Graphs on groups, rings, and maybe YBE solutions

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Groups, Rings and YBE
Blankenberge, 21 June 2023

I know something about groups, and a bit about rings, but very little about the Yang–Baxter equation. That would be "nothing" but for Tatiana Gateva-Ivanova, who got me interested in it during a programme on Combinatorics and Statistical Mechanics, at the Isaac Newton Institute in Cambridge fifteen years ago.

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I haven’t got much to say on this yet but I hope that something interesting may develop.

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The prototype is the commuting graph of a finite group G, where the vertex set is G (or possibly some subset), and g and h are joined by an edge if they commute.

This was used by Brauer and Fowler in 1955 to show that there are only finitely many finite simple groups with a given involution centraliser, one of the basic results in the Classification of Finite Simple Groups, leading to a large amount of work characterising particular simple groups by their involution centralisers, and yielding several new sporadic simple groups along the way.

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In fact, the word "graph" does not occur in the paper; but Brauer and Fowler carefully define the graph metric and use this instead.

Graphs on groups and rings

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Much of the literature on these graphs consists of calculating various graph-theoretic parameters of these graphs. I will not cover most of this.

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1. Can we obtain new results about groups by considering these graphs?
2. Can we recognise old and new classes of groups by means of graphs?
3. Can we construct beautiful graphs in this way (possibly after some post-processing)?

I will give examples of all three.

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Recently, Parthajit Bhowal, Rajat Kanti Nath, Benjamin Sambale and I showed:

Theorem

There is a function f such that a finite group whose scc-graph has clique number k has order at most $f(k)$.

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Find such bounds!

2. Defining group classes

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2. Choose two types of graph on groups, say t_1 and t_2, so that $t_1(G)$ is an induced subgraph of $t_2(G)$, and ask: *For which groups G is $t_1(G) = t_2(G)$?*

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There are several examples of each in the literature. I will concentrate on the second.

Two examples

We have seen the commuting graph ($g \sim h$ if $gh = hg$) and the power graph ($g \sim h$ if one of g and h is a power of the other). Between them is the enhanced power graph, with $g \sim h$ if there exists k such that g and h are powers of k.

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Let G be a finite group.

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2. *The enhanced power graph of G is equal to the commuting graph if and only if G contains no two commuting subgroups of the same prime order.*

I will briefly discuss the two classes.

Two classes of groups

The first class consists of EPPO groups, those in which every element has prime power order. (In other terminology these are groups whose Gruenberg–Kegel graph is null.) After pioneering work by Higman on solvable groups in the 1950s and Suzuki on simple groups in the 1960s, they were all determined by Brandl in a somewhat obscure paper in 1981.

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All these results are without using CFSG.

The deep commuting graph

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The deep commuting graph of G is the graph with vertex set G in which x and y are joined if and only if their preimages in every central extension of G commute.

The deep commuting graph is contained in the commuting graph (in the sense of spanning subgraph, that is, its edge set is a subset of that of the commuting graph), and contains the enhanced power graph (since a central extension of a cyclic group is abelian).

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Hence if G is simple then its commuting and deep commuting graphs are equal if and only if its Schur multiplier is trivial.

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- 2-Engel groups (those satsfying the commutator identity $[g, h, h] = 1$).

In many other cases, work is in progress. For example, the power graph of any finite group is perfect (that is, every induced subgraph has clique number equal to chromatic number): this condition is equivalent to forbidding odd cycles (of length greater than 3) and their complements as induced subgraphs, according to the Strong Perfect Graph Theorem.

More on perfect graphs

There is no analogue for the enhanced power graph or commuting graph: these are universal (every finite graph occurs as an induced subgraph). We do not know which groups have one or other of these graphs perfect (this has been studied for the commuting graph by Britnell and Gill, who found all *perfect* groups for which this graph is perfect).

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There is no analogue for the enhanced power graph or commuting graph: these are universal (every finite graph occurs as an induced subgraph). We do not know which groups have one or other of these graphs perfect (this has been studied for the commuting graph by Britnell and Gill, who found all *perfect* groups for which this graph is perfect). Veronica Phan and I proved that the enhanced power graph of any finite group is weakly perfect – this means that the graph itself has clique number equal to chromatic number, though this may fail for induced subgraphs.

3. Finding beautiful graphs

If you choose your favourite group and ask the computer to construct one of these graphs and tell you how many automorphisms it has, you are in for a shock. For example, the commuting group of the alternating group A_5 (a group of order 60) has 477090132393463570759680000 automorphisms. In fact, most of this is rubbish; in the case of A_5 it is all rubbish. But sometimes there is a jewel buried in the heart of the lotus flower.

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Our graphs on groups tend to have many pairs of twins. If x and y generate the same cyclic subgroup of G, then they are twins in all the graphs mentioned so far, and essentially all others as well.

Twin reduction

Twin reduction is the process of choosing a pair of twins and identifying them, repeating the process until no twins remain. The resulting graph is (up to isomorphism) independent of the way the reduction is carried out. I will call it the cokernel of the original graph (no connection with homological algebra implied).

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A graph is called a cograph if it has no induced subgraph isomorphic to the 4-vertex path. Cographs form the smallest class of graphs which can be built from 1-vertex graphs by the operations of disjoint union and complementation.

Proposition

A graph is a cograph if and only if its cokernel is the 1*-vertex graph.*

The search

The above result gives added significance to the question:

Problem

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Partial answers are known in some cases. In particular, Pallabi Manna, Ranjit Mehatari and I have determined the finite simple groups whose power graph is a cograph; Xuanlong Ma, Natalia Maslova and I have done the same for the commuting graph.

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The simplest results are for what I will call the difference graph, whose edges are those in the enhanced power graph but not in the power graph.

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- the difference graph is a cograph, so its cokernel has a single vertex;
- the cokernel of the difference graph has many very small connected components, all isomorphic;
- the cokernel is connected; its full automorphism group is the same as the automorphism group of the simple group with which we began; and the graph has nice properties (for example, large girth).

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For example, if G is the Matheu group M_{11}, then the cokernel of the difference graph is bipartite, with blocks of size 165 and 220; the valencies of vertices in the two blocks are 4 and 3 respectively; the graph is connected, with diameter and girth 10; and its automorphism group is M_{11}.

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More exploration remains to be done …

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To begin at the beginning: the set-theoretic Yang–Baxter equation is an equation for a function $r : X \times X \to X \times X$ satisfying

$$r_{12}r_{23}r_{12} = r_{23}r_{12}r_{23},$$

where this equation refers to maps on $X \times X \times X$, and r_{ij} replaces the pair (x_i, x_j) by the pair of coordinates of $r(x_i, x_j)$.

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- r is an involution (this implies that it is a bijection);
- r is non-degenerate (see next slide).

Monoids and groups

As usual, an endomorphism of (X, r) is a self-map of X whose induced action on X^2 commutes with r. An invertible endomorphism whose inverse is also an endomorphism is an automorphism. So we have an endomorphism monoid and an automorphism group.

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The Yang–Baxter monoid and group have completely different definitions; how are they related?

Yang–Baxter monoid and group

We can write $r(x, y)$ as $(\lambda_x(y), \rho_y(x))$, where, for any $x, y \in X$, the functions λ_x and ρ_y map X to X. We say that our solution is non-degenerate if these functions are bijections for all choices of x and y.

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Now we regard the permutations λ_x and ρ_y as generators of a group $G(r)$ acting on X. Warning: It is customary to regard the λ_x as acting on the left and the ρ_y on the right: as a mnemonic, $r(x, y)$ is often written as $({}^x y, x^y)$.

Yang–Baxter monoid and group

We can write $r(x,y)$ as $(\lambda_x(y), \rho_y(x))$, where, for any $x, y \in X$, the functions λ_x and ρ_y map X to X. We say that our solution is non-degenerate if these functions are bijections for all choices of x and y.

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The YBE and the extra conditions imply that the ρs can be written in terms of the λs, and *vice versa*; so the groups generated by the λs and by the ρs are equal. This is the Yang–Baxter permutation group associated with the solution.

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Note: we should certainly be open to relaxing the non-degeneracy condition and working with monoids rather than groups; but their theory is less developed.

Connections

The representation theory of permutation groups is based on the relation between the permutation group and its centralizer algebra, using the double centralizer theory. Can something similar be done here? We have three objects in play, the monoid (or group) generated by r; the endomorphism monoid or automorphism group of (X, r); and the Yang–Baxter transformation monoid or permutation group.

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Problem

What are the relations among these?

In the case of the trivial solution $r(x, y) = (y, x)$, the YB group is trivial and the automorphism group is the symmetric group.

Cayley graph

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What can we do with this set-up?

What to do?

More questions:

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… for your attention.