Mixing Colour(ing)s in Graphs

JAN VAN DEN HEUVEL

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Department of Mathematics
London School of Economics and Political Science

- reporting research by : PAUL BONSMA (ex-Twente)
  LUIS CERECEDA (ex-LSE)
  JVDH (LSE)
  and MATTHEW JOHNSON (Durham)
  - in several different combinations

- and it all started with a question of
  HAJO BROERSMA (Durham)

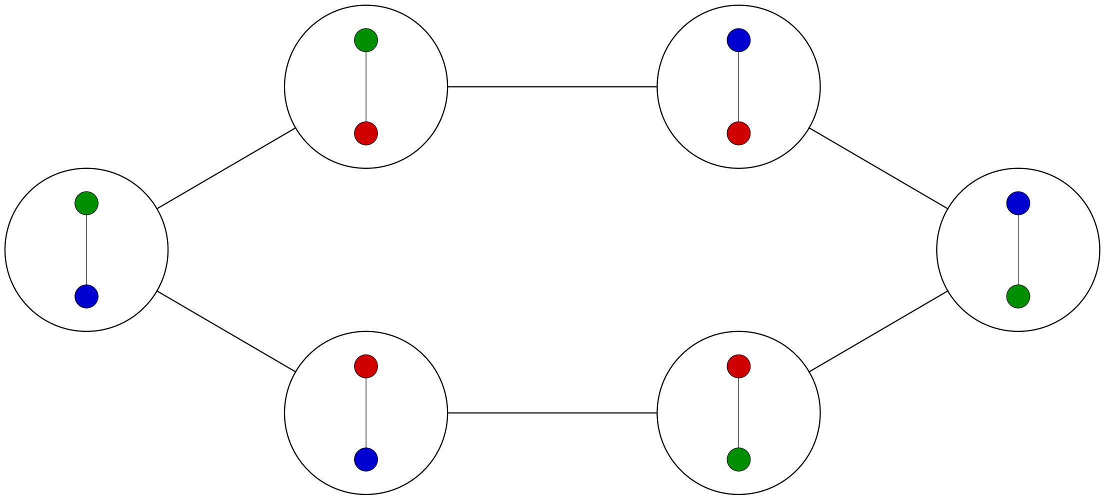
First definitions

- *graph* $G = (V, E)$: finite, simple, no loops, n vertices
- *k-colouring* of G : proper vertex-colouring
  using colours from $\{1, 2, \ldots, k\}$
  - we always assume $k \geq \chi(G)$
  - we use $\alpha, \beta, \ldots$ to indicate k-colourings
- *k-colour graph* $\mathcal{C}(G; k)$
  - vertices are the k-colourings of G
  - two k-colourings are adjacent
    if they differ in the colour on exactly one vertex of G

Small example

- 2-colour graph for K_2 :

- 3-colour graph for K_2 :



Central question

General question

- Given G and k,
  what can we say about the colour graph $\mathcal{C}(G;k)$?

In particular

- is $\mathcal{C}(G;k)$ connected ?

  good way to think about it :

  - can we go from any k-colouring to any other k-colouring by recolouring one vertex at the time ?

Terminology : $\mathcal{C}(G;k)$ is connected $\iff$ G is <u>k-mixing</u>

Research on $\mathcal{C}(G;k)$

- not much research on this in pure graph theory

- related to work in theoretical physics on

  Glauber dynamics of k-state anti-ferromagnetic Potts models at zero temperature

- related to work in theoretical computer science on

  Markov chain Monte Carlo methods for generating random k-colourings (“rapid mixing”)

Some first results on mixing

- $k \geq \Delta(G) + 2 \quad \Longrightarrow \quad G$ is k-mixing ("Well-known")

- $D(G) = \max\{\,\delta(H) \mid H \subseteq G\,\}$ (degeneracy)

Property (Dyer et al., 2004)

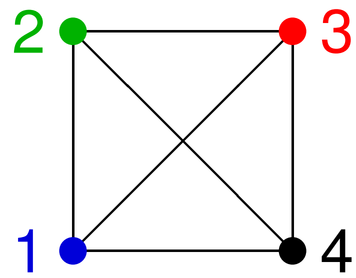
- $k \geq D(G) + 2 \quad \Longrightarrow \quad G$ is k-mixing

Theorem (Choo & MacGillivray, 2006)

- $k \geq D(G) + 3 \quad \Longrightarrow \quad \mathcal{C}(G;k)$ is Hamiltonian

Extremal graphs for the degree bounds

- "boring" extremal graph : complete graph K_m
  - $\Delta(K_m) + 1 = D(K_m) + 1 = m$
  - all m-colourings look the same :
  - no vertex can change colour

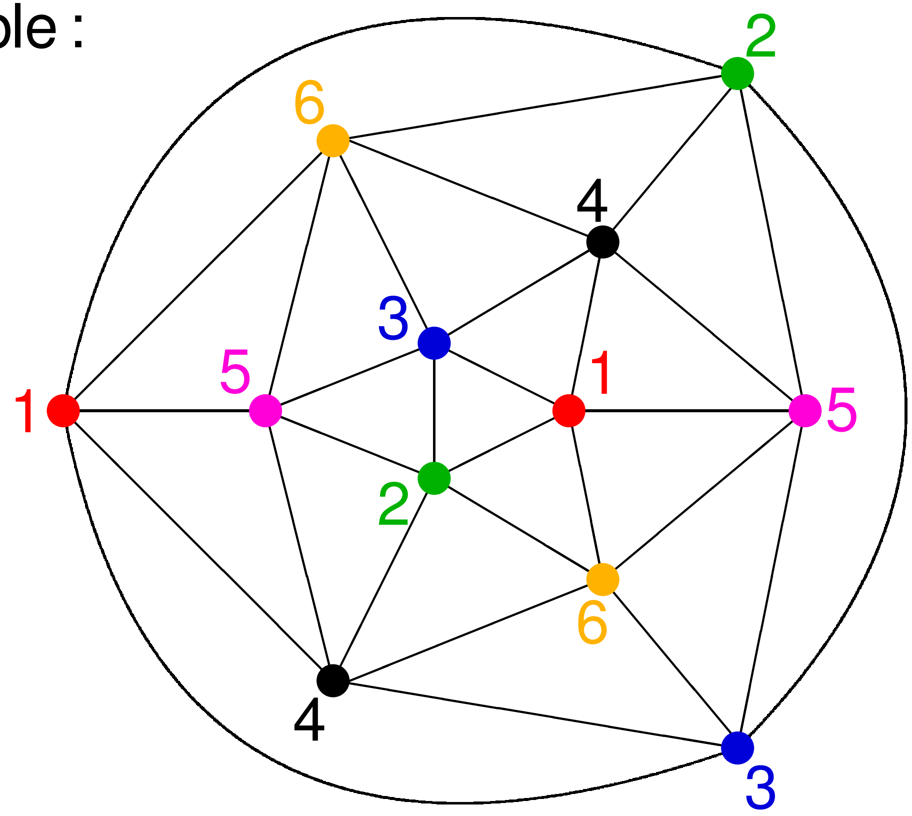


Terminology

- frozen k-colouring : colouring in which no vertex can change colour
  - frozen colourings form isolated nodes in $\mathcal{C}(G; k)$
  - immediately mean G is not k-mixing

The case for planar graphs

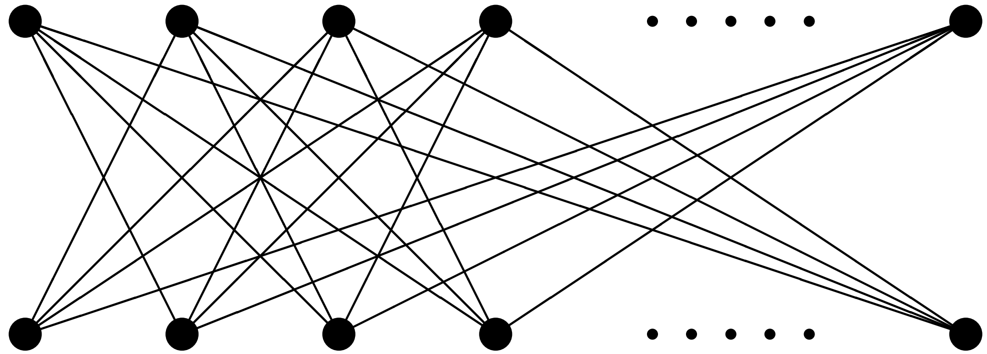
- G planar $\Longrightarrow$ $D(G) \leq 5$ $\Longrightarrow$ k-mixing for $k \geq 7$
- best possible :



frozen 6-colouring of the icosahedron

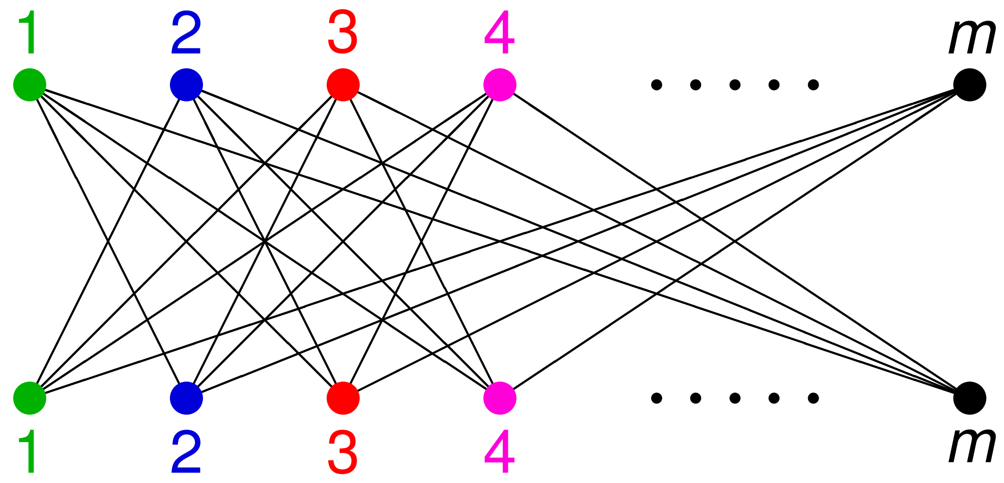
More interesting extremal graphs

- graph L_m : $K_{m,m}$ minus a perfect matching ($m \geq 3$)
  - $\Delta(L_m) + 1 \ = \ D(L_m) + 1 \ = \ m$



More interesting extremal graphs

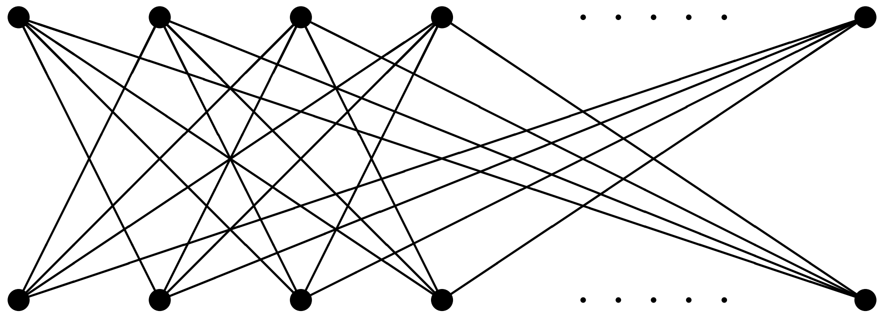
- graph L_m: $K_{m,m}$ minus a perfect matching ($m \geq 3$)
  - $\Delta(L_m)+1 \;=\; D(L_m)+1 \;=\; m$



  - has frozen m-colourings – hence L_m is not m-mixing
- **so**:
  bipartite graphs can be non-k-mixing for arbitrarily large k

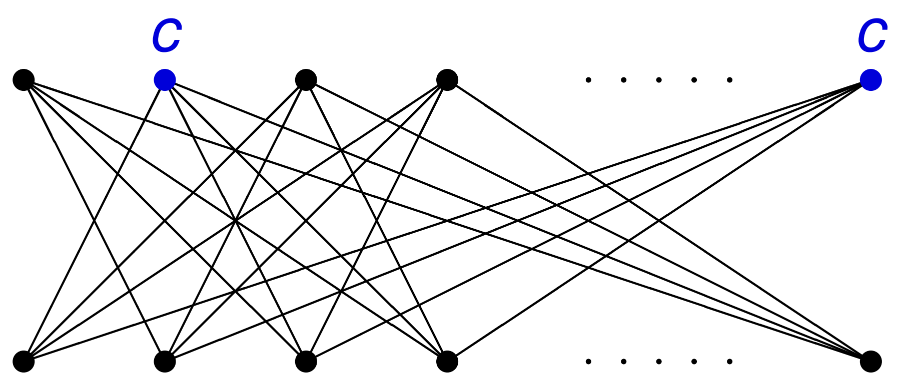
More interesting properties of L_m

- non-k-mixing for $k = m$ colours



More interesting properties of L_m

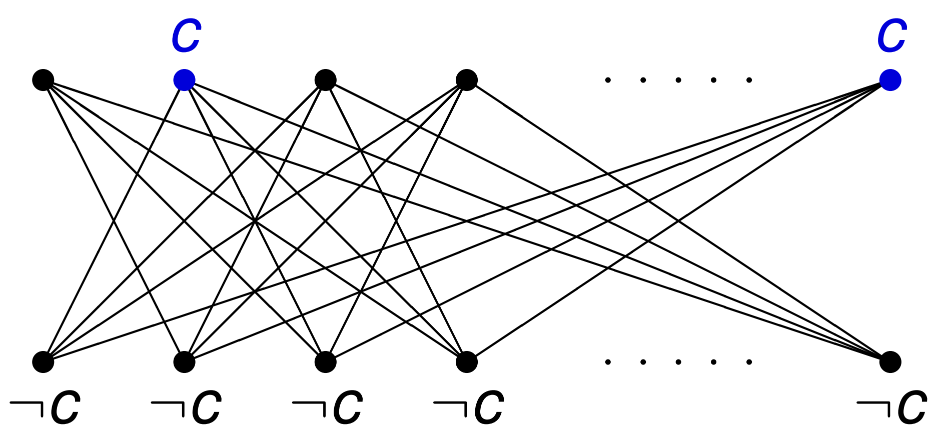
- non-k-mixing for $k = m$ colours
- but k-mixing for $3 \leq k \leq m - 1$
  - suppose L_m coloured with $k \leq m - 1$ colours



  - some colour c must appear more than once on the top

More interesting properties of L_m

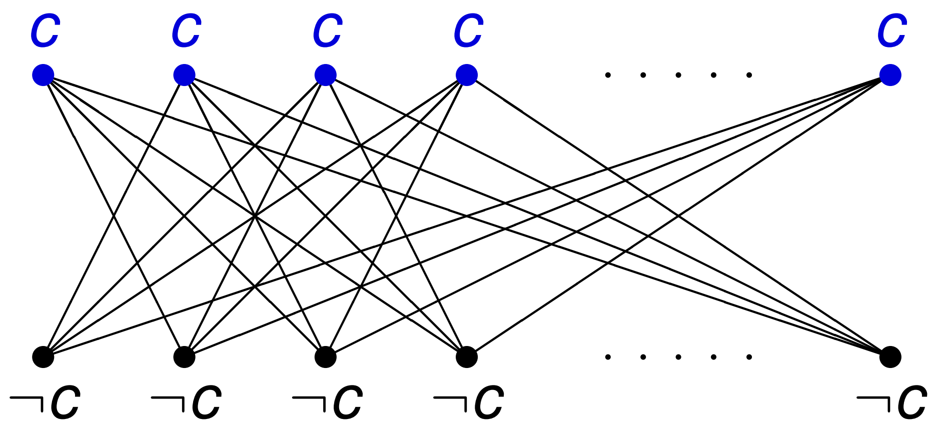
- non-k-mixing for $k = m$ colours
- but k-mixing for $3 \leq k \leq m - 1$
  - suppose L_m coloured with $k \leq m - 1$ colours



  - that colour c can't appear among the bottom vertices

More interesting properties of L_m

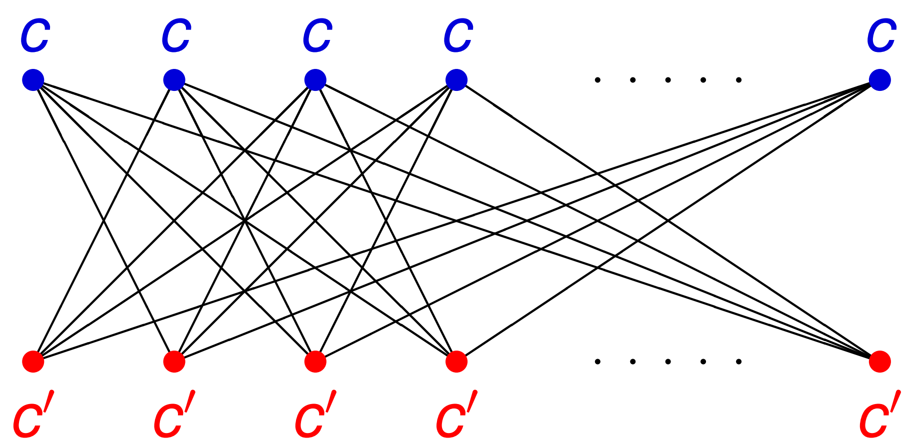
- non-k-mixing for $k = m$ colours
- but k-mixing for $3 \le k \le m-1$
  - suppose L_m coloured with $k \le m-1$ colours



  - so all vertices on the top can be recoloured to c

More interesting properties of L_m

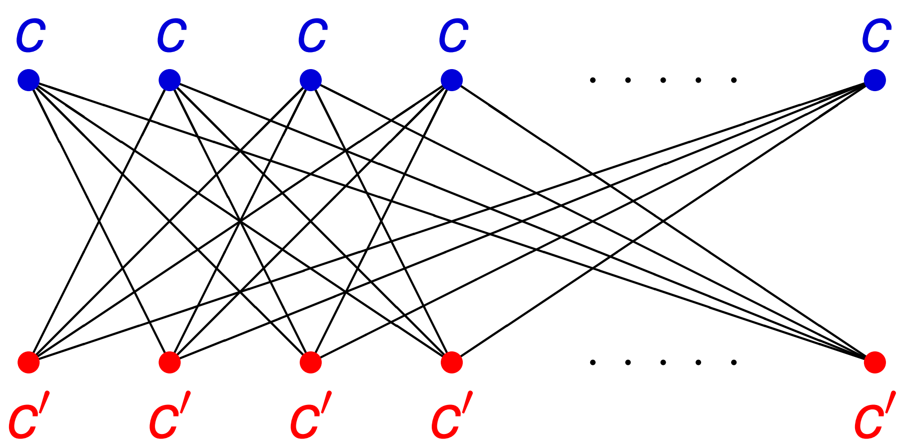
- non-k-mixing for $k = m$ colours
- but k-mixing for $3 \le k \le m-1$
  - suppose L_m coloured with $k \le m-1$ colours



  - then the bottom can be recoloured to some $c' \ne c$

More interesting properties of L_m

- non-k-mixing for $k = m$ colours
- but k-mixing for $3 \le k \le m-1$
  - suppose L_m coloured with $k \le m-1$ colours

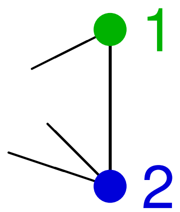


  - hence any colouring is connected to a 2-colouring
  - easy to see that all these 2-colourings are connected

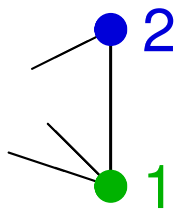
- **so** : mixing is not a monotone property

Mixing for small values of k

- smallest possible is $k = \chi(G)$
- $\chi(G) = 1$: graph without edges – boring
- $\chi(G) = 2$: bipartite graph with at least one edge
  - not-mixing for $k = 2$:



can't become



The case $k = \chi = 3$

- $\chi(G) = 3$: 3-colourable graph with at least one odd cycle

- cycle C_3 has six 3-colourings, all frozen

  $\Longrightarrow \quad C_3$ is not 3-mixing

- cycle C_5 has 30 3-colourings, none of them frozen

  - the colour graph $\mathcal{C}(C_5; 3)$ is formed of two 15-cycles

    $\Longrightarrow \quad C_5$ is not 3-mixing

Theorem

- $\chi(G) = 3 \quad \Longrightarrow \quad G$ is not 3-mixing

Proof looks at 3-colourings of cycles

- suppose α is a 3-colouring of G
  and C is a cycle in G
  - choose an orientation $\vec{C}$ of the cycle
  - weight of an arc of $\vec{C}$:

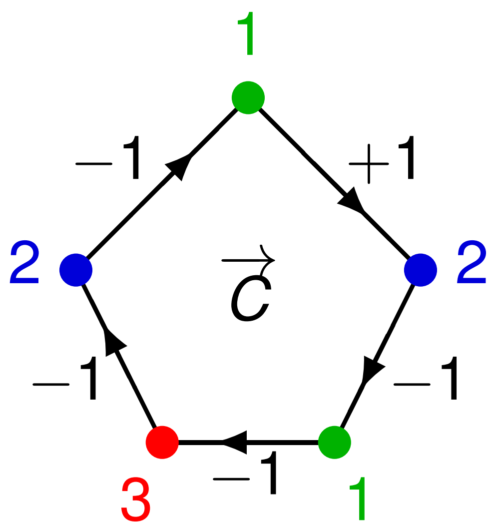
    $\boxed{+1}$ if $1 \to 2$ or $2 \to 3$ or $3 \to 1$

    $\boxed{-1}$ if $2 \to 1$ or $3 \to 2$ or $1 \to 3$

  - weight of the oriented cycle :
    $w(\vec{C};\alpha) =$ sum of the weights of the arcs

Proof looks at 3-colourings of cycles

- Example :

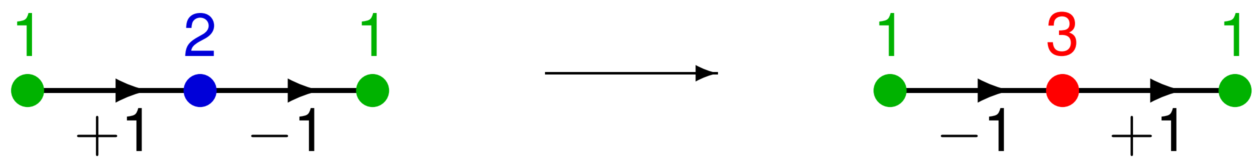


$$w(\overrightarrow{C};\alpha) = -3$$

Weights of 3-colourings of cycles

- recolour one vertex to go from α to β

e.g.:



$$\Longrightarrow \quad w(\overrightarrow{C};\alpha) = w(\overrightarrow{C};\beta)$$

Property

- α and β connected by a path in $\mathcal{C}(G;3)$

$\Longrightarrow$ for all cycles C in G : $w(\overrightarrow{C};\alpha) = w(\overrightarrow{C};\beta)$

Weights of 3-colourings of cycles

- given 3-colouring α, form α^* by swapping colours 1 and 2

  $\Longrightarrow$ all arcs change sign

  $\Longrightarrow$ so for all C in G : $w(\overrightarrow{C};\alpha^*) = -w(\overrightarrow{C};\alpha)$

<u>**now**</u> : take 3-chromatic graph G with a 3-colouring α,
and take an odd cycle C in G

- $\Longrightarrow$ $w(\overrightarrow{C};\alpha) \neq 0$ (odd sum of $+1$s and -1s)

  $\Longrightarrow$ $w(\overrightarrow{C};\alpha^*) = -w(\overrightarrow{C};\alpha) \neq w(\overrightarrow{C};\alpha)$

  $\Longrightarrow$ α and α^* not connected in $\mathcal{C}(G;3)$

  $\Longrightarrow$ $\mathcal{C}(G;3)$ not connected

Mixing for larger values of $k = \chi$

- $\chi(G) = 2 \quad \Longrightarrow \quad G$ is not 2-mixing
- $\chi(G) = 3 \quad \Longrightarrow \quad G$ is not 3-mixing

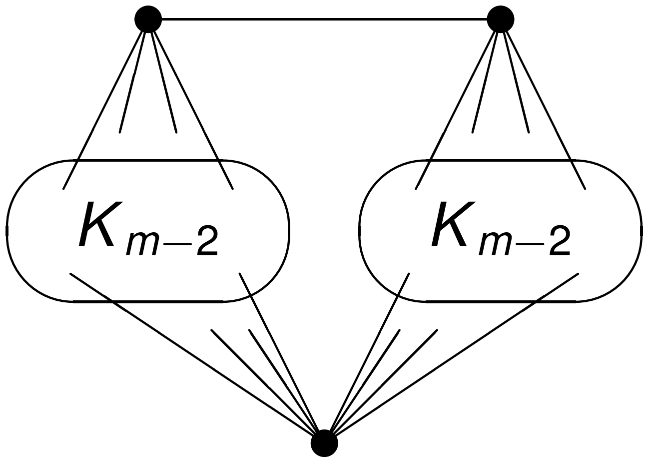
- What about $k \geq 4$?

- complete graph K_k has frozen k-colourings

  so : G has K_k as a subgraph $\quad \Longrightarrow \quad G$ not k-mixing

Mixing for larger values of $k = \chi$

- Hajos' graph H_m $\quad (m \geq 3)$



- has $\chi(H_m) = m$
- and is m-mixing for $m \geq 4$
- **so** : graphs with $k = \chi(G) \geq 4$
  can be k-mixing or not k-mixing

Decision problems

k-MIXING

Input : graph G

Question : is G k-mixing ?

- probably very hard, since finding one k-colouring of a graph G is probably very hard, even if we know $k \geq \chi(G)$

Maybe easier :

BIPARTITE-k-MIXING

Input : bipartite graph G

Question : is G k-mixing ?

Is a given bipartite graph k-mixing ?

- trivial for $k=2$ ("yes" if and only if G has no edges)

necessary for $k=3$:

- for all 3-colourings α and cycles C in G : $w(\vec{C};\alpha)=0$

Theorem

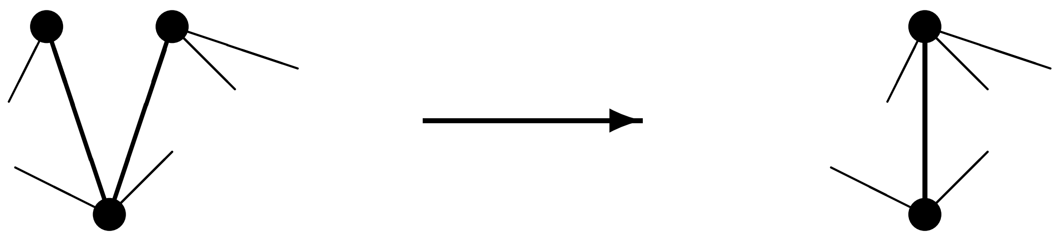
- the condition is also **sufficient** for a graph to be 3-mixing

- **so** : BIPARTITE-3-MIXING is in coNP

- certificate for not 3-mixing :
  3-colouring α and cycle C in G with $w(\vec{C};\alpha)\neq 0$

A structural certificate for bipartite non-3-mixing

- fold of two vertices at distance 2 :



- G foldable to H : sequence of folds changes G to H

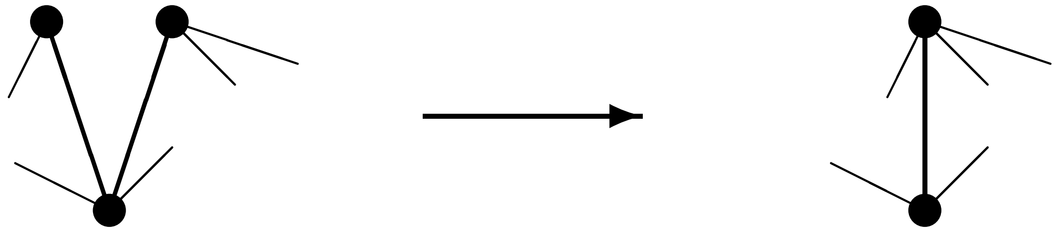
Theorem (Cook and Evans, 1979)

- G connected

$$\Longrightarrow \quad \chi(G) = \min\{\, k \mid G \text{ is foldable to } K_k \,\}$$

A structural certificate for bipartite non-3-mixing

- fold of two vertices at distance 2 :



- G foldable to H : sequence of folds changes G to H

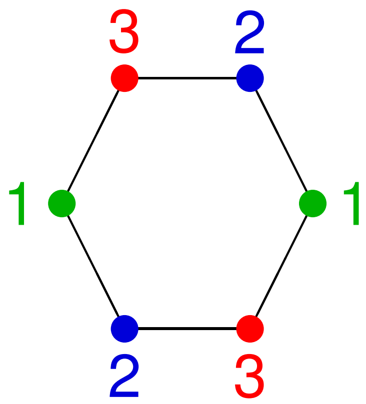
Theorem

- connected bipartite G is not 3-mixing

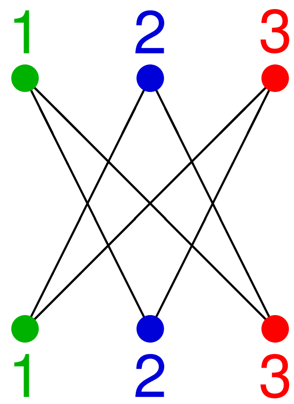
  $\iff$ G is foldable to a chordless 6-cycle

Why the 6-cycle ?

- $C_6 \cong L_3$ – so C_6 is not 3-mixing



$\cong$



- **note** : C_4 is 3-mixing

Deciding bipartite mixing

- bipartite G not 3-mixing $\iff$ G foldable to C_6

Theorem

- deciding foldability to C_6 is NP-complete

hence

- BIPARTITE-3-MIXING is coNP-complete

Theorem

- BIPARTITE-3-MIXING is polynomial for planar graphs

open : what happens for $k \geq 4$?

A decision problem for general graphs

k-COLOUR-PATH

Input : graph G and two k-colourings α and β

Question : is there is a path in $\mathcal{C}(G;k)$ from α to β ?

or : "are α and β connected ?"

- this question might be doable for any k
- trivially decidable for $k = 2$

Connected 3-colourings

- **necessary condition 1**

  for two 3-colourings α and β to be connected :

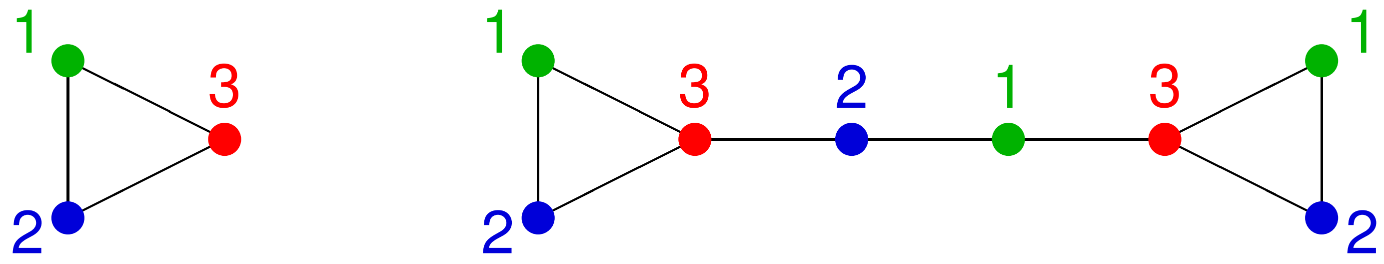
  - for all cycles C in G : $w(\overrightarrow{C};\alpha) = w(\overrightarrow{C};\beta)$

- but **not sufficient** :

Connected 3-colourings

- fixed vertex of a colouring : can never change colour

examples



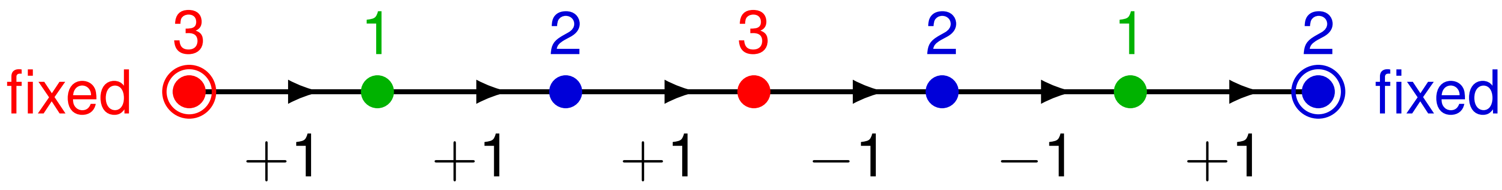
- **necessary condition 2**

  for two 3-colourings α and β to be connected :

  - all fixed vertices in α must be fixed in β as well and must have the same colour in both

Connected 3-colourings

- a path P with two fixed end vertices
  can also be given a weight $w(\overrightarrow{P};\alpha)$



- and this weight stays the same when recolouring

- **necessary condition 3**
  for two 3-colourings α and β to be connected :
  - for all fixed-ends paths P : $w(\overrightarrow{P};\alpha) = w(\overrightarrow{P};\beta)$

Connected 3-colourings

- two 3-colourings α and β can only be connected if :
  - for all cycles C in G: $w(\overrightarrow{C};\alpha) = w(\overrightarrow{C};\beta)$
  - for all fixed-ends paths P: $w(\overrightarrow{P};\alpha) = w(\overrightarrow{P};\beta)$
  - the sets of fixed vertices in α and β must be identical

Theorem

- the conditions above are also **sufficient**
- the conditions can be checked in polynomial time

and

- if connected, then there is a path of length $O(n^2)$

k-COLOUR-PATH for $k \geq 4$

Theorem

- for $k \geq 4$, k-COLOUR-PATH is PSPACE-complete

PSPACE

- decision problems that can be solved using a polynomial amount of memory (no restrictions on time)
- contains NP and coNP
- equal to its non-deterministic variant NPSPACE

k-COLOUR-PATH for $k \geq 4$

Theorem

k-COLOUR-PATH for bipartite, planar graphs :

- $k = 2$: trivially decidable
- $k = 3$: decidable in polynomial time
- $k = 4$: PSPACE-complete
- $k \geq 5$: always "YES"

Length of paths between connected colourings

Theorem

- for $k \geq 4$, k-COLOUR-PATH is PSPACE-complete

- if NP $\neq$ PSPACE (similar status as P $\neq$ NP), then no PSPACE-complete problem should have polynomial length certificates

so : for $k \geq 4$ path length between two connected k-colourings should not always be polynomial

Length of paths between connected colourings

Theorem

- for all $k \geq 4$, there exists graphs G with two k-colourings α and β so that
  - α and β are connected
  - the shortest path from α to β has exponential length

- the graphs can be bipartite
- and for $k = 4$ even bipartite and planar

Something different : using extra colours

- given a graph G and two k-colourings α and β
- suppose we can "buy" extra colours to go from α to β

how many extra colours do we need ?

Theorem

- $\chi(G) - 1$ extra colours is always enough

$\chi - 1$ *extra colours are always enough*

sketch of the proof

- take a χ-colouring using colours $-1, -2, \ldots, -\chi$

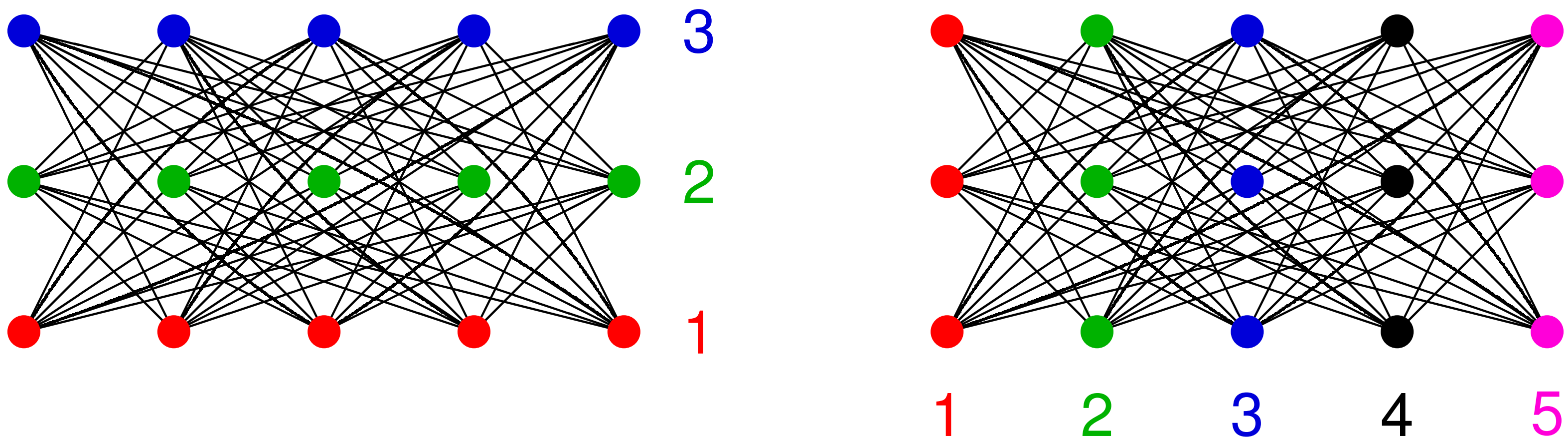
  say with colour-classes $V_{-1}, V_{-2}, \ldots, V_{-\chi}$
- starting with the k-colouring α (using colours $1, 2, \ldots, k$)
  - recolour vertices in V_{-1} with colour -1
  - recolour vertices in V_{-2} with colour -2
  - etc., until vertices in $V_{-(\chi-1)}$ with colour $-(\chi - 1)$
- the remaining vertices in $V_{-\chi}$ form an independent set
  - hence can be recoloured to their colours according to β
- now recolour vertices in $V_{-1} \cup V_{-2} \cup \cdots \cup V_{-(\chi-1)}$

  according to β as well

$\chi - 1$ *extra colours may be needed*

Theorem

- for all C, k with $k \geq C \geq 2$
  there exists graphs G with $\chi(G) = C$
  and two k-colourings α and β so that
  - to get from α to β requires $C - 1$ extra colours



the graph for $C = 3$ and $k = 5$

Open problems I

we know

- BIPARTITE-2-MIXING is trivial (so certainly in P)
- BIPARTITE-3-MIXING is coNP-complete
- BIPARTITE-4-COLOUR-PATH is PSPACE-complete

- what is the complexity of BIPARTITE-4-MIXING ?
- maybe easier if the graph is cubic ?

- what can we say in general if $k = \Delta + 1$ or $k = \Delta$?

Open problems II

- what more can we say about the structure of the k-colour graph $\mathcal{C}(G; k)$?

Open problems III

- what happens if we use a different recolouring rule ?
- *Kempe recolouring* :
  - changing the colour of one vertex v from c_1 to c_2
  - by swapping colours on the component induced by vertices coloured c_1 or c_2 containing v

Folklore

- G bipartite $\Longrightarrow$ G is Kempe-k-mixing for all k

- what is the complexity of KEMPE-k-PATH or KEMPE-k-MIXING for non-bipartite graphs ?