex v is drawn from the set A_v.

We would be done if we could find *some* class X, *some* orientation Z, and *some* condition Y, that would enable a proof, such that the squares with orientation Z belong to X, and:

$$Y(n \times n \quad \text{square with orientation Z}) = [|A_{i,j}| \geq n, \ \text{for all } 1 \leq i,j \leq n] \quad .$$

Our best bet would be an inductive proof, since graphs are so amenable to induction. Such a proof would presumably consist in a recursive algorithm to color the vertices that would involve, at each step, getting rid of some of the vertices and edges, as well as of some of the colors, thus shrinking the graph, that must stay in our class X, whatever it is, and shrinking the sets A_v, in such a way that condition Y, whatever it is, still holds.

But first let's impose some natural restrictions on the orientation Z of the graph of the square. One of the great principles of mathematics (and life) is *symmetry* and *balance* (e.g. balancing the budget.) The number of neighbors of each of the n^2 vertices of the $n \times n$ square is $2n-2$. When we stick arrows in the edges, it makes sense to do it in such a way that at each vertex there would be as many outgoing edges as incoming edges. So let's impose, tentatively of course, the following condition on the still elusive orientation Z:

The orientation Z of the $n \times n$ square should be such that in the resulting directed graph, every vertex has outdegree $n-1$.

(The *outdegree* of a vertex is the number of edges coming out of it.)

Now it is time to think of condition Y. The larger the cardinality of the set A_v, the more options we have to color the vertex v. On the other hand the larger the outdegree of v, the more restrictions we have. Since more freedom should go hand in hand with more responsibility, it makes sense that the condition Y regarding the cardinality of the set A_v should be related to the outdegree of the vertex v. Since the color of any vertex v should be different than all its (outgoing) neighbors, that might happen to be all distinct, the number of 'optional colors' at v, i.e. the cardinality of A_v, should be at least one more than the outdegree of v. But wait a minute! In our 'symmetric orientation' Z, the outdegrees are all $n-1$ and in the statements of Dinitz's conjecture all the cardinalities of the sets A_v are $\geq n$, one more than the outdegree. This leads us to conjecture that the condition $Y = Y(G)$ should be: $|A_v| \geq outdegree(v) + 1$.

Plugging this (tentative!) condition Y into the 'undetermined generalization' of the Dinitz conjecture, we are lead to the following statement:

If G is any directed graph in a class X (that includes the squares with orientation Z), then whenever each vertex v is assigned a set of colors A_v of cardinality $>$ outdegree(v), it is always possible to properly color the graph in such a way that the color of v is drawn from A_v.

It now remains to find the class X that will make the proof work, and then make sure that there is an orientation Z of the $n \times n$ square such that the outdegree of every vertex is $n-1$, and that belongs to X.

It is easy to see that the class of *all* directed graphs is too big (why?). On the other extreme the empty class X obviously (and vacuously) satisfies the theorem, but no orientation of the square can ever belong to it, of course.

Anyway, let's leave the nature of the class X blank for now, and try and prove the 'generalized' Dinitz statement. Pick one of the colors in the union of the A_v's, let's call it 'red'. We would like to color 'red' at least one of the vertices that are allowed to be colored 'red', remove these vertices and their incident edges, thereby getting a smaller graph to which we would like to apply induction. In order for the induction to work, the smaller graph G' must still belong to the class X and satisfy condition Y (that the corresponding sets A'_v will have cardinality strictly larger then the outdegree of v for every vertex v in the reduced graph G'.)

When we pick a subset of the vertices to be colored 'red', this subset should be *independent*, i.e.

no pair of its members can be connected by an edge, or else the coloring would not be proper.

These vertices, that were colored 'red', were chosen amongst all those vertices v that had the 'red' option, i.e. for which 'red' $\in A_v$. All the other ones that had 'red' as one of their options, but were *not* colored 'red', now lose that option. For induction to work, we need that the reduced graph should still satisfy condition Y, which means that these vertices, which are still waiting their turn to be colored, but just lost one of their options, should also lose one of their (outgoing) neighbors. The only way that this could happen is for the 'frustrated red' vertices to have had at least one neighbor amongst the 'departing reds'. Then having colored the 'realized red' vertices 'red', and having removed them, leaves us a graph in which each of the 'frustrated red' vertices gets compensated for their loss of the 'red' option, by getting rid of (at least) one of their annoying (outbound) neighbors.

So in order for the difference between the cardinality of the sets A_v and the outdegree of v to be still ≥ 1, we need that out of all the vertices that have 'red' as one of their options, it is possible to pick an *independent* subset of vertices that would exercise that option, in such a way that all the other vertices, that had 'red' as one of their options before, but did not use this option, would have an edge leading to one of those vertices that did get colored 'red'. If this is the case, removing the vertices that were just colored 'red', and the edges adjacent to them, would then yield a smaller graph G' , that should still belong to X, with correspondingly smaller sets A_v that still satisfy condition Y.

Since we don't know beforehand which of the vertices would have 'red' (or later, 'green' or any other color) as one of their options, and also want property X to be 'hereditary' (with respect to induced subgraphs), we should 'leave our options open' and require that *any* subset S of vertices should have this property of there always being an *independent* subset $S' \subset S$ such that every vertex in $S - S'$ has an edge directed toward some vertex of S'. This is exactly the property X that we have been looking for, and the proof that we already have, works with that property X. So now we can formulate:

Definition: *A directed graph G has property X if for every subset of vertices S there is an independent subset $S' \subset S$ such that every vertex in $S - S'$ has an edge directed toward a vertex of S'.*

We have just proved:

The 'Trivializing' Generalization: *Let G be a directed graph having property X (defined above). If every vertex v is given a set of colors A_v whose cardinality exceeds the outdegree of v, then it is always possible to properly color G in such a way that the color of v is picked from A_v.*

But is this indeed a generalization of the statement of the Dinitz conjecture? We still need to find an orientation Z of the graph of the $n \times n$ square such that every vertex has outdegree $n-1$, and that has property X.

One of the many possible ways of picking Z is by picking the following orientation. Looking at the Latin square (L) given above, the horizontal (vertical) edges are directed from the smaller (larger) entries to larger (smaller) ones. In other words:

$$(i,j) \to (i',j) \quad if \quad [\,(i+j-2) \quad mod \quad n\,] > [\,(i'+j-2) \quad mod \quad n\,] \quad ,$$

$$(i,j) \to (i,j') \quad if \quad [\,(i+j-2) \quad mod \quad n\,] < [\,(i+j'-2) \quad mod \quad n\,] \quad .$$

To prove property X, Galvin invokes the famous Gale-Shapley 'Stable Marriage' theorem ([GS],[PTW]), with the rows representing men, the columns representing women, and an arrow from (i,j) to (i',j) meaning that Ms. j prefers Mr. i' to Mr. i while an arrow from (i,j) to (i,j') meaning that Mr. i prefers Ms. j' to Ms. j. Having property X is easily seen to be equivalent to the existence of a stable marriage, even if some of the relationships are removed, because of the laws of the land.[5] In this more general situation, it is no longer guaranteed that everybody gets married, but those who do, do so without fear of being scorned.

I believe that even if the Gale-Shapley algorithm and/or theorem did not exist, it would not have been too hard to either discover it from scratch, or prove by other means (e.g. induction) that there is some orientation Z (in particular the one given above), that satisfies property X. We invite the reader to do this right now! $\square$

Postscript: The true story is even more amazing, and I hope that Galvin would write up the story that he told me after he received the first draft of this paper. Since this is *his* story, not mine, I will not give it away, except to quote Noga Alon who said: 'The moral of the (true) story of how Galvin found his proof is not to follow Hilbert, but to follow a simpler adage: *Know where to look things up'*. Of course, just like Hilbert's advice, this is easier said than done, and it takes someone like Galvin to use this so effectively. It is interesting to note that the right Y and Z were already present in [AT] and [J].

Noga Alon has informed me that Kalai's two-and-a-half page exposé was based on a one-page description that Alon has sent Kalai, and that Alon wrote up based on Galvin's letter to him. I wish to thank Mireille Bousquet-Mélou, Fred Galvin, Bruno Salvy and Herb Wilf for helpful remarks on an earlier version.

Note: John Noonan, of Temple University, has written Maple programs that implement the algorithm in Galvin's proof and the Gale-Shapley algorithm. They are available by anonymous `ftp` to `ftp.math.temple.edu` in directory `pub/noonan`, or via Mosaic to `http://www.math.temple.edu/~noonan`.

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[5] For example forbidding (i,j) where Mr. i is a Cohen and Ms. j is a divorcée.

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