Representing groups by endomorphisms of the random graph

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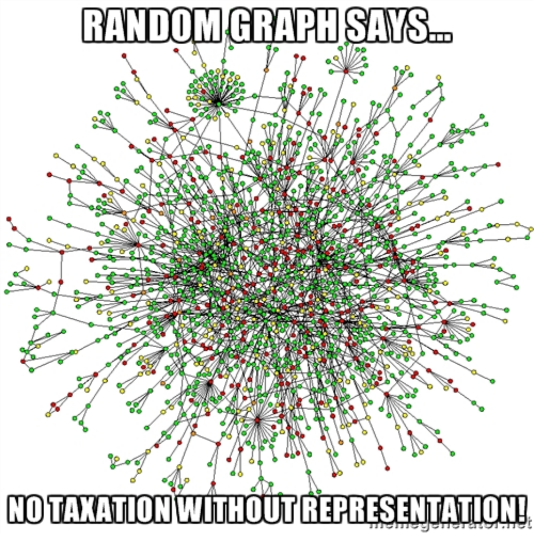
This talk is dedicated to...

...my very first encounter with alcohol – and beer in particular – almost exactly 30 years ago (on the evening of 30 April 1986, to be exact) in a certain pub/brewery in Prague.

Representation is an important issue




SO, WHO IS THIS RANDOM GRAPH CHARACTER?
I HATE IT ALREADY
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Ready for take-off: Homogeneous structures

Let $\mathcal{A}$ be a (countable) first order structure. $\mathcal{A}$ is said to be (ultra)homogeneous if any isomorphism

$$\iota : \mathcal{B} \to \mathcal{B}'$$

between its finitely generated substructures is a restriction of an automorphism α of $\mathcal{A}$: $\iota = \alpha|_B$.

Remark

If we restrict to relational structures, 'finitely generated' becomes simply 'finite'.

Classification programme for countable ultrahomogeneous structures

- finite graphs (Gardiner, 1976)
- posets (Schmerl, 1979)
- undirected graphs (Lachlan & Woodrow, 1980)
- tournaments (Lachlan, 1984)
- directed graphs (Cherlin, 1998 – Memoirs of AMS, 160+ pp.)
- semilattices (Droste, Kuske, Truss, 1999)
- finite groups (Cherlin & Felgner, 2000)
- permutations (Cameron, 2002)
- multipartite graphs (Jenkinson, Truss, Seidel, 2012)
- coloured multipartite graphs (Lockett, Truss, 2014)
- lattices – 'unclassifiable' (Abogatma, Truss, 2015)
- ...

Fraïssé theory

Fact

For any countably infinite ultrahomogeneous structure $\mathcal{A}$, its age $\mathrm{Age}(\mathcal{A})$ (the class of its finitely generated substructures) has the following properties:

- it has countably many isomorphism types;
- it is closed for taking (copies of) substructures;
- it has the joint embedding property (JEP);
- it has the amalgamation property (AP).

A class of finite(ly generated) structures with such properties is called a Fraïssé class.

Theorem (Fraïssé)

Let $\mathbf{C}$ *be a Fraïssé class. Then there exists a unique countably infinite ultrahomogeneous structure* $\mathcal{F}$ *such that* $\mathrm{Age}(\mathcal{F}) = \mathbf{C}$.

Fraïssé theory (continued)

The structure $\mathcal{F}$ from the previous theorem is called the Fraïssé limit of **C**.

Classical examples:

- finite chains $\longrightarrow (\mathbb{Q}, <)$
- finite undirected graphs $\longrightarrow$ the random graph R
- finite posets $\longrightarrow$ the random poset
- finite tournaments $\longrightarrow$ the random tournament
- finite metric spaces with rational distances $\longrightarrow$ the rational Urysohn space $\mathbb{U}_{\mathbb{Q}}$
- finite permutations $\longrightarrow$ the random permutation

Fraïssé limits over finite relational languages are ω-categorical, have quantifier elimination, oligomorphic automorphism groups,...

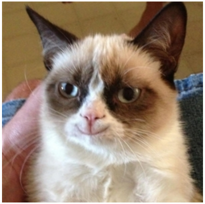
The random graph R

R = the unique countable existentially closed graph

You can get anything you want
at Alice's Restaurant

Arlo Guthrie: Alice's Restaurant Massacre (1967)

= for any disjoint finite sets of vertices A and B there is a vertex $v \notin A \cup B$ adjacent to all vertices from A and to none of B




ENDOMORPHISM MONOIDS?
MMM, DELICIOUS...
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Endomorphism monoids

Endomorphism of a first-order structure $\mathcal{A} = (A, R^{\mathcal{A}}, F^{\mathcal{A}}, C^{\mathcal{A}})$ = a transformation $f : A \to A$ preserving all relations from $R^{\mathcal{A}}$, all operations from $F^{\mathcal{A}}$, and all constants from $C^{\mathcal{A}}$.

All endomorphisms of $\mathcal{A}$ for a monoid (semigroup with 1) under composition of functions: $\mathrm{End}(\mathcal{A})$.

There are two ways in which groups can appear within a semigroup S:

- overt: as maximal subgroups of S;
- covert: as Schützenberger groups (of $\mathscr{D}$-classes of S)

Sometimes, there is a very fine line between overt and covert... ☺


IGOR!
Y U NO SEMIGROUP THEORY?
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Green's relations

The most fundamental tool in studying the structure of semigroups. (Named after J. Alexander "Sandy" Green (1926–2014).)

$$a \mathscr{R} b \iff aS^1 = bS^1 \iff (\exists x, y \in S^1)\, ax = b \,\&\, by = a$$

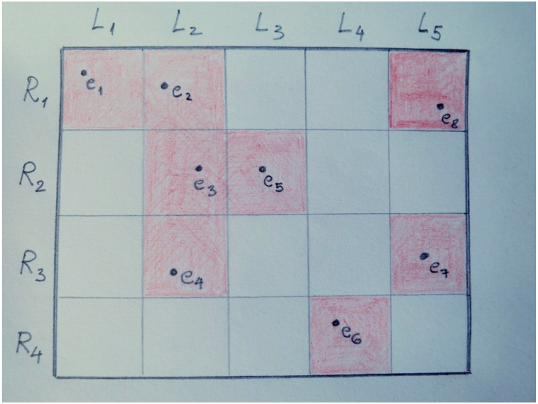
$$a \mathscr{L} b \iff S^1 a = S^1 b \iff (\exists u, v \in S^1)\, ua = b \,\&\, vb = a$$

$$\mathscr{D} = \mathscr{R} \circ \mathscr{L} = \mathscr{L} \circ \mathscr{R}$$

$$\mathscr{H} = \mathscr{R} \cap \mathscr{L}$$

$$a \mathscr{J} b \Leftrightarrow S^1 a S^1 = S^1 b S^1 \Leftrightarrow (\exists x, y, u, v \in S^1)\, uax = b \,\&\, vby = a$$

The eggbox picture of a $\mathscr{D}$-class



Groups (overt): $\mathscr{H}$-classes shaded red (these are all isomorphic)

maximal subgroups of a semigroup = $\mathscr{H}$-classes containing idempotents

Regularity

$a \in S$ is regular if

$$a = axa$$

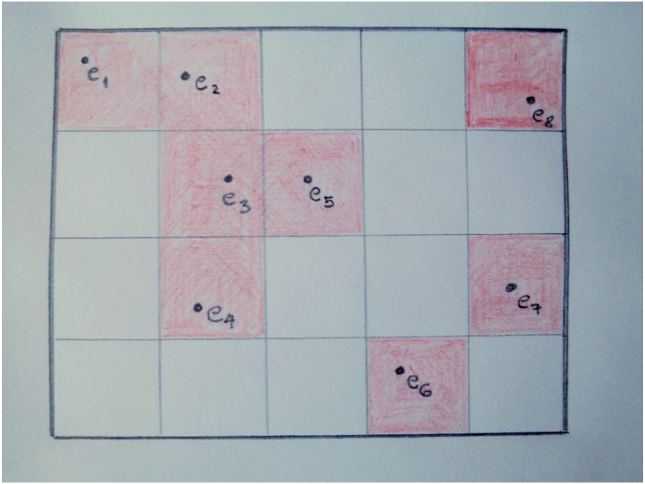
for some $x \in S$.

Fact

For any $\mathscr{D}$-class D, either all elements of D are regular or none of them.

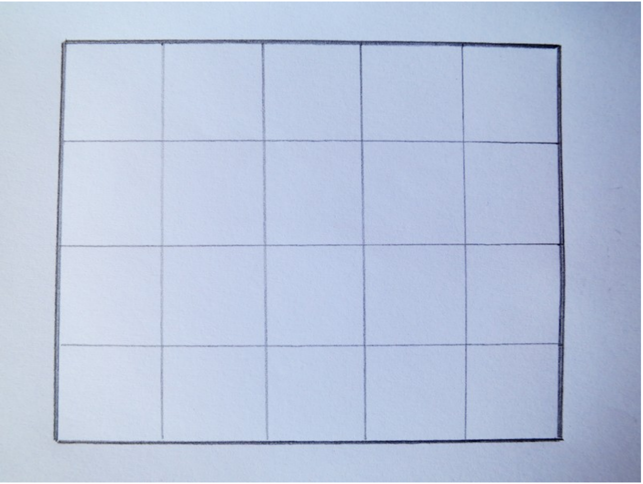
Hence, a is regular $\iff$ $a \mathrel{\mathscr{D}} e$ for and idempotent e.

A regular $\mathscr{D}$-class

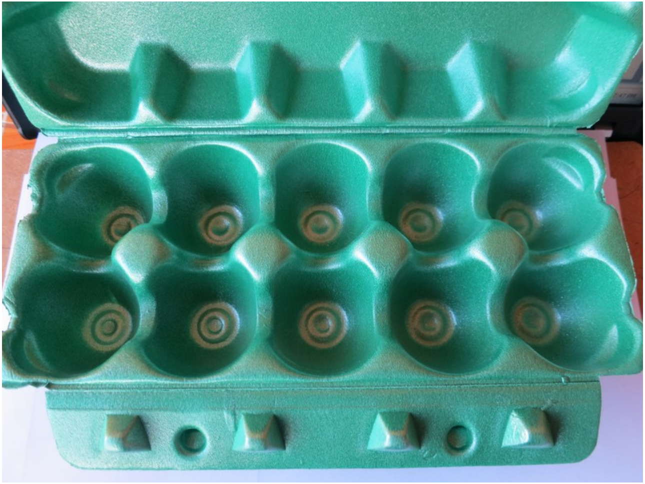


A regular eggbox

A non-regular $\mathscr{D}$-class



A non-regular eggbox



Schützenberger groups – groups the never were

There is a 'hidden' / covert group capturing the structure of a (non-regular) $\mathscr{D}$-class D, called the Schützenberger group of D.

Namely, let H be an $\mathscr{H}$-class within a $\mathscr{D}$-class D, and consider $T_H = \{t \in S^1 : \; Ht \subseteq H\}$.

Basic results of semigroup theory (Green's Lemma) show that each $\rho_t : H \to H$ ($t \in T_H$) defined by

$$h\rho_t = ht$$

is a permutation of H.

Hence, $S_H = \{\rho_t : \; t \in T_H\}$ is a permutation group on H. This is the (right) Schützenberger group of H.

Schützenberger groups – groups the never were

Fact

If both H_1, H_2 belong to D, then $S_{H_1} \cong S_{H_2}$. Hence the Schützenberger group is really an invariant of a $\mathscr{D}$-class of a semigroup.

Fact

If H is a group (so that D is regular), then $S_H \cong H$.

A classical example: $\mathcal{T}_X$

Fact

In $\mathcal{T}_X$ we have:

(1) $f \mathscr{R} g \iff \ker(f) = \ker(g)$;

(2) $f \mathscr{L} g \iff \mathrm{im}(f) = \mathrm{im}(g)$;

(3) $f \mathscr{D} g \iff \mathrm{rank}(f) = |im(f)| = |\mathrm{im}(g)| = \mathrm{rank}(g)$;

(4) $\mathscr{J} = \mathscr{D}$;

(5) if $e = e^2$ and $\mathrm{rank}(e) = k$, then $H_e \cong \mathbb{S}_k$;

(6) $\mathcal{T}_X$ is regular.


COULD WE GO
BACK TO ENDOMORPHISM MONOIDS, PLEASE?

End($\mathcal{A}$)

Let $\mathcal{A}$ be a first-order structure. Since $\mathrm{End}(\mathcal{A}) \leq \mathcal{T}_A$, if $f, g \in End(\mathcal{A})$ are $\mathscr{R}$-/$\mathscr{L}$-related in $\mathrm{End}(\mathcal{A})$ they are certainly $\mathscr{R}$-/$\mathscr{L}$-related in $\mathcal{T}_A$. Hence,

(i) $f \mathrel{\mathscr{R}} g \implies \ker(f) = \ker(g)$;

(ii) $f \mathrel{\mathscr{L}} g \implies \mathrm{im}(f) = \mathrm{im}(g)$.

Remark

We must be careful with the notion of an 'image' of an endomorphism if our language contains relational symbols, because besides $\mathrm{im}(f)$ we also have $\langle Af \rangle$, the induced substructure of A on Af.

Lemma

$f \mathrel{\mathscr{D}} g \implies \langle Af \rangle \cong \langle Ag \rangle$.

Regular elements in End($\mathcal{A}$)

Proposition (Magill, Subbiah, 1974)

If $f \in End(\mathcal{A})$ *is regular, then* $\mathrm{im}(f) = \langle Af \rangle$.

Lemma (Magill, Subbiah, 1974)

Let $f, g \in End(\mathcal{A})$ *be regular. Then:*

(i) $f \mathscr{R} g \iff \ker(f) = \ker(g)$;

(ii) $f \mathscr{L} g \iff \mathrm{im}(f) = \mathrm{im}(g)$;

(iii) $f \mathscr{D} g \iff \mathrm{im}(f) \cong \mathrm{im}(g)$;

(iv) *if* e *is idempotent, then* $H_e \cong \mathrm{Aut}(\mathrm{im}(e)) \cong \mathrm{Aut}(\mathrm{im}(f))$ *for any* $f \in D_e$.

Schützenberger groups in End($\mathcal{A}$)

Proposition

Let $f \in \mathrm{End}(\mathcal{A})$ *and* $H = H_f$.

(i) *If* $t \in T_H$*, then* $t|_{Af}$ *is an automorphism of both* $\langle Af \rangle$ *and* $\mathrm{im}(f)$;

(ii) *the mapping* $\phi : \rho_t \mapsto t|_{Af}$ *is an embedding of* S_H *into* $\mathrm{Aut}(\langle Af \rangle) \cap \mathrm{Aut}(\mathrm{im}(f))$.

So, what the heck are the images of (idempotent) endomorphisms of Fraïssé limits?

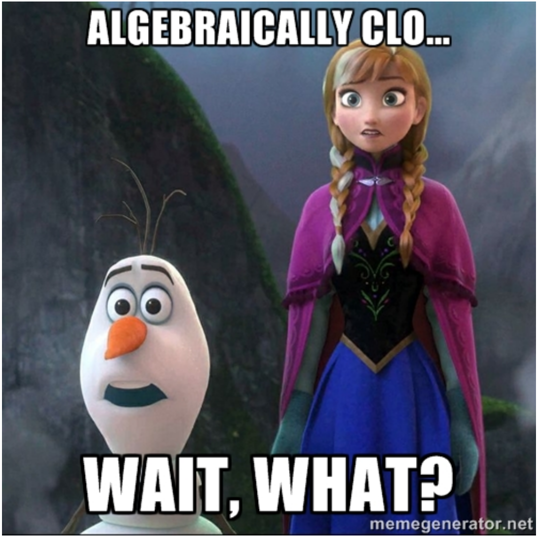
Call a Fraïssé class **C** neat if it consists of finite structures, and for each $n \geq 1$ the number of isomorphism types of n-generated structures in **C** is finite.

Examples:

- relational structures
- Fraïssé classes of algebras contained in locally finite varieties

Theorem (ID, 2012)

Let **C** *be a neat Fraïssé class enjoying the strict AP and the 1PHEP. Then there exists and (idempotent) endomorphism f of F, the Fraïssé limit of* **C**, *such that $\mathcal{A} \cong \mathrm{im}(f)$ if and only if $\mathcal{A}$ is algebraically closed in* $\overline{\mathbf{C}}$.


ALGEBRAICALLY CLO...
WAIT, WHAT?
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Algebraically closed stuff

An L-formula $\Phi(\mathbf{x})$ is primitive if it is of the form

$$(\exists \mathbf{y}) \bigwedge_{i<k} \Psi_i(\mathbf{x}, \mathbf{y})$$

where each Ψ_i is a literal: an atomic formula or its negation. No negation $\longrightarrow$ primitive positive formula.

Let $\mathbf{K}$ be a class of L-structures. An L-structure $\mathcal{A}$ is existentially (algebraically) closed (in $\mathbf{K}$) if for any primitive (positive) formula $\Phi(\mathbf{x})$ and any tuple $\mathbf{a}$ from A we have already $\mathcal{A} \models \Phi(\mathbf{a})$ whenever there is an extension $\mathcal{A}' \in \mathbf{K}$ of $\mathcal{A}$ such that $\mathcal{A}' \models \Phi(\mathbf{a})$.

Graphs

Countable e.c. graphs: R (Alice's Restaurant property)
Countable a.c. graphs: any finite set of vertices has a common neighbour ($\Rightarrow$ infinitely many of them)

In the rest of this talk we will be concerned with simple graphs and $\mathrm{End}(R)$. However, all these results can be adapted for:

- the random digraph,
- the random bipartite graph,
- the random (non-strict) poset,
- ...

Proposition

A countable graph (V, E) is a.c. if and only if there exists $E' \subseteq E$ such that $(V, E') \cong R$ (that is, it is e.c.). Consequently, for any a.c. graph Γ there is a bijective homomorphism $R \to \Gamma$.


WOW, COOL!
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Frucht's Theorem (1939)

Any finite group is $\cong \mathrm{Aut}(\Gamma)$ for a finite graph Γ.

de Groot / Sabidussi (1959/60) $\Rightarrow$ automorphism groups of countable graphs include all countable groups.

Name of the game: Strengthen this for countable a.c. graphs.

The team

Point Guard:
Martyn Quick

Forward:
"Baby" James Mitchell

Center:
Jillian "Jay" McPhee

Shooting Guard:
Robert "Bob" Gray

Power Forward:
Dr. D

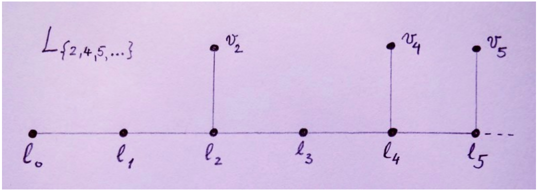
Automorphism groups of countable a.c. graphs

Theorem

Let Γ be a countable graph. Then there exist $2^{\aleph_0}$ pairwise non-isomorphic countable a.c. graphs whose automorphism group is $\cong \mathrm{Aut}(\Gamma)$.

Proof. For a (simple) graph Δ, let $\Delta^\dagger$ denote its complement.

- $\mathrm{Aut}(\Delta^\dagger) = \mathrm{Aut}(\Delta)$.
- Δ any graph, Λ infinite locally finite graph $\Rightarrow (\Delta \uplus \Lambda)^\dagger$ is a.c.
- The central idea – consider l.f. graphs L_S for $S \subseteq \mathbb{N} \setminus \{0,1\}$:



Automorphism groups of countable a.c. graphs

Proof (cont'd).

- Properties of L_S $(S, T \subseteq \mathbb{N} \setminus \{0,1\})$:
  - Each L_S is rigid ($\mathrm{Aut}(L_S) = \mathbf{1}$).
  - $L_S \cong L_T \iff S = T$.
- If L_S is isomorphic to no connected component of Γ (and this excludes only countably many choices of S), then

$$\mathrm{Aut}(\Gamma \uplus L_S)^{\dagger} = \mathrm{Aut}(\Gamma \uplus L_S) \cong \mathrm{Aut}(\Gamma) \times \mathrm{Aut}(L_S) \cong \mathrm{Aut}(\Gamma).$$

- $S_1 \neq S_2$ yield non-isomorphic a.c. graphs.

Images of idempotent endomorphisms

Theorem (Bonato, Delić, 2000; ID, 2012)

Let Γ be a countable graph. There exists an idempotent $f \in \mathrm{End}(R)$ such that $\mathrm{im}(f) \cong \Gamma$ if and only if Γ is a.c.

Theorem

If Γ is a countable a.c. graph, then there exists an (induced) subgraph $\Gamma' \cong \Gamma$ of R such that there are $2^{\aleph_0}$ idempotent endomorphisms f of R such that $\mathrm{im}(f) = \Gamma'$.

The number of regular $\mathscr{D}$-classes with a given group $\mathscr{H}$-class

Theorem

(i) *Let* Γ *be a countable graph. Then there exist* $2^{\aleph_0}$ *distinct regular* $\mathscr{D}$*-classes of* $\mathrm{End}(R)$ *whose group* $\mathscr{H}$*-classes are* $\cong \mathrm{Aut}(\Gamma)$.

(ii) *Every regular* $\mathscr{D}$*-class contains* $2^{\aleph_0}$ *distinct group* $\mathscr{H}$*-classes.*

Corollary

$\mathrm{End}(R)$ *has* $2^{\aleph_0}$ *regular* $\mathscr{D}$*-classes. (You know, the ones with eggs...)*

The size of a regular eggbox

Theorem

Every regular $\mathscr{D}$-class of End(R) *contains* $2^{\aleph_0}$ *many* $\mathscr{R}$*- and* $\mathscr{L}$*-classes.*

Proof. Let e be an idempotent endomorphism of R, and let $\Gamma = \text{im}(e)$ (a.c.).

$\mathscr{R}$-classes: Assume R is constructed as R_Γ. (Start with Γ; at each stage, for any finite subset S of vertices of the existing graph, add a new vertex adjacent to S and nothing else; iterate this $\aleph_0$ times.)

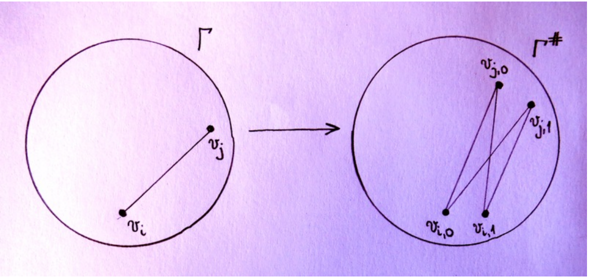
We already know that the identity mapping on Γ can be extended to $f \in \text{End}(R)$ in $2^{\aleph_0}$ ways such that $\text{im}(f) = \text{im}(e)$.

All such f are idempotents, and $f \mathrel{\mathscr{D}} e$, moreover, $f \mathrel{\mathscr{L}} e$.

However, all these idempotents are not $\mathscr{R}$-related.

The size of a regular eggbox

$\mathscr{L}$-classes: Key idea – construct the graph $\Gamma^\sharp$ from Γ by replacing each edge by the following gadget:



Construct R around $\Gamma^\sharp$, so that $R = R_{\Gamma^\sharp}$.

Γ a.c. $\Longrightarrow$ $\Gamma^\sharp$ a.c. Hence, the identity map on $\Gamma^\sharp$ can be extended to an endomorphism $g : R \to \Gamma^\sharp$.

The size of a regular eggbox

For each binary sequence $\mathbf{b} = (b_i)_{i \in \mathbb{N}}$ define a map $\psi_\mathbf{b}$ on $\Gamma^\sharp$ by

$$v_{i,r}\psi_\mathbf{b} = v_{i,b_i}$$

for all $i \in \mathbb{N}$ and $r \in \{0, 1\}$. Easy: $\psi_\mathbf{b} \in \mathrm{End}(\Gamma^\sharp)$ and $\mathrm{im}(\psi_\mathbf{b}) \cong \Gamma$ is induced by $\{v_{i,b_i} : i \in \mathbb{N}\}$.

$g\psi_\mathbf{b} \in \mathrm{End}(R)$ are idempotents, $\mathrm{im}(g\psi_\mathbf{b}) \cong \Gamma \Rightarrow$ all these idempotents are $\mathscr{D}$-related to e.

Different images $\Rightarrow$ they are not $\mathscr{L}$-related.

Non-regular eggboxes

Theorem

Let $\Gamma \not\cong R$ be a countable a.c. graph. Then there exists a non-regular endomorphism of R such that $\mathrm{im}(f) \cong \Gamma$ and D_f contains $2^{\aleph_0}$ many $\mathscr{R}$- and $\mathscr{L}$-classes.

The proof is a variation of the idea of $\Gamma^\sharp$ and binary sequences.

Theorem

There are $2^{\aleph_0}$ non-regular $\mathscr{D}$-classes in $\mathrm{End}(R)$.

Open Problem

Are there any non-regular eggboxes of some other size?

Schützenberger groups in End(R)

Let $\Gamma = (V_0, E_0)$ be a countable a.c. graph. Then, as we already know, there is a subset $F \subseteq E_0$ such that $(V_0, F) \cong R$. Now build $R_\Gamma \cong R$ around Γ, and let $f : R_\Gamma \to (V_0, F)$ be an isomorphism. Then f is an injective endomorphism of R; if $F \neq E_0$ then f is non-regular.

Proposition

Let f be an injective endomorphism of $R = (V, E)$ as described above, with $Vf = V_0$. Then

$$S_{H_f} \cong \mathrm{Aut}(\langle V_0 \rangle) \cap \mathrm{Aut}(\mathrm{im}(f))$$

Schützenberger groups in End(R)

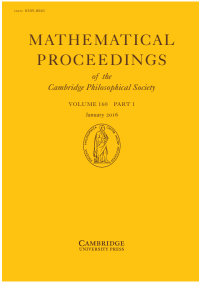
So, to show a universality result for Schützenberger groups in End(R), one needs to extend the Frucht-de Groot-Sabidussi Theorem to countable a.c. graphs with 2-coloured edges (blue and red, say) where the 'red graph' is $\cong R$.

This is what we did via an involved construction that again uses the rigid graphs L_S (for a particular countable family of sets S).

Theorem

Let Γ be any countable graph. There are $2^{\aleph_0}$ non-regular $\mathscr{D}$-classes of End(R) *such that the Schützenberger groups of the $\mathscr{H}$-classes within them are* $\cong$ Aut(Γ).

Reference



ID, R.D.Gray, J.D.McPhee, J.D.Mitchell, M.Quick:
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Math. Proc. Cambridge Phil. Soc. **160** (2016), 437–462.

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THANK YOU!

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