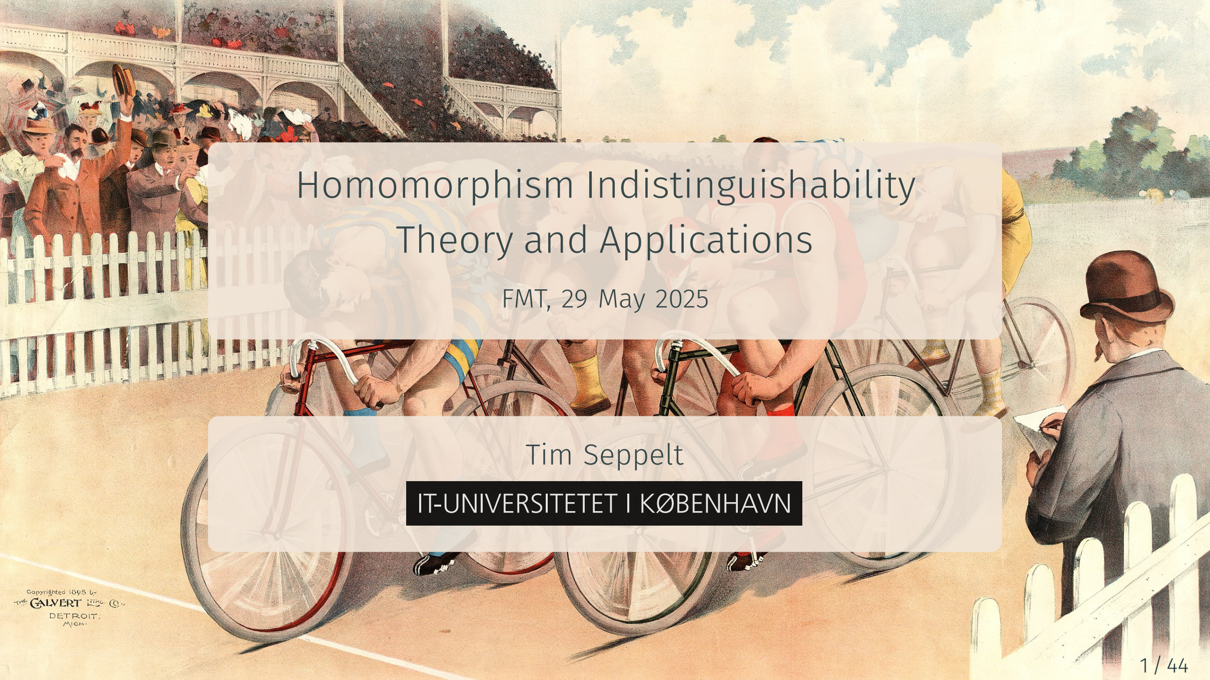
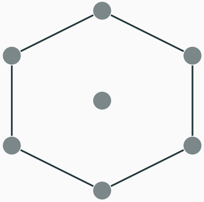


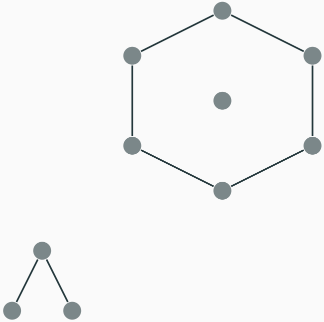
Homomorphism Indistinguishability
Theory and Applications

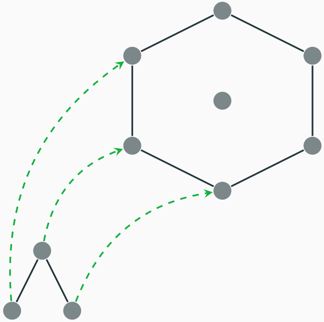
FMT, 29 May 2025

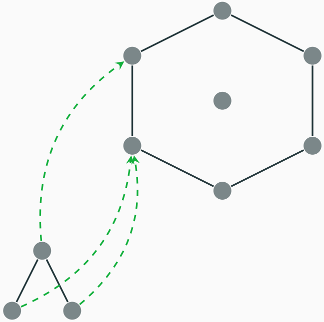
Tim Seppelt

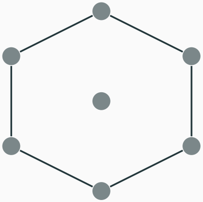
IT-UNIVERSITETET I KØBENHAVN

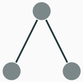












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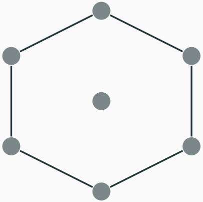

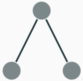

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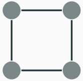

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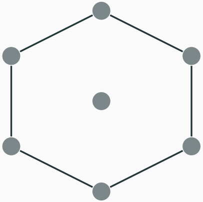
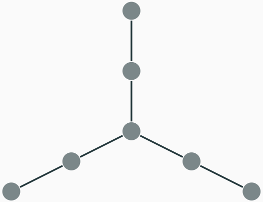
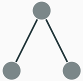
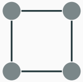
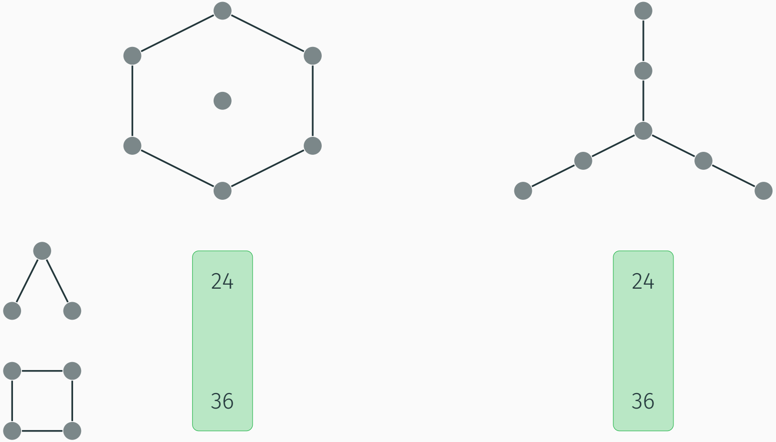
		
	24	24
	36	36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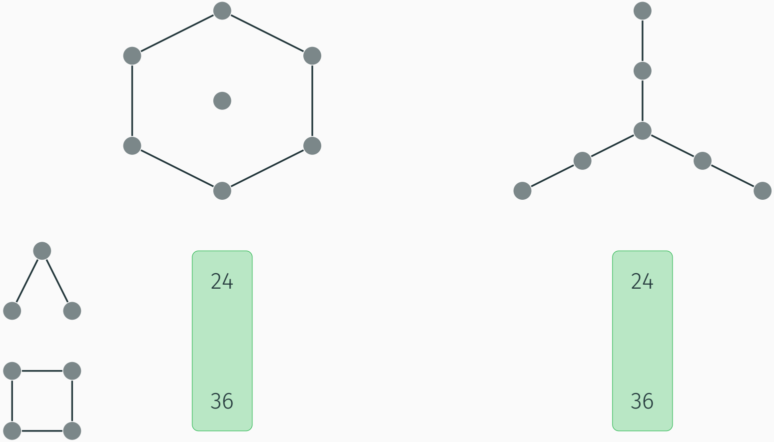
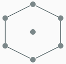
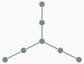


The graphs  and  are **homomorphism indistinguishable** over $\{$, $\}$.

graph class $\mathcal{F}$	relation $\equiv_{\mathcal{F}}$	
all graphs	isomorphism	Lovász (1967)

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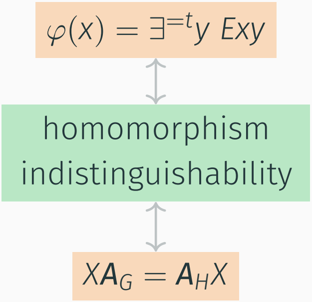
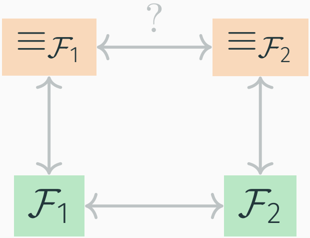
	Graph Neural Networks	Xu, Hu, Leskovec, & Jegelka (2018); Morris, Ritzert, Fey, Hamilton, Lenssen, Rattan, & Grohe (2019)



Characterisations
How to characterise $\equiv_{\mathcal{F}}$?

Distinguishing Power
What's the power of $\equiv_{\mathcal{F}}$?

Complexity
How to test $\equiv_{\mathcal{F}}$?



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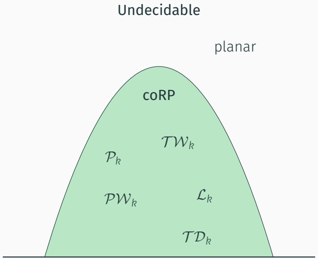

Characterisations

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How to test $\equiv_{\mathcal{F}}$?

$\varphi(x) = \exists^{=t} y\ Exy$

↕

homomorphism indistinguishability

↕

$XA_G = A_H X$

Characterisations

How to characterise $\equiv_{\mathcal{F}}$?

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What's the power of $\equiv_{\mathcal{F}}$?

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Observation

Two graphs if, and only if, they are homomorphism indistinguishable over {●}.

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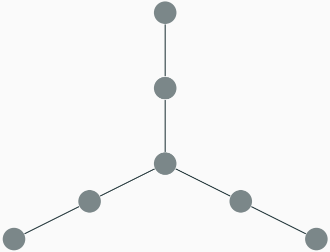

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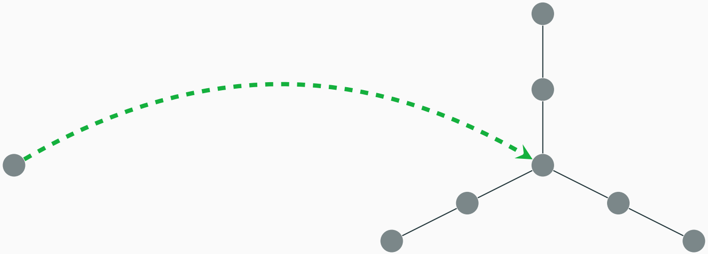

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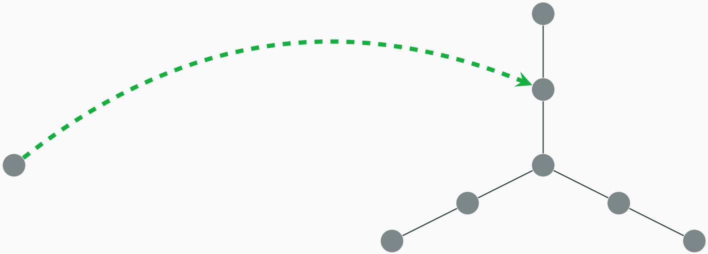

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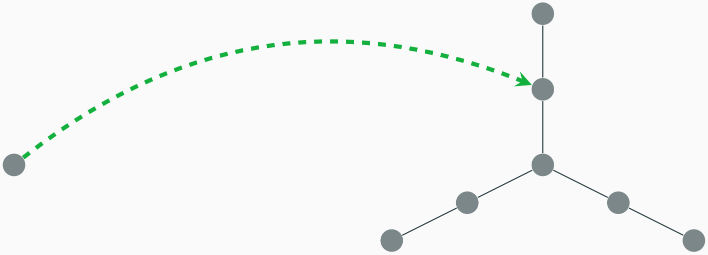
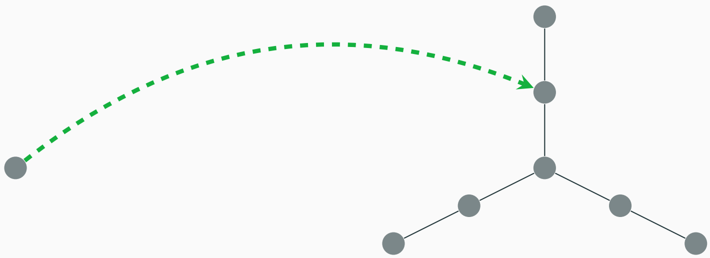


$$\hom(\bullet, G) = |V(G)|.$$

Observation

Two graphs have the same number of vertices if, and only if, they are homomorphism indistinguishable over {●}.



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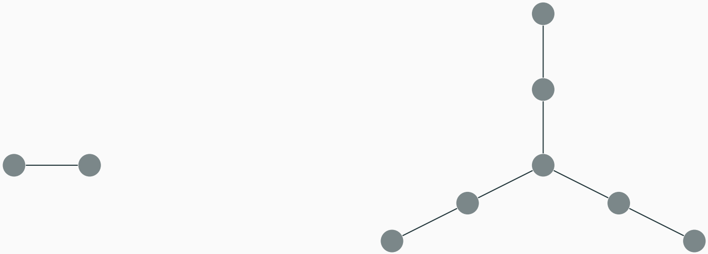

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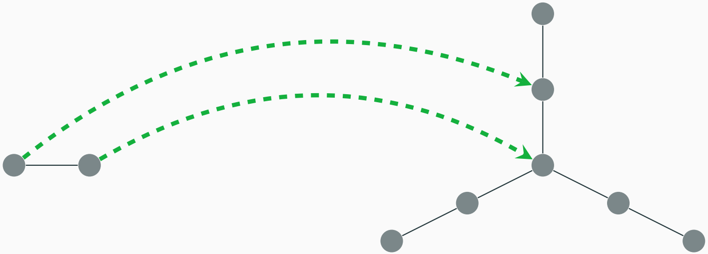

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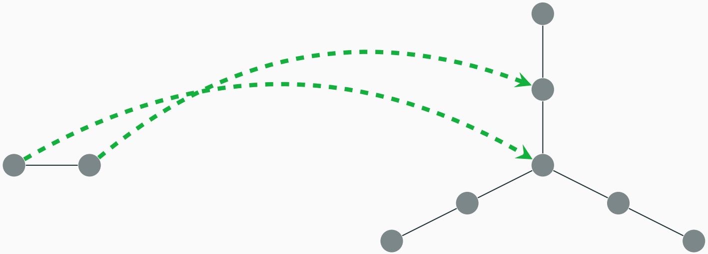
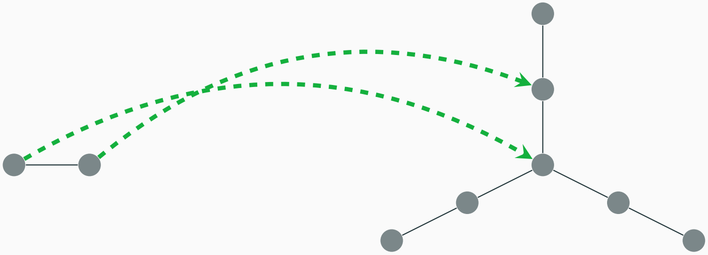


Observation

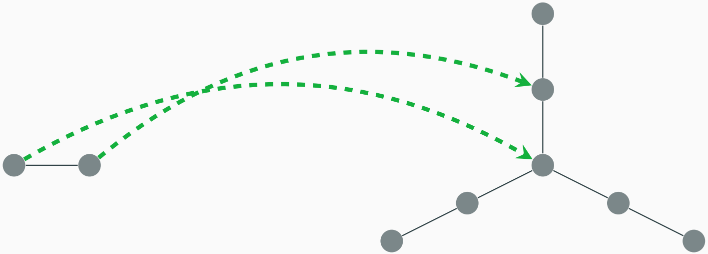
Two graphs if, and only if, they are homomorphism indistinguishable over $\{\bullet\!-\!\bullet\}$.



$$\hom(\bullet\!-\!\bullet, G) = 2|E(G)|.$$

Observation

Two graphs have the same number of edges if, and only if, they are homomorphism indistinguishable over {●–●}.



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Two graphs if, and only if, they are homomorphism indistinguishable over stars.

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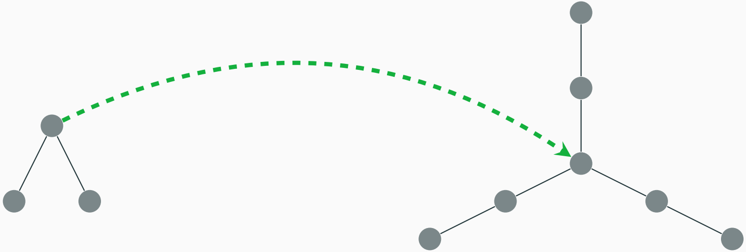

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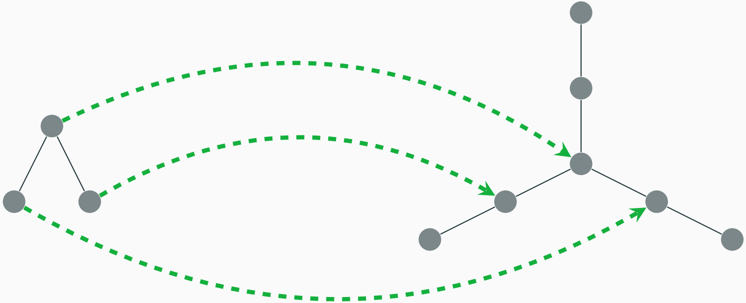

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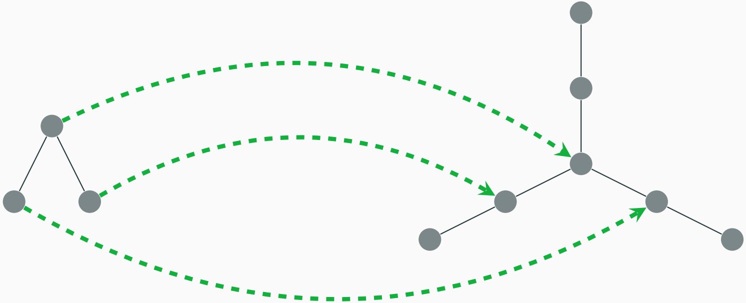
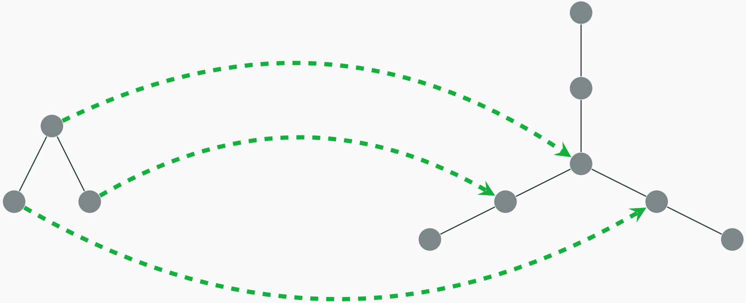


$$\hom(S_\ell, G) = \sum_{v \in V(G)} (\deg(v))^\ell$$

Observation

Two graphs have the same degree sequence if, and only if, they are homomorphism indistinguishable over stars.



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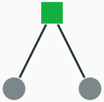
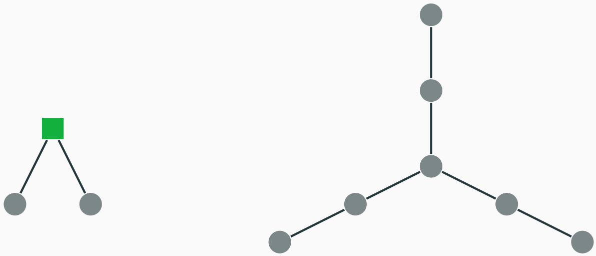
Theorem (Dvořák (2010); Dell, Grohe, & Rattan (2018))

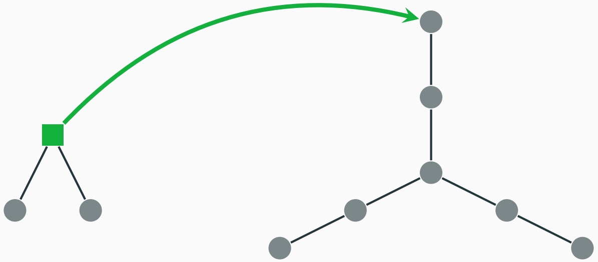
Two graphs are C^k-equivalent if, and only if, they are homomorphism indistinguishable over the graphs of treewidth $< k$.

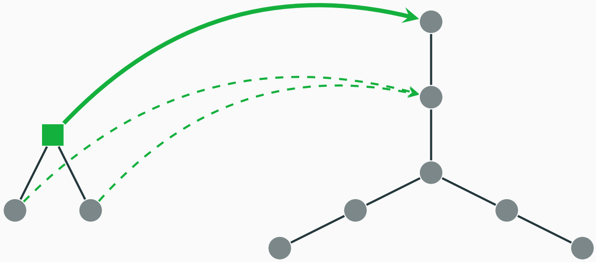
Theorem (Mančinska & Roberson (2020))

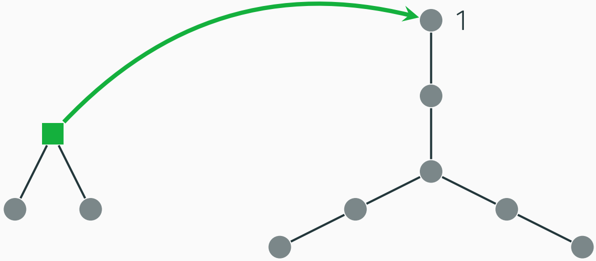
Two graphs are quantum isomorphic if, and only if, they are homomorphism indistinguishable over all planar graphs.







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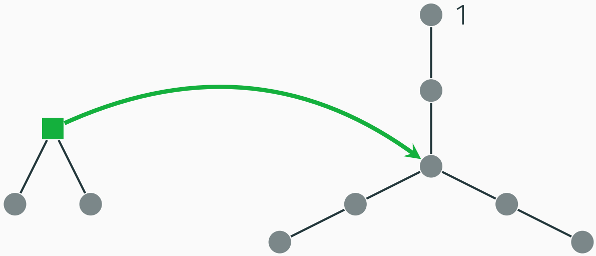
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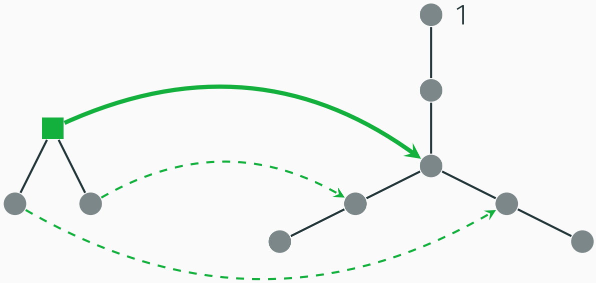
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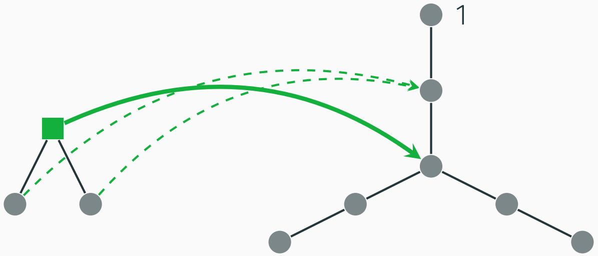
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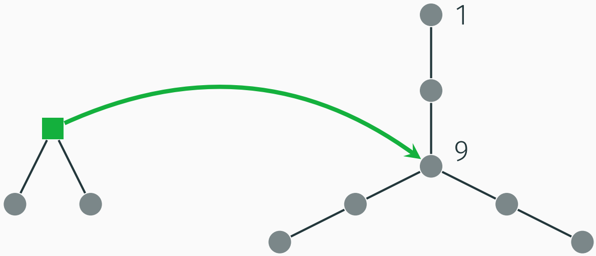
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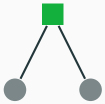
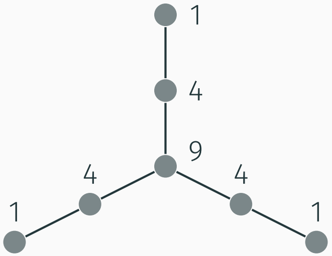
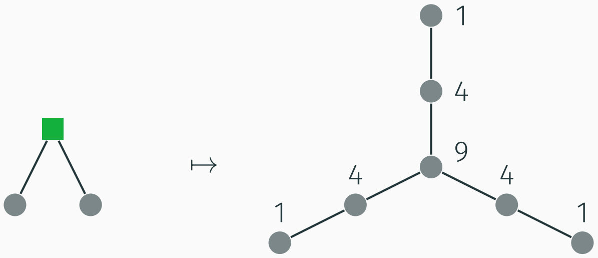
labelled graphs $\rightarrow$ homomorphism vectors $\subseteq \mathbb{R}^{V(G)}$



$\mapsto$

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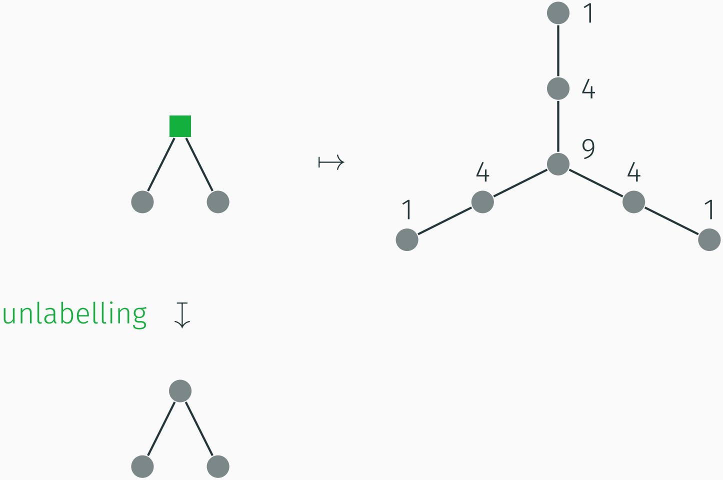
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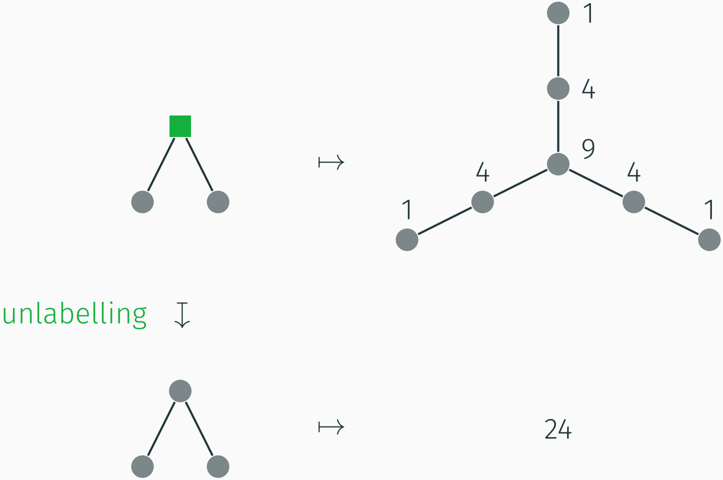
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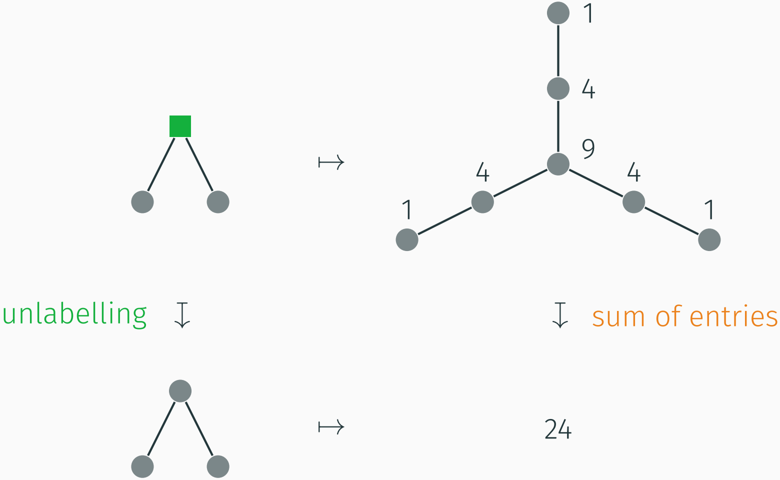
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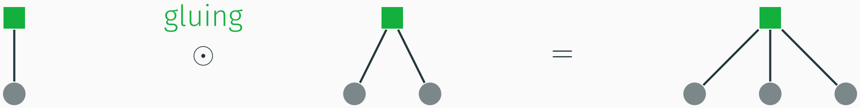
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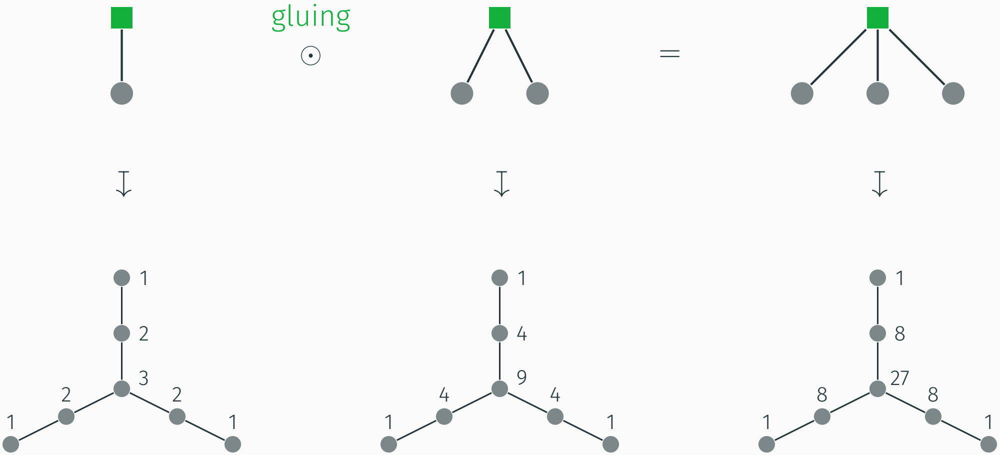
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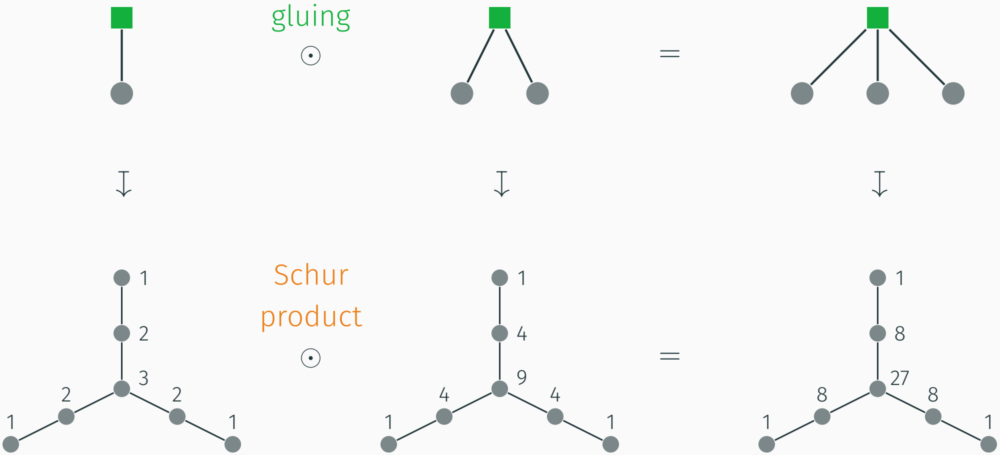
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Theorem (Dvořák (2010); Dell, Grohe, & Rattan (2018))

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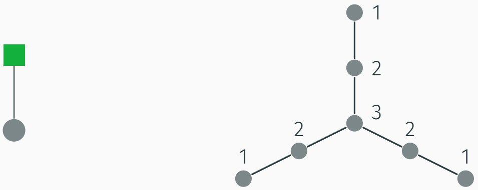

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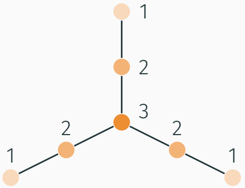

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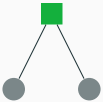

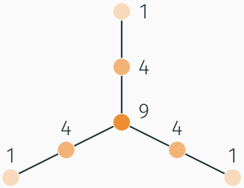

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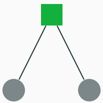

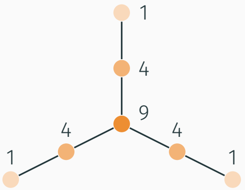

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C_q	treedepth $\leq q$	Grohe (2020)
C^k_q	k-pebble forest cover of depth $\leq q$	Dawar, Jakl, & Reggio (2021)
		Fluck, S., Spitzer (2024)
$\curlywedge\mathsf{C}^k$	pathwidth $< k$	Montacute & Shah (2022)

$\varphi(x) = \exists^{=t} y\ Exy$

↕

homomorphism indistinguishability

↕

$XA_G = A_H X$

Characterisations

How to characterise $\equiv_{\mathcal{F}}$?

Distinguishing Power

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A matrix $X = (x_{ij})$ over some C^*-algebra is a *quantum permutation matrix* if

$$x_{ij}^2 = x_{ij} = x_{ij}^*, \qquad \sum_k x_{ik} = 1 = \sum_k x_{kj}.$$

$$XA_G = A_H X$$

planar graphs
quantum permutation

Lupini, Mančinska, & Roberson (2020); Mančinska & Roberson (2020); Lovász (1967); Dell, Grohe, & Rattan (2018); Grohe, Rattan, & S. (2022); S. (2024).

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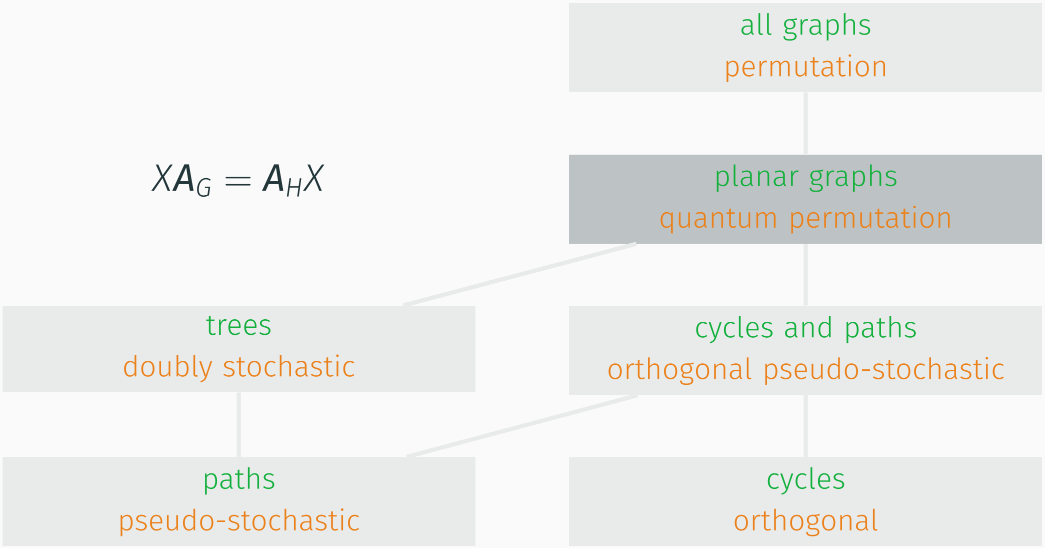

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$$\mapsto \begin{matrix} 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{matrix}$$

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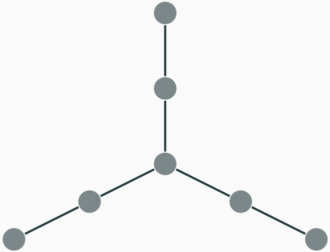
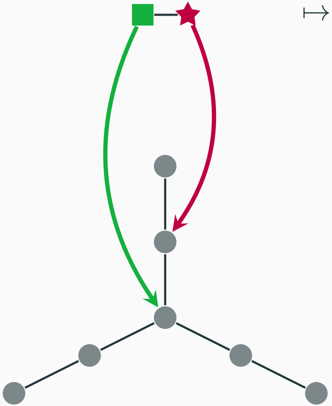
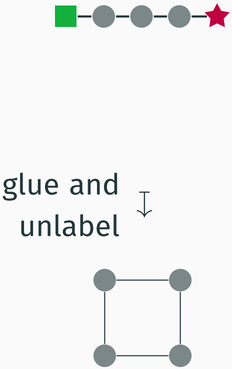


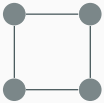


$$\mapsto \left\{ \begin{matrix} 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{matrix} \right.$$


glue and
unlabel

$$\mapsto \begin{matrix} 12 & 0 & 4 & 0 & 4 & 0 & 4 \\ 0 & 6 & 0 & 5 & 0 & 5 & 0 \\ 4 & 0 & 2 & 0 & 1 & 0 & 1 \\ 0 & 5 & 0 & 6 & 0 & 5 & 0 \\ 4 & 0 & 1 & 0 & 2 & 0 & 1 \\ 0 & 5 & 0 & 5 & 0 & 6 & 0 \\ 4 & 0 & 1 & 0 & 1 & 0 & 2 \end{matrix}$$

glue and unlabel ↧



↦

12	0	4	0	4	0	4
0	6	0	5	0	5	0
4	0	2	0	1	0	1
0	5	0	6	0	5	0
4	0	1	0	2	0	1
0	5	0	5	0	6	0
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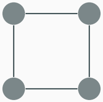
glue and unlabel ↧

↧ trace



↦ 36

Theorem

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Theorem (Specht (1940))

For symmetric matrices A and B, there is an orthogonal matrix X such that $XA = BX$ if, and only if, $\mathrm{tr}(A^n) = \mathrm{tr}(B^n)$ for all $n \in \mathbb{N}$.

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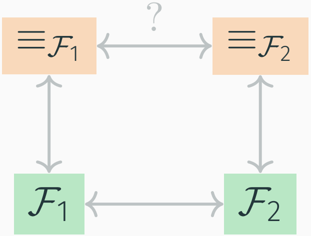
- Russell (2023): the NPA hierarchy converges.

Characterisations

How to characterise $\equiv_{\mathcal{F}}$?



Distinguishing Power

What's the power of $\equiv_{\mathcal{F}}$?

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Homomorphism indistinguishability over cycles is not isomorphism.

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A graph class $\mathcal{F}$ is homomorphism distinguishing closed if, for all $F' \notin \mathcal{F}$,

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Observation

If $\mathcal{F}_1$ is homomorphism distinguishing closed, then

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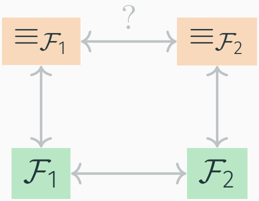

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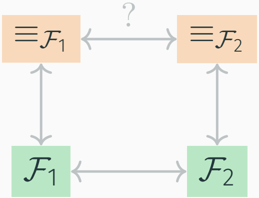

- optimisation — Roberson & S. (2023)
- machine learning — Zhang, Gai, Du, Ye, He, & Wang (2024)
- finite model theory — Adler, Fluck, S., & Spitzer (2025)

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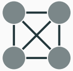
- planar graphs — Roberson (2022)
- treewidth $\leq k$ — Neuen (2024)
- treedepth $\leq q$ — Fluck, S., & Spitzer (2024)
- k-pebble forest cover of depth $\leq q$ — Adler & Fluck (2024)
- pathwidth $\leq k$ — S. (2024)
- essentially finite graph classes — S. (2023)
- outerplanar graphs — Neuen & S. (2024)



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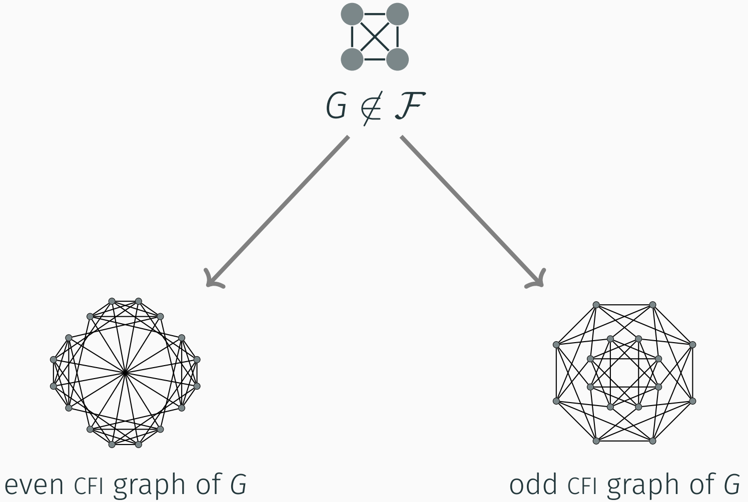
$G \notin \mathcal{F}$
even CFI graph of G
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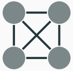

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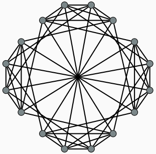

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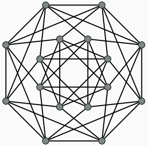

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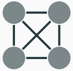

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Graph searching game

Robber

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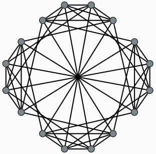

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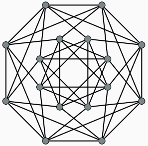

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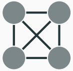

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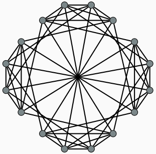

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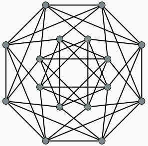

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Graph searching game

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Model comparison game

Duplicator

Theorem (Roberson (2022))

For a connected graph G and any graph F, tfae:

1. $\hom(F, G_0) \neq \hom(F, G_1)$,
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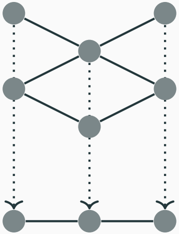
If $F \to G$ is a weak oddomorphism, then

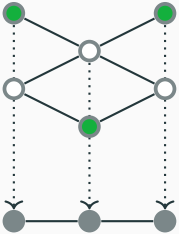
- $\mathrm{tw}(F) \geq \mathrm{tw}(G)$, Neuen (2024)
- $\mathrm{td}(F) \geq \mathrm{td}(G)$, Fluck, S., & Spitzer (2024)
- $\mathrm{pw}(F) \geq \mathrm{pw}(G)$, S. (2024)
- F planar $\implies$ G planar, Roberson (2022)
- $\Delta(F) \geq \Delta(G)$, Roberson (2022)
- F outerplanar $\implies$ G outerplanar. Neuen & S. (2024)

Let $\varphi\colon F \to G$ be a homomorphism.



Let $\varphi\colon F \to G$ be a homomorphism.

A vertex $a \in V(F)$ is φ-even / φ-odd if $|N_F(a) \cap \varphi^{-1}(u)|$ is even / odd for every $u \in N_G(\varphi(a))$.



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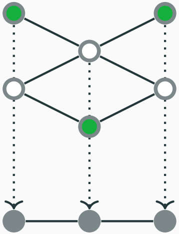

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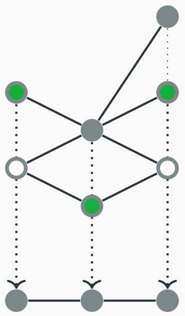

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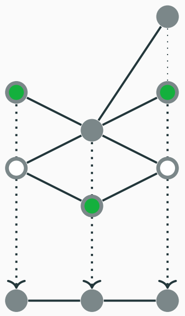

Hypothesis

If $F \to G$ is a weak oddomorphism, then G is a minor of F.

Theorem (S. (2023))

For every homomorphism distinguishing closed graph class $\mathcal{F}$,

$$\mathcal{F} \text{ is minor-closed} \iff \equiv_{\mathcal{F}} \text{ is preserved under complements.}$$

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- Typical graph isomorphism relaxations are preserved under complements.
- Towards a **theory of homomorphism indistinguishability**, we can focus on minor-closed graph classes.

Theorem (Roberson (2022))

There are uncountably many homomorphism distinguishing closed graph classes.

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Theorem (van Dobben de Bruyn, Marquès, Roberson, S., Zeman (2025+))

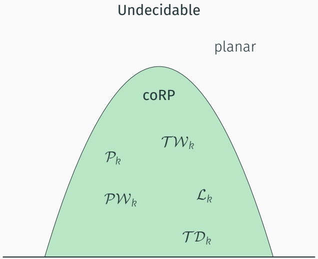
There is a topology whose closed sets are precisely the homomorphism distinguishing closed sets.

Characterisations

How to characterise $\equiv_{\mathcal{F}}$?

Distinguishing Power

What's the power of $\equiv_{\mathcal{F}}$?



Complexity

How to test $\equiv_{\mathcal{F}}$?

Let $\mathcal{F}$ be minor-closed and proper.

HomInd($\mathcal{F}$)	
Input	Graphs G and H.
Decide	$G \equiv_{\mathcal{F}} H$.

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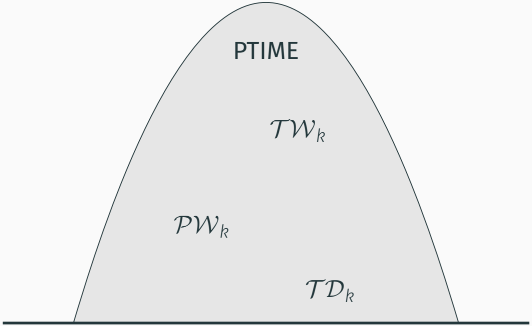

Dell, Grohe, & Rattan (2018); Dvořák (2010); Grohe (2020); Grohe, Rattan, S. (2022)

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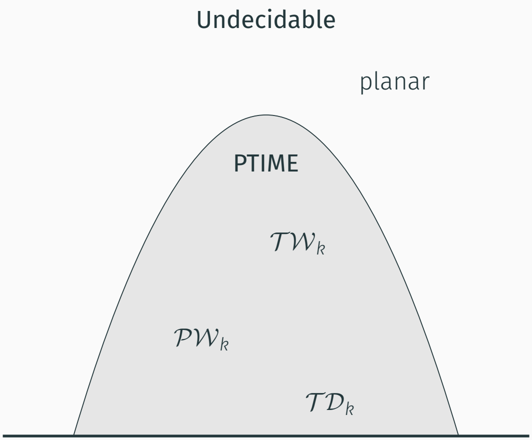

Dell, Grohe, & Rattan (2018); Dvořák (2010); Grohe (2020); Grohe, Rattan, S. (2022); Mančinska & Roberson (2020); Atserias, Mančinska, Roberson, Šámal, Severini, & Varvitsiotis (2019); Slofstra (2019)

Theorem (S. (2024))

If $\mathcal{F}$ is recognisable and of bounded treewidth, then $\textsc{HomInd}(\mathcal{F})$ *is in* coRP.

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Reduction to equivalence testing for $\mathbb{Q}$-weighted tree automata, which is LOGSPACE interreducible with arithmetic circuit identity testing.

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Reduction to equivalence testing for $\mathbb{Q}$-weighted automata. Tzeng (1996)

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Corollary (S. (2024); Kar, Roberson, S., & Zeman (2025))

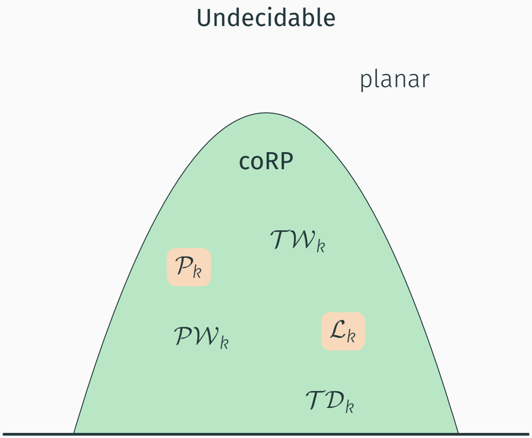
The following problems are in coRP*:*

- *exact feasibility of the level-k Lasserre relaxation of graph isomorphism,*
- *exact feasibility of the level-k NPA relaxation of quantum isomorphism.*

Let $\mathcal{F}$ be minor-closed and proper.

Theorem (S. (2024))

If $\mathcal{F}$ has bounded treewidth, then HomInd($\mathcal{F}$) *is in* coRP.



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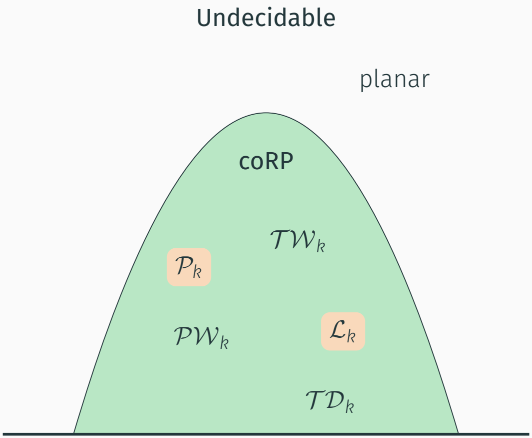

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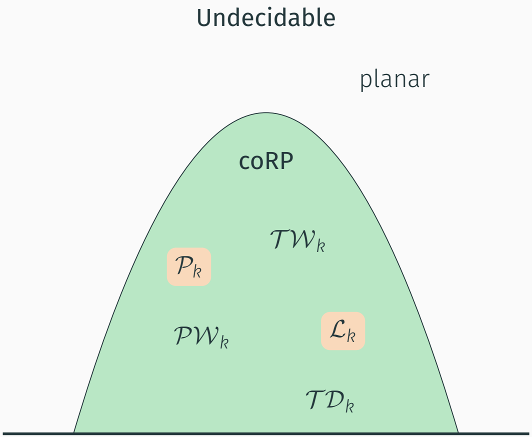
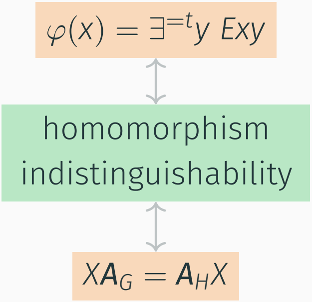
Otherwise, HomInd($\mathcal{F}$) *is undecidable.*





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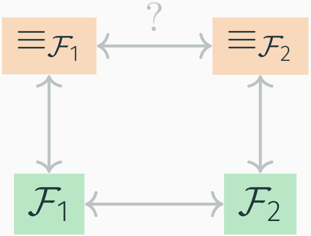

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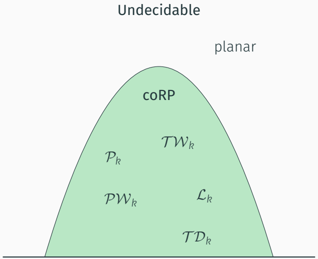

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$\varphi(x) = \exists^{=t} y \; Exy$

↕

homomorphism indistinguishability

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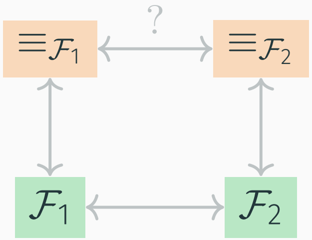
- Results by Lovász (1967); Dvořák (2010); Mančinska & Roberson (2020)
- **Tools:** labelled graphs and homomorphism vectors



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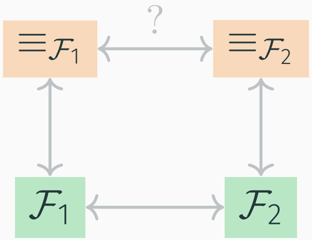

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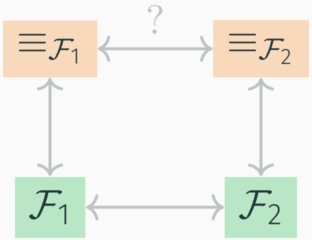

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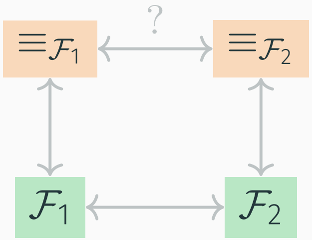
Theory of Homomorphism Indistinguishability



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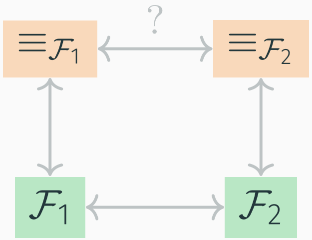

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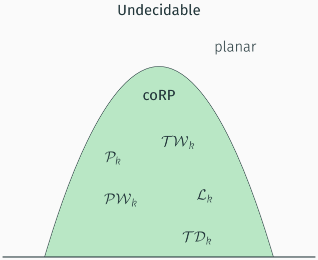
- minor-closed graph classes play a central role.
- **Open:** Roberson's conjecture



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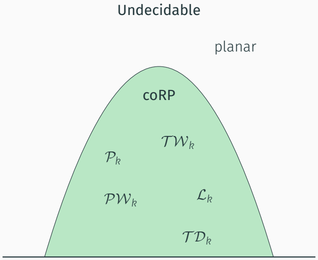

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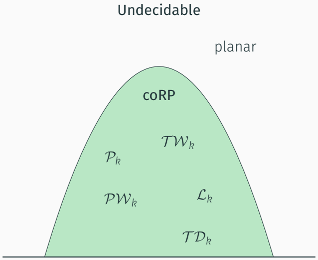

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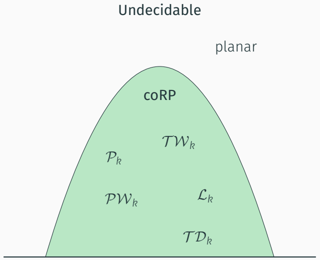

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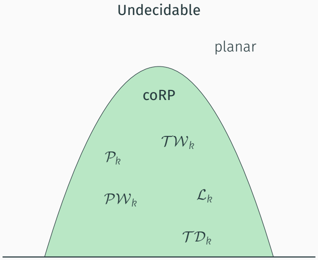

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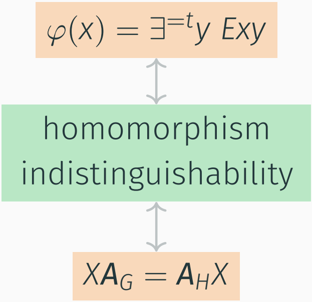
- coRP-algorithms for SDP relaxations of (quantum) isomorphism

Homomorphism Indistinguishability Zoo

`tseppelt.github.io/homind-database`

Graph classes and their homomorphism indistinguishability properties.



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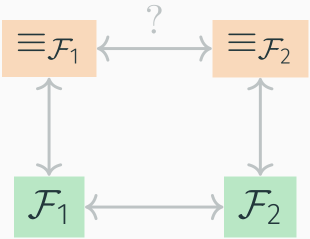

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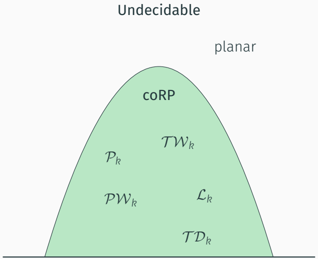

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Title Picture: 'Bicycle race scene. A peloton of six cyclists crosses the finish line in front of a crowded grandstand, observed by a referee.' (1895) by Calvert Lithographic Co., Detroit, Michigan, Public Domain, via Wikimedia Commons. `https://commons.wikimedia.org/wiki/File:Bicycle_race_scene,_1895.jpg`