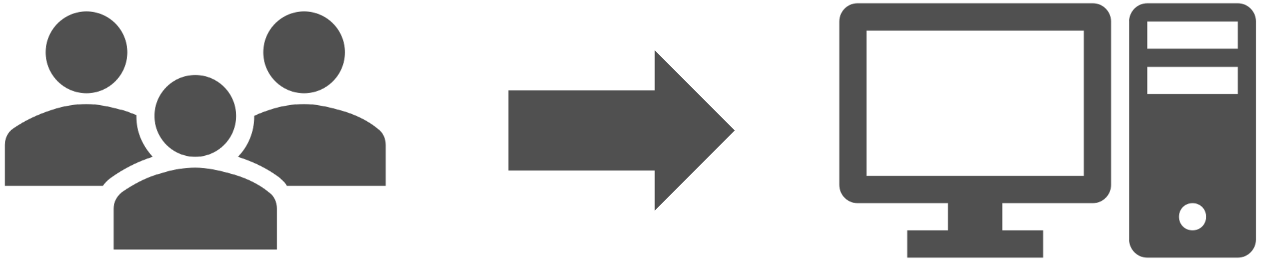
Jukka Suomela
Aalto University

Can we automate our own work

— or show that it is hard?

Computer science: ***what can be automated?***

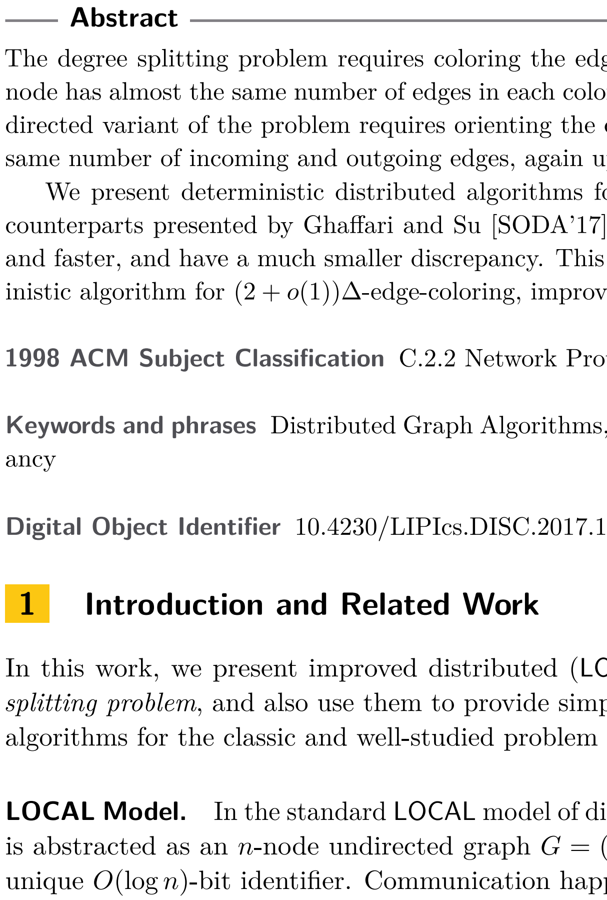


Computer science: ***what can be automated?***

Today: ***can we automate our own work?***

Focus: ***theory of distributed computing***

Consider a typical theory paper in e.g. PODC or DISC…



Abstract

The degree splitting problem requires coloring the edg
node has almost the same number of edges in each colo
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We present deterministic distributed algorithms fo
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1998 ACM Subject Classification C.2.2 Network Pro

Keywords and phrases Distributed Graph Algorithms,
ancy

Digital Object Identifier 10.4230/LIPIcs.DISC.2017.1

1 Introduction and Related Work

In this work, we present improved distributed (LO
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LOCAL Model. In the standard LOCAL model of di
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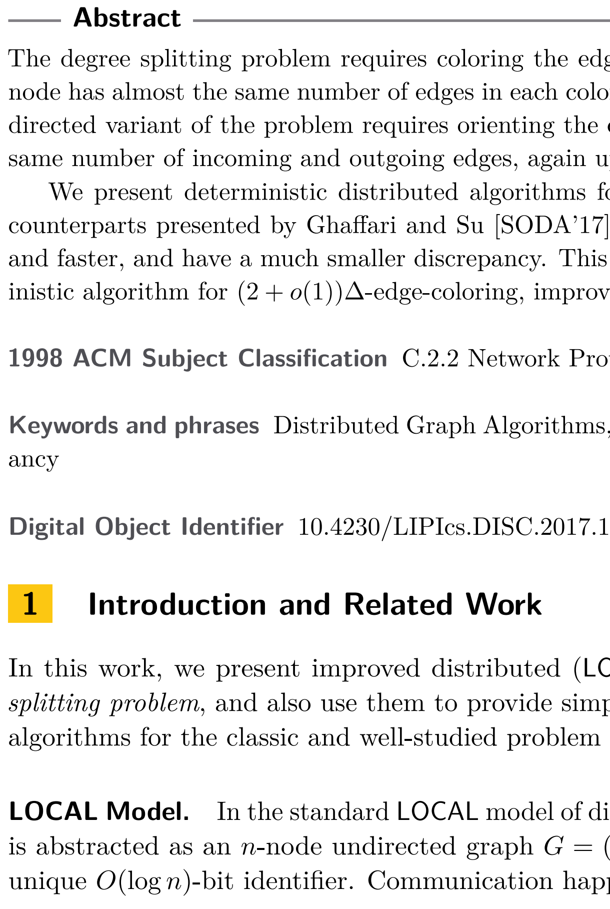

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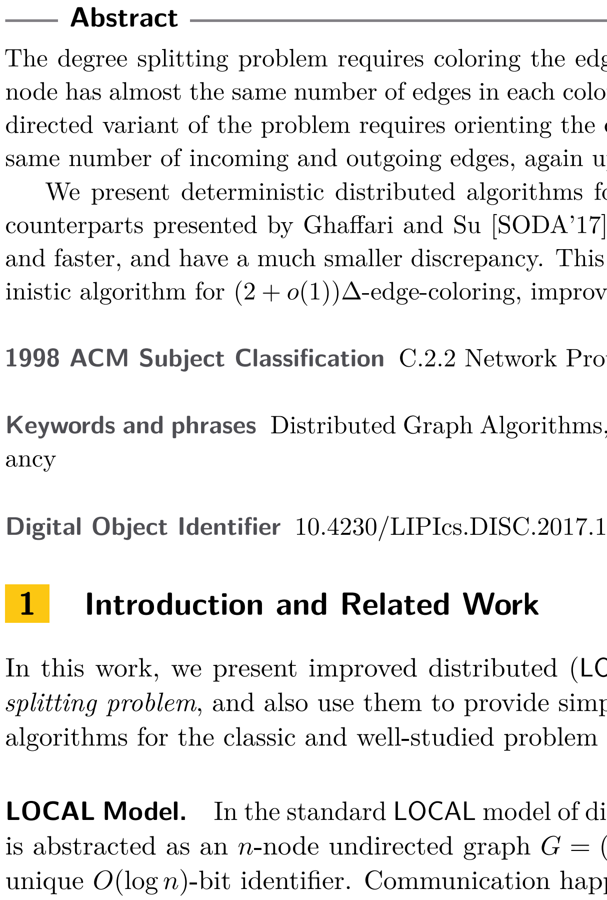
How much of it could be done with computers?



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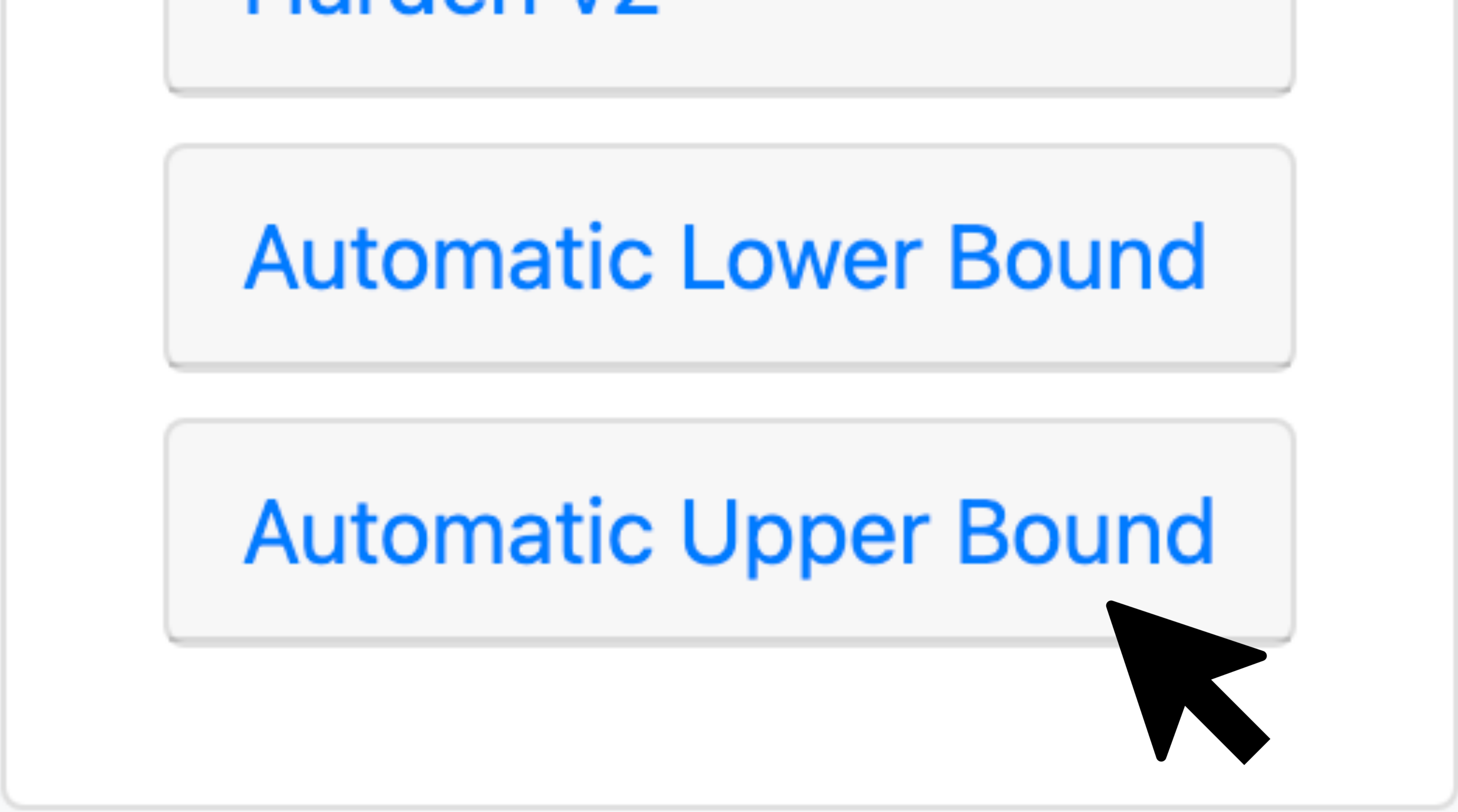
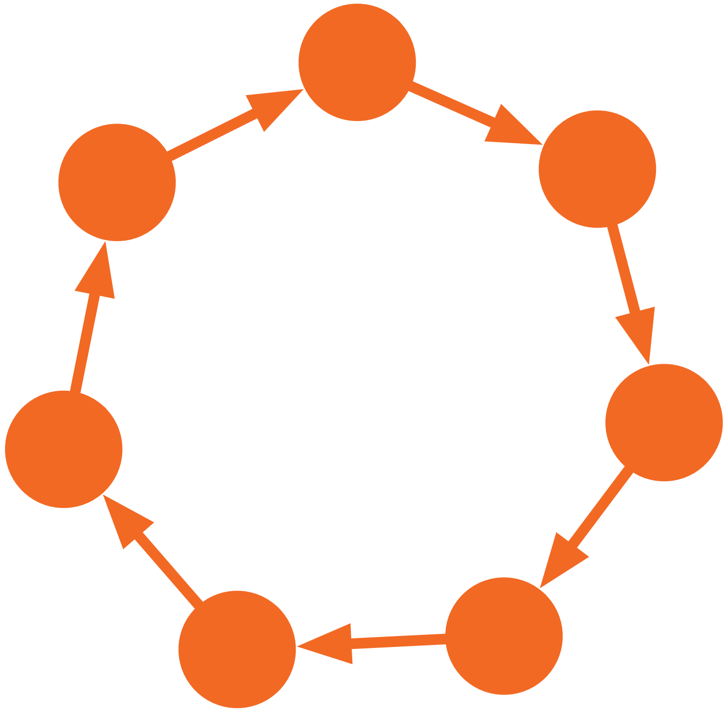

Harden V2
Automatic Lower Bound
Automatic Upper Bound

Lost sanity?

Toy example:
Locally checkable problems in cycles

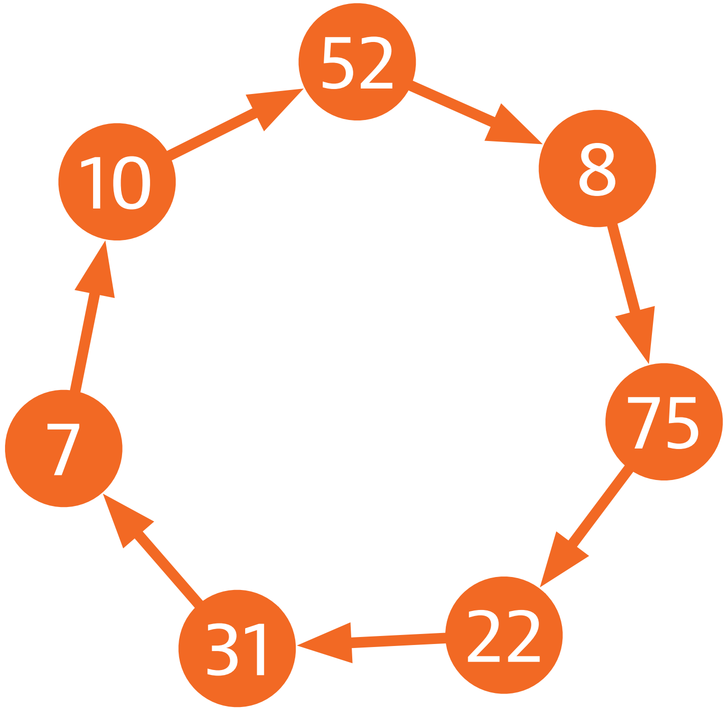
Setting

- ***Computer network:*** **cycle** of *n* computers
  - globally consistent orientation
  - each node has one “successor” and one “predecessor”



Setting

- ***Computer network:*** **cycle** of *n* computers
- ***Model of computing:*** **LOCAL model**
  - synchronous communication rounds
  - time = number of rounds until all nodes stop
  - unbounded message size
  - unlimited local computation
  - unique identifiers



Setting

- ***Computer network:*** **cycle** of *n* computers
- ***Model of computing:*** **LOCAL model**
- ***Problem:*** any discrete problem you can define with **local constraints**
    - finite number of output labels
    - relation that tells which label sequences are valid

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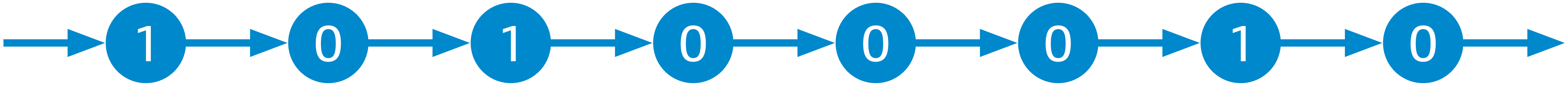
Example: maximal independent set



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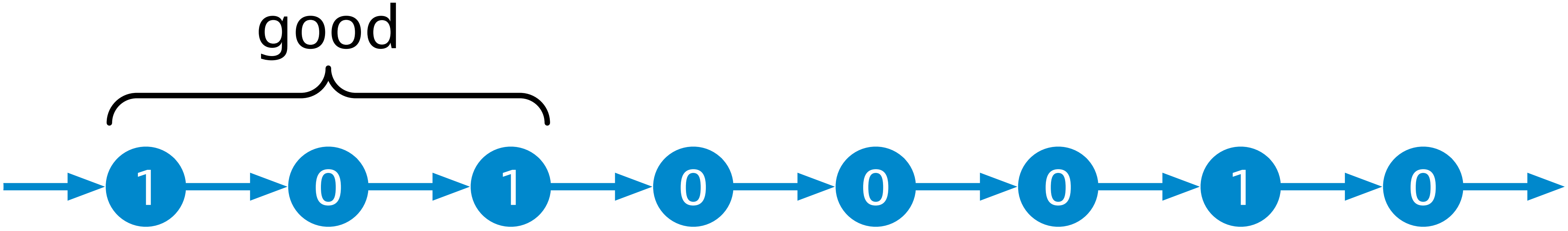

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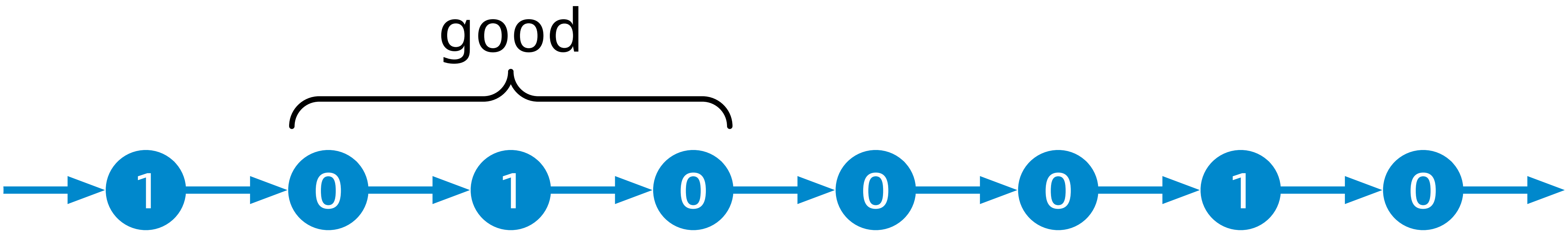

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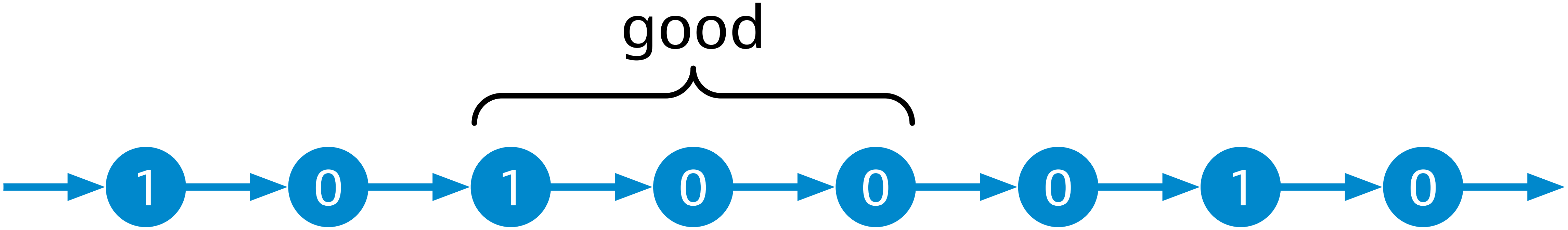

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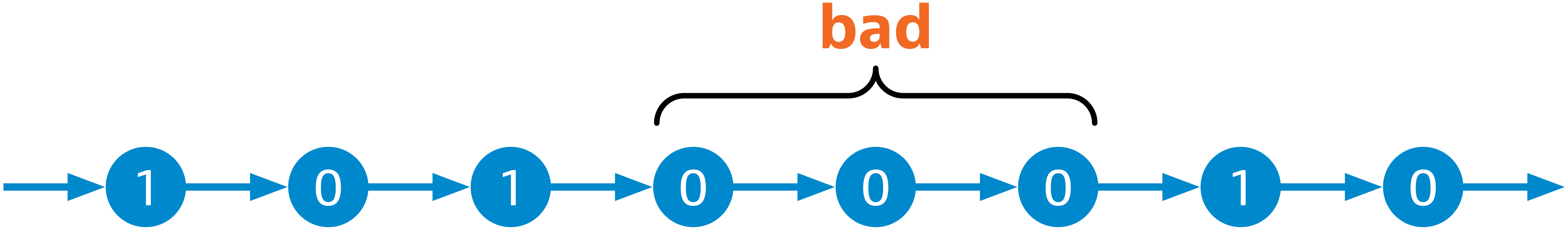

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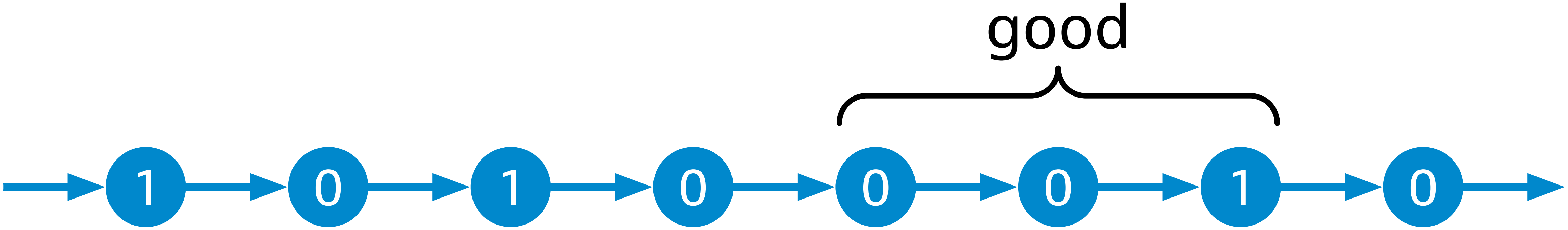

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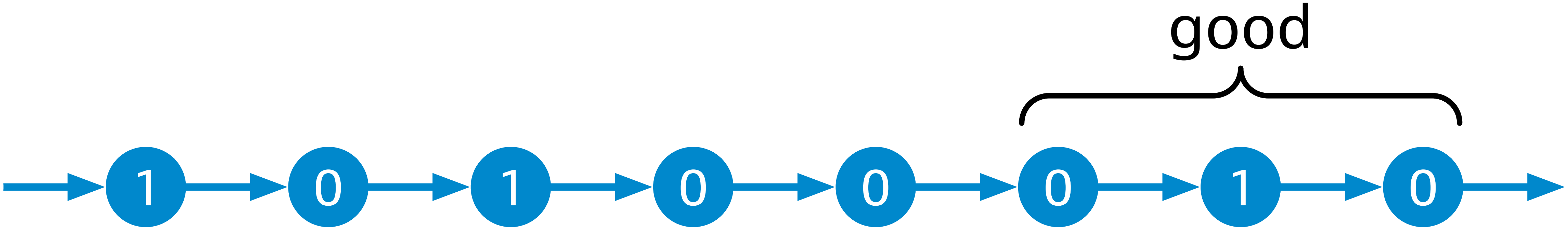

Valid label sequences

- *2-coloring:* **12, 21**
- *3-coloring:* **12, 21, 13, 31, 23, 32**
- *Independent set:* **01, 10, 00**
- *Maximal independent set:* **001, 010, 100, 101**
- *Distance-2 coloring with 3 colors:* **123, 132, 213, 231, 312, 321**

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- *Distance-2 coloring with 3 colors:*
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All possible output labelings in a window of size *k*

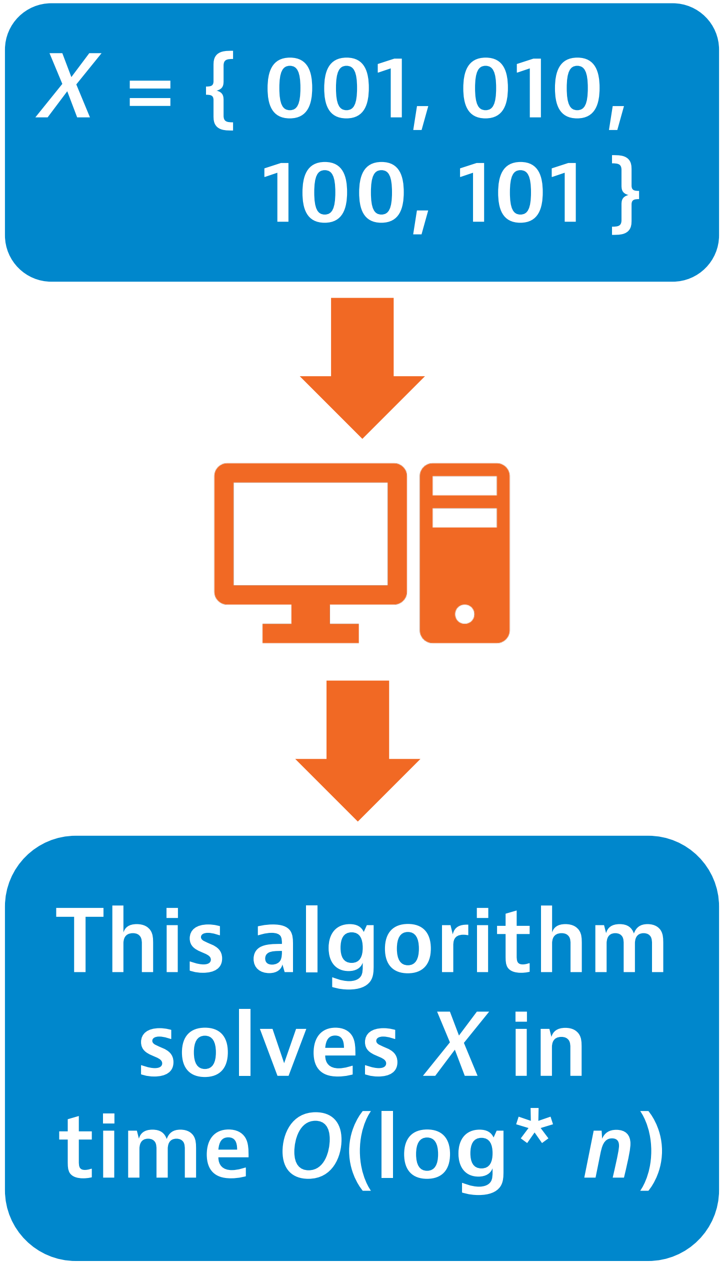
Fully automatic

X = { 001, 010, 100, 101 }

- Write down the specification of *any locally checkable problem X*

Fully automatic

- Write down the specification of ***any locally checkable problem X***
- Then you can ***find efficiently***
  - distributed round complexity of *X*
  - asymptotically optimal distributed algorithm for *X*



$X = \{ 001, 010, 100, 101 \}$

This algorithm solves *X* in time *O*(log* *n*)

Fully automatic

- Write down the specification of ***any locally checkable problem X***
- Then you can ***find efficiently***
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Polynomial time (in the size of problem description)

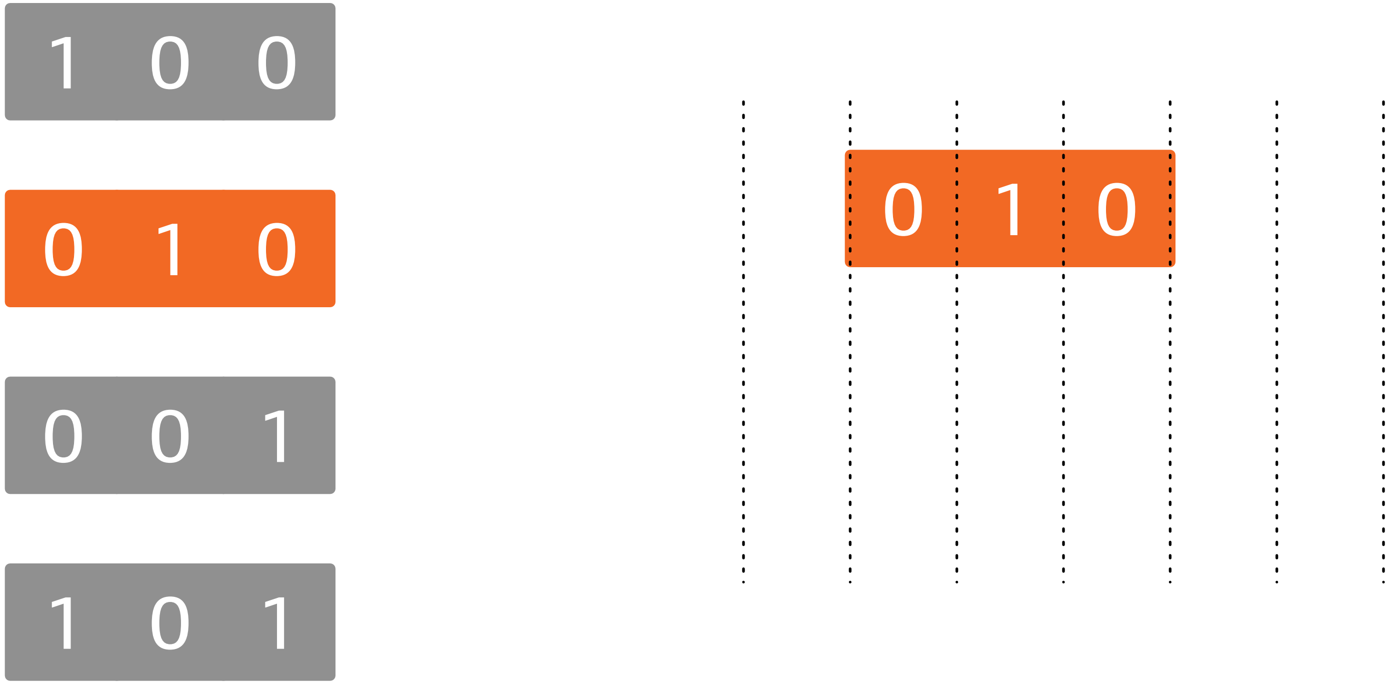
1 0 0

0 1 0

0 0 1

1 0 1

Example:
X = maximal independent set problem



1 0 0

0 1 0

0 0 1

1 0 1

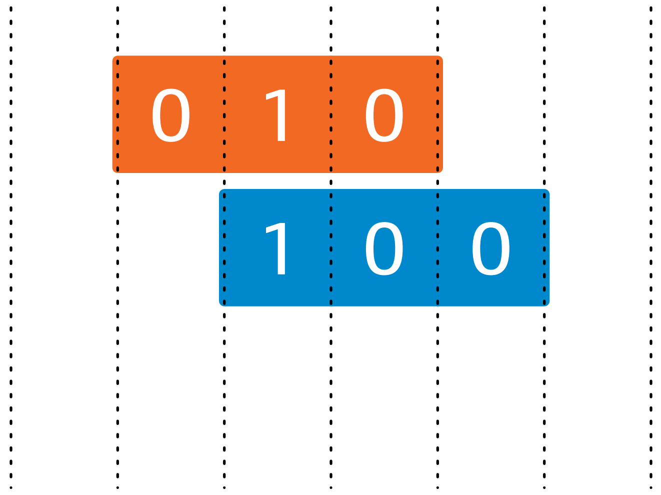
0 1 0

1 0 0

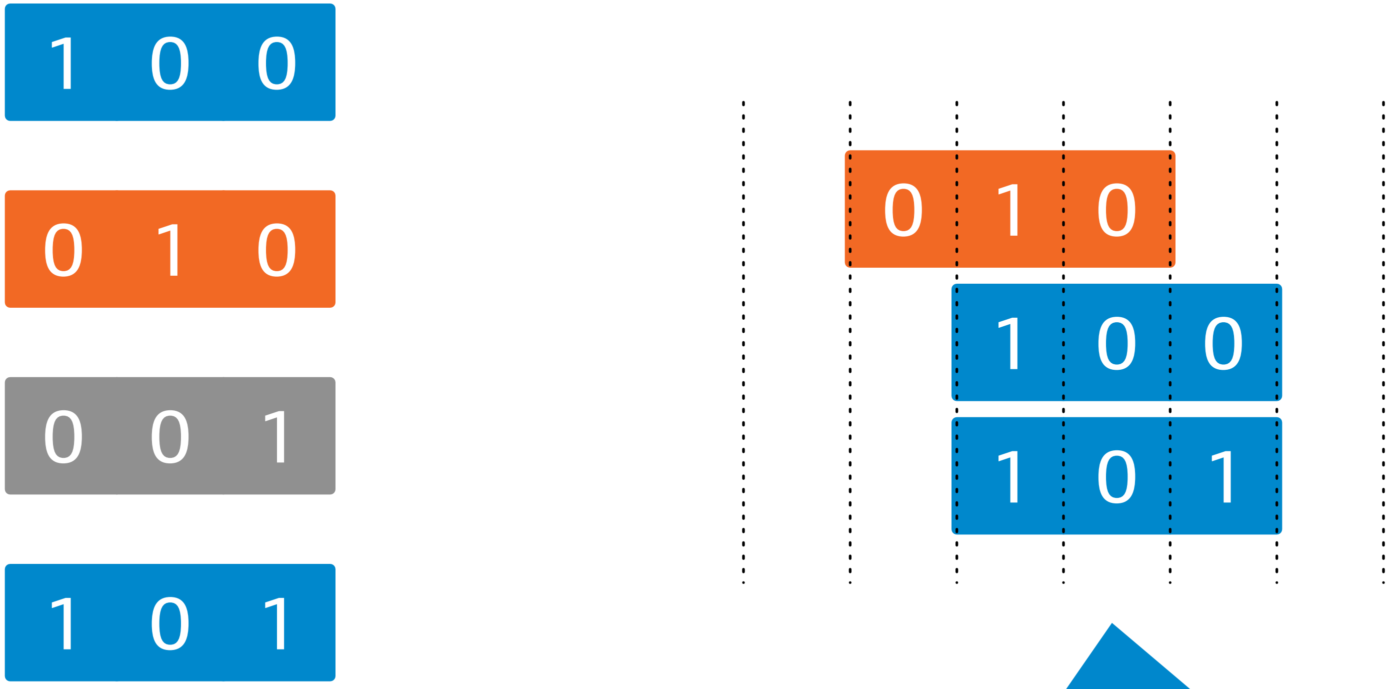
0 1 0

0 0 1

1 0 1



Compatible neighborhoods for adjacent nodes



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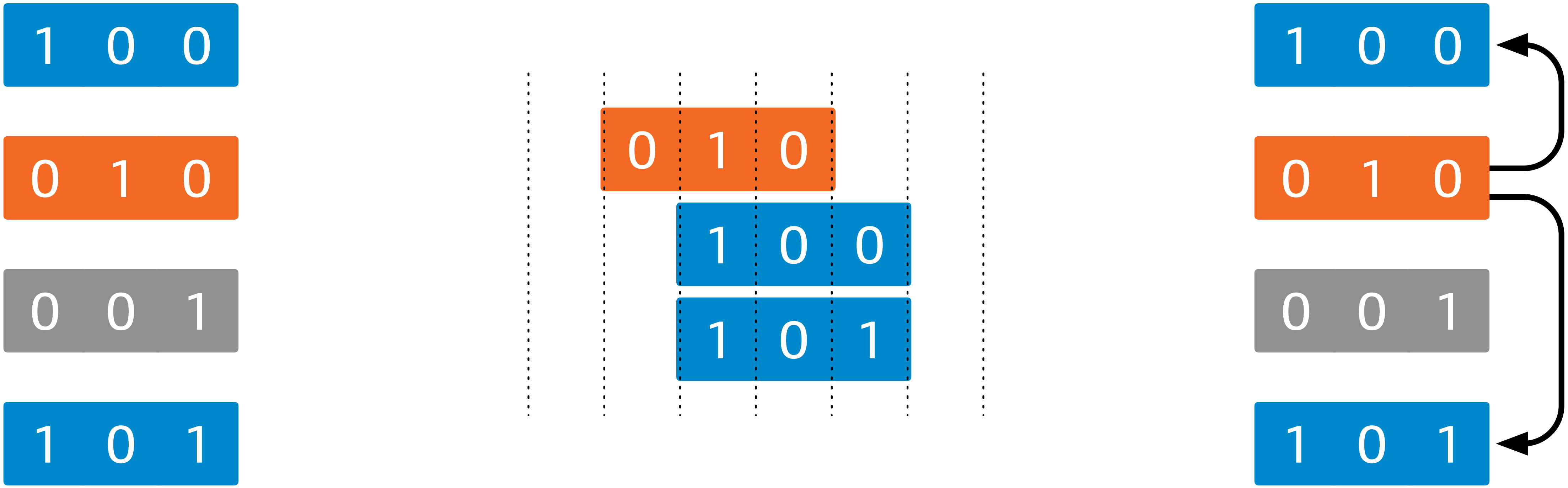

1 0 0

0 1 0

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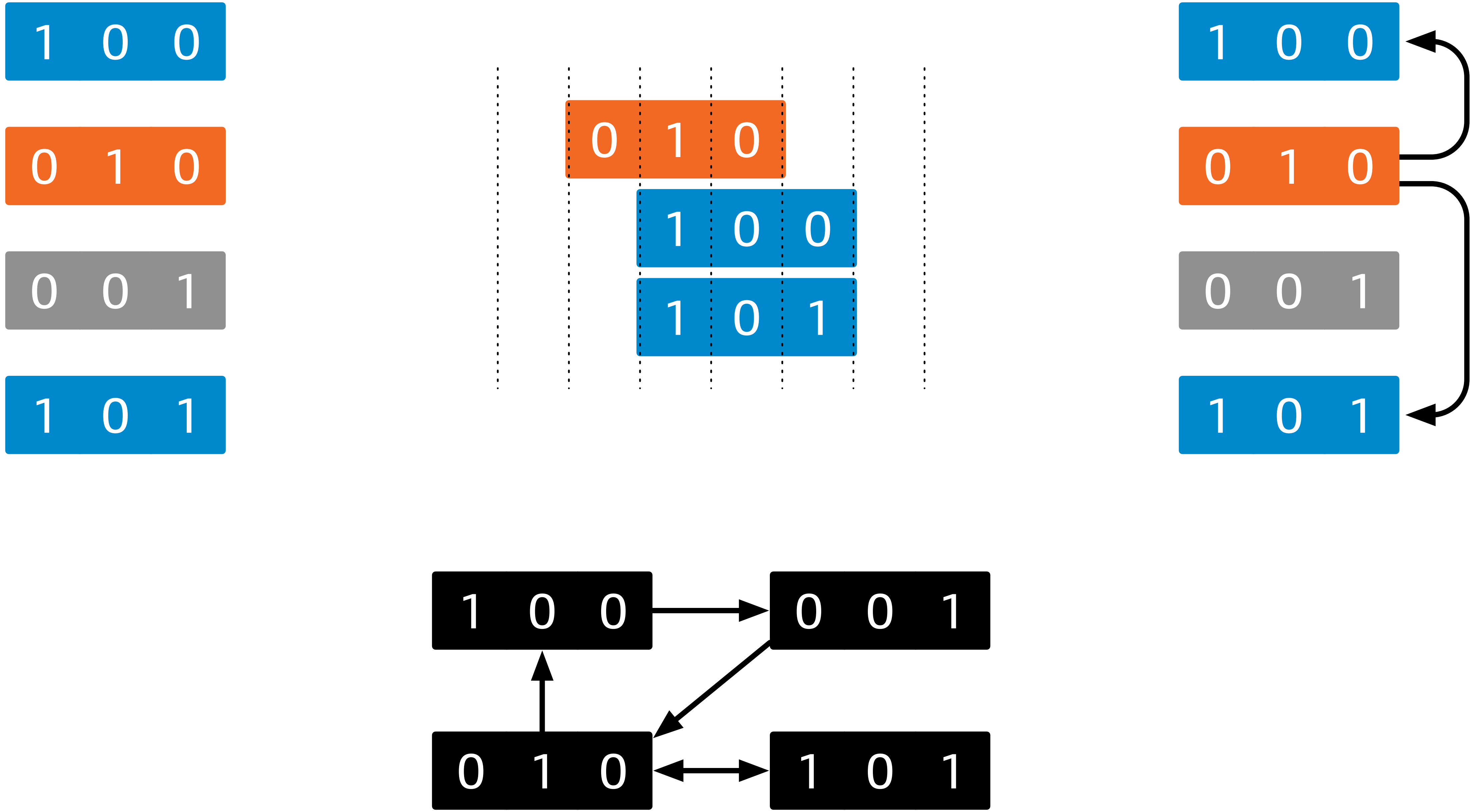

1 0 0

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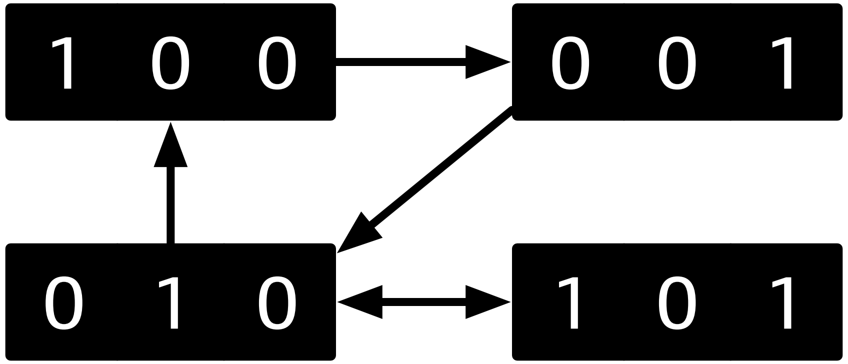
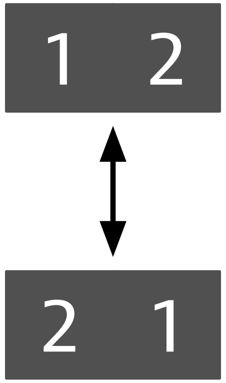
This graph is all that we need!

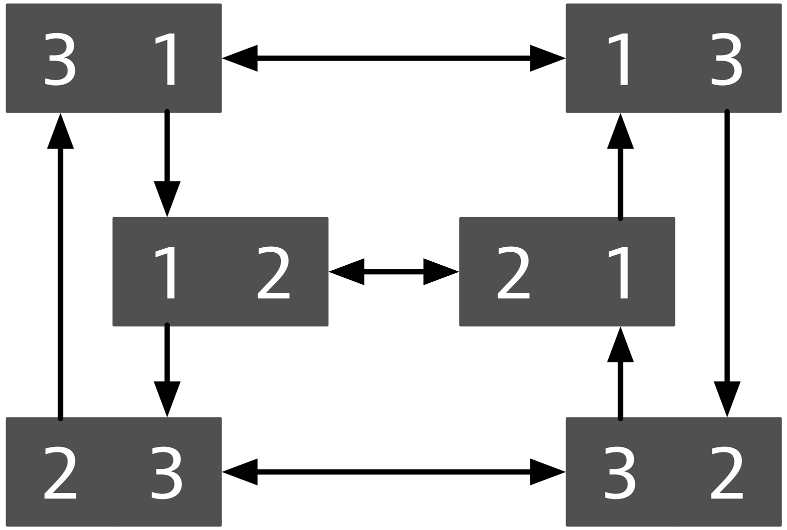




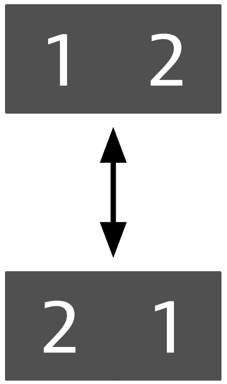
1 2

2 1

2-coloring



3-coloring



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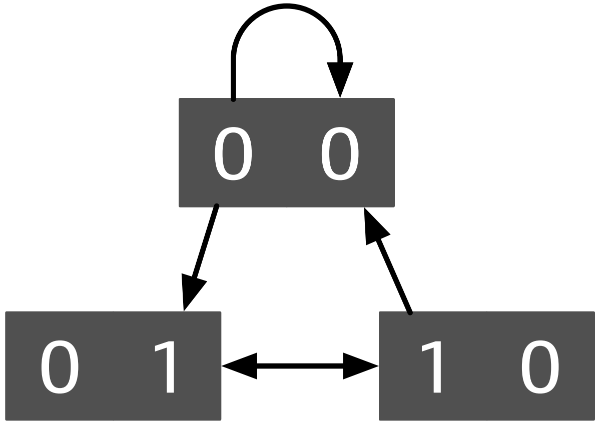
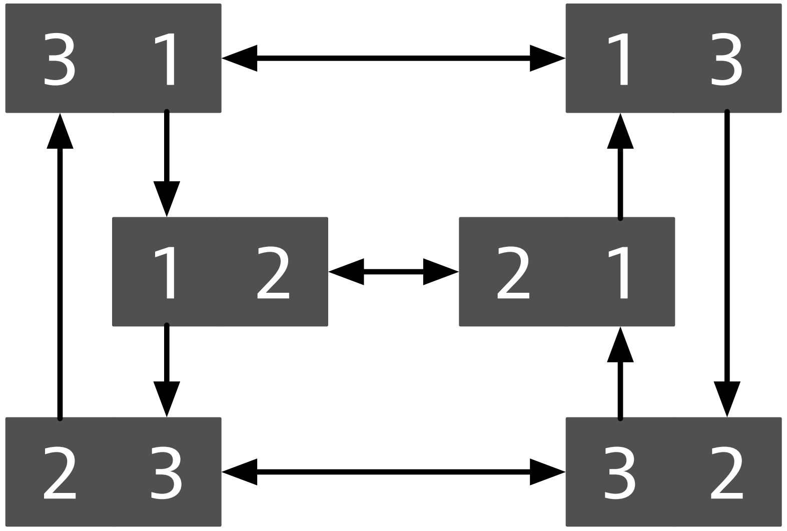


independent set



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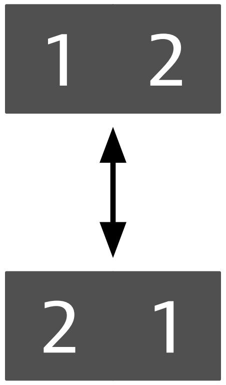

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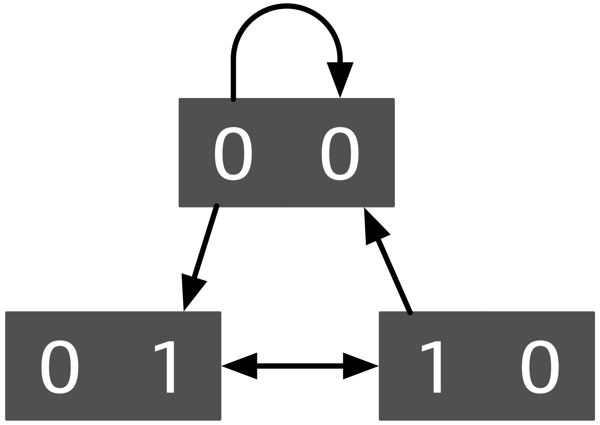

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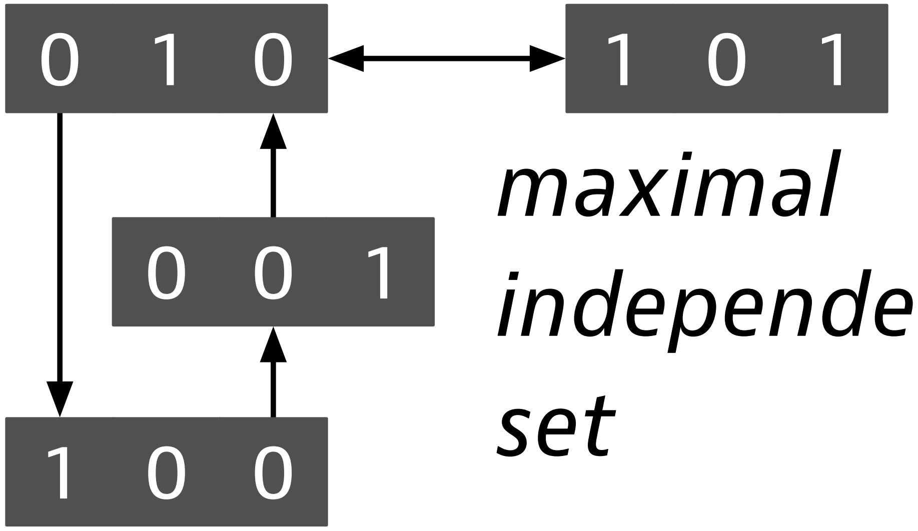
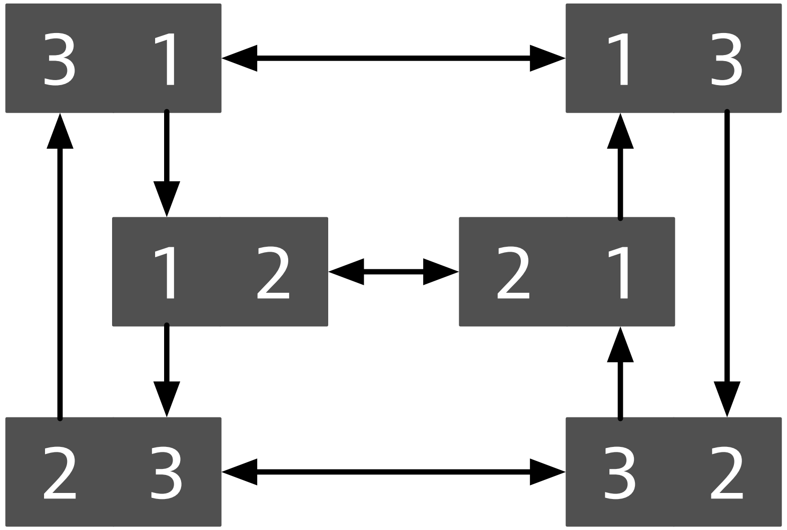


maximal independent set



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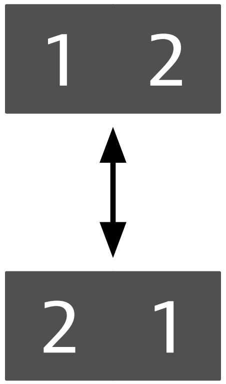

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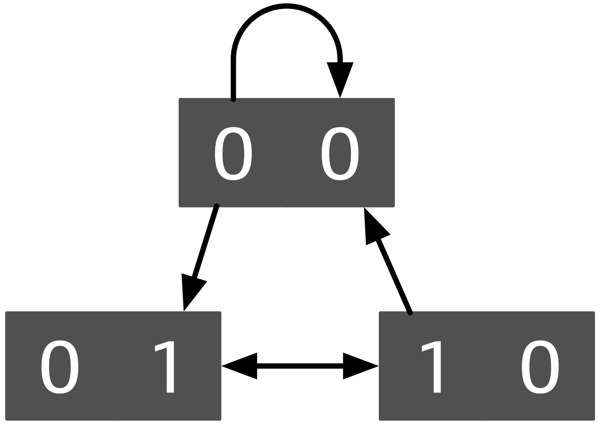

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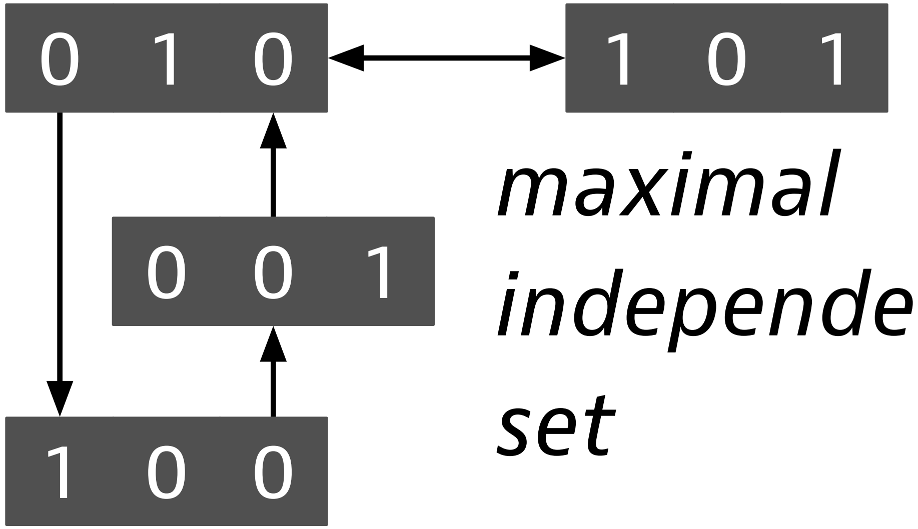

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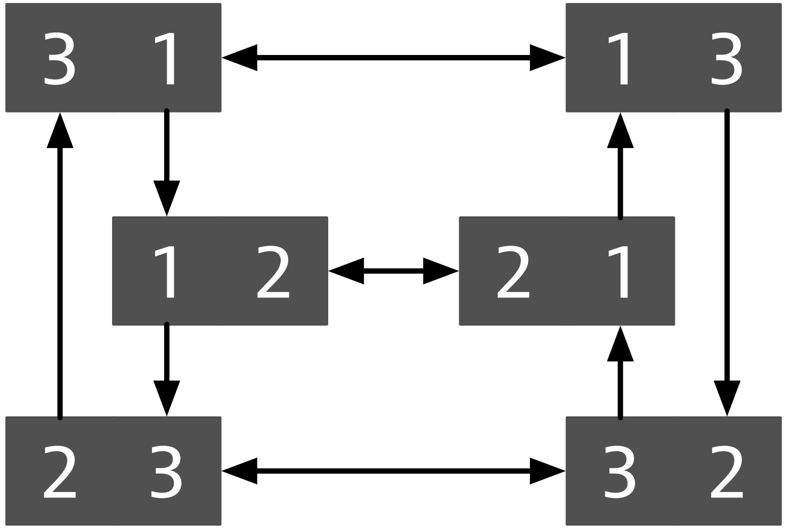

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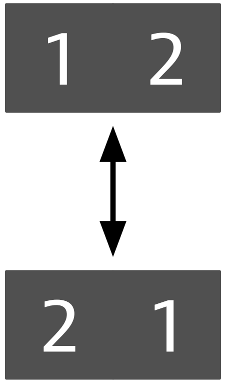

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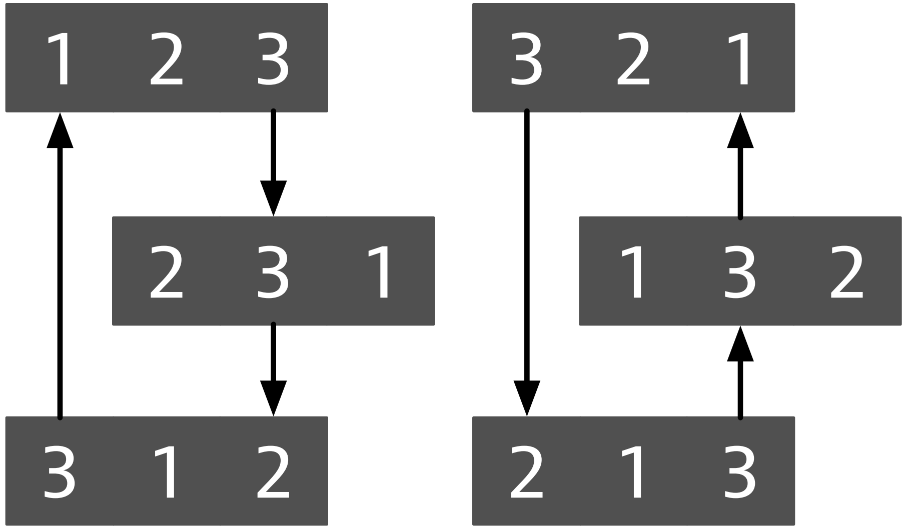

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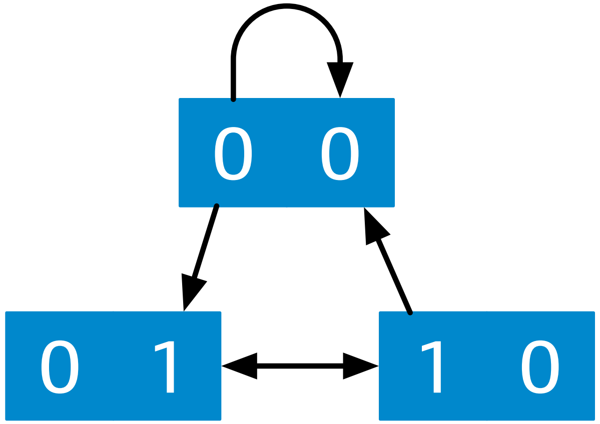

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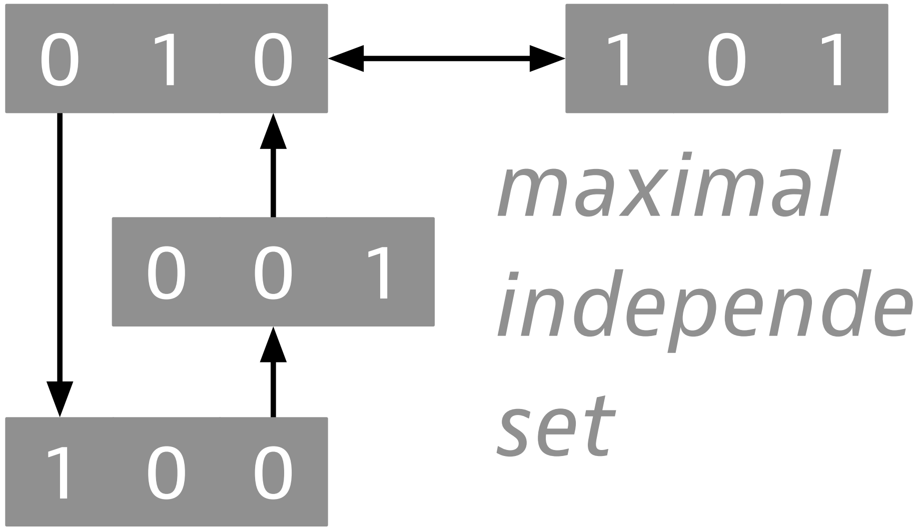

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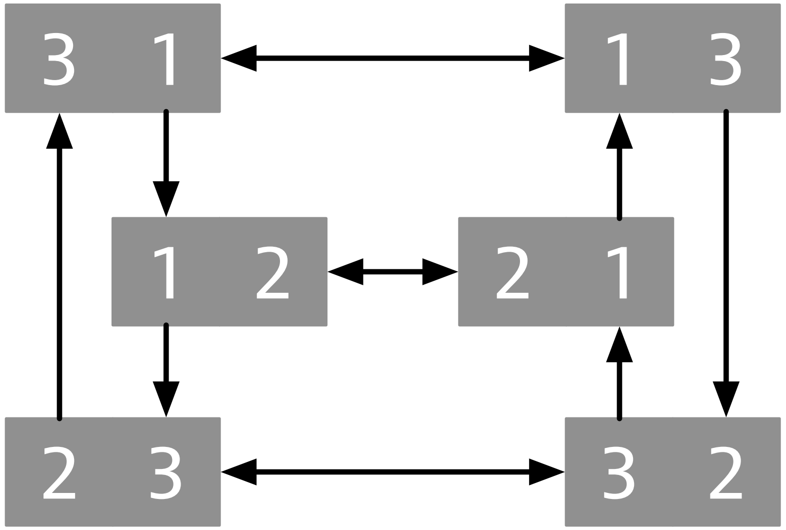

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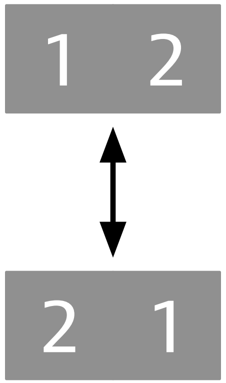

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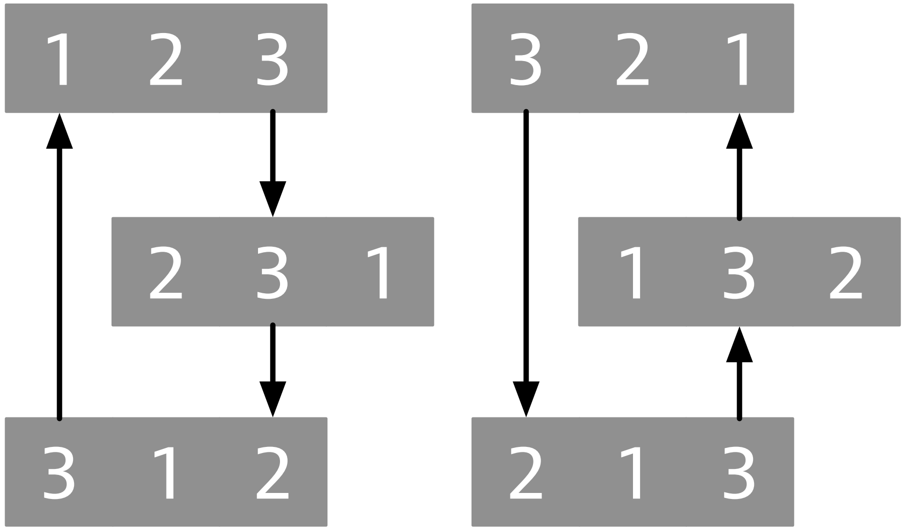

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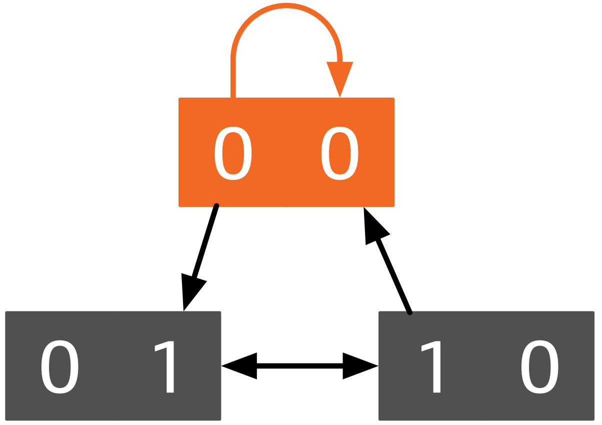
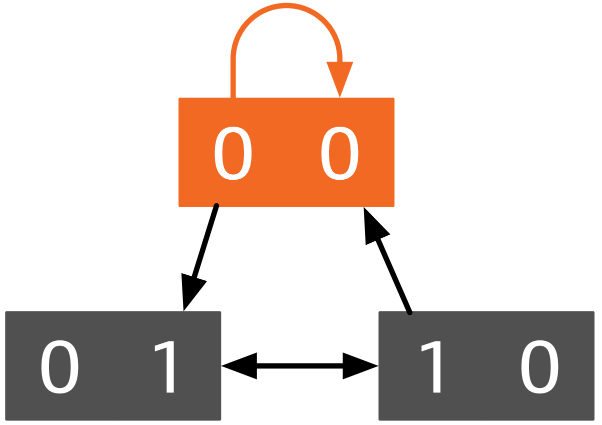


independent set

self-loop



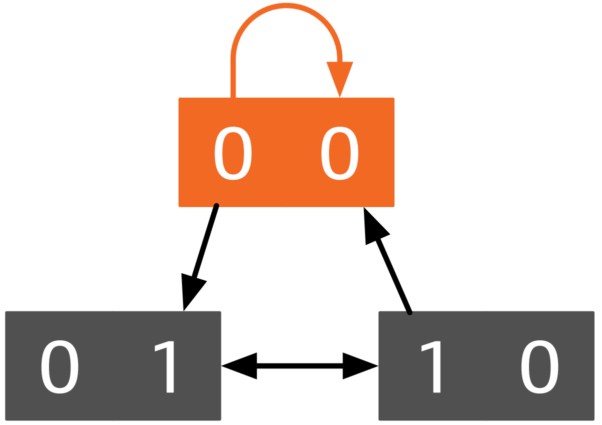
independent set

self-loop

↓

solvable in $O(1)$ rounds

Algorithm:
Constant output
(e.g. here all-0)



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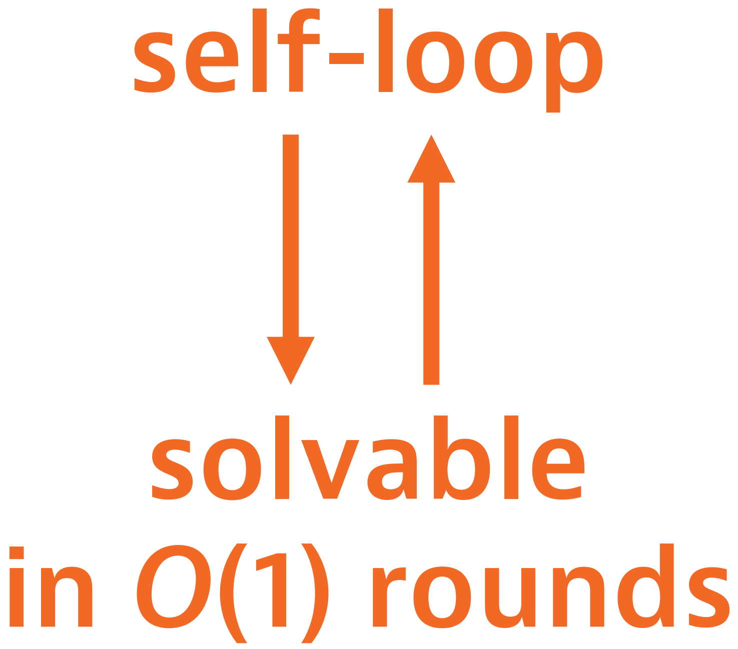
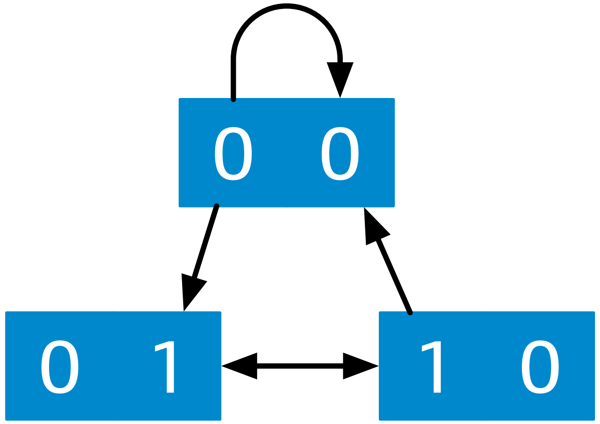


self-loop

solvable in $O(1)$ rounds

Proof: No self-loop
→ any solution breaks symmetry everywhere
→ can be used to find 3-coloring
→ not possible in $o(\log^* n)$ rounds



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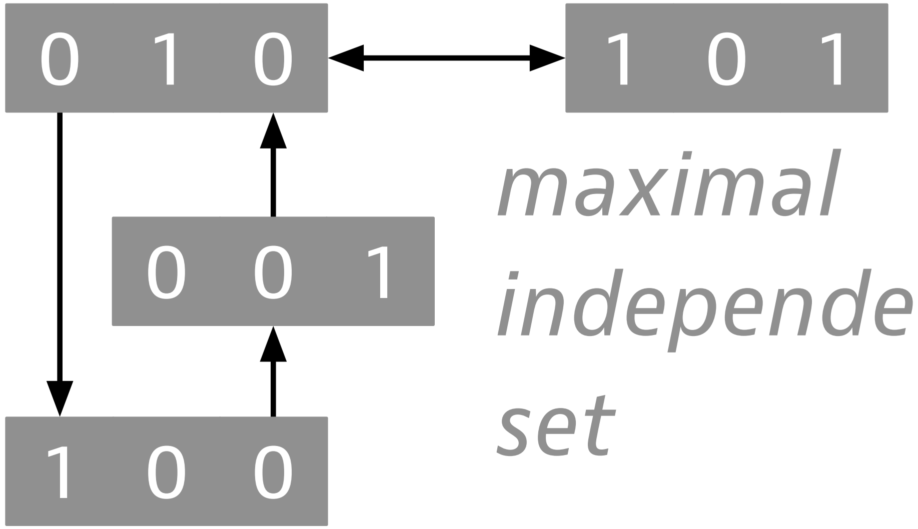

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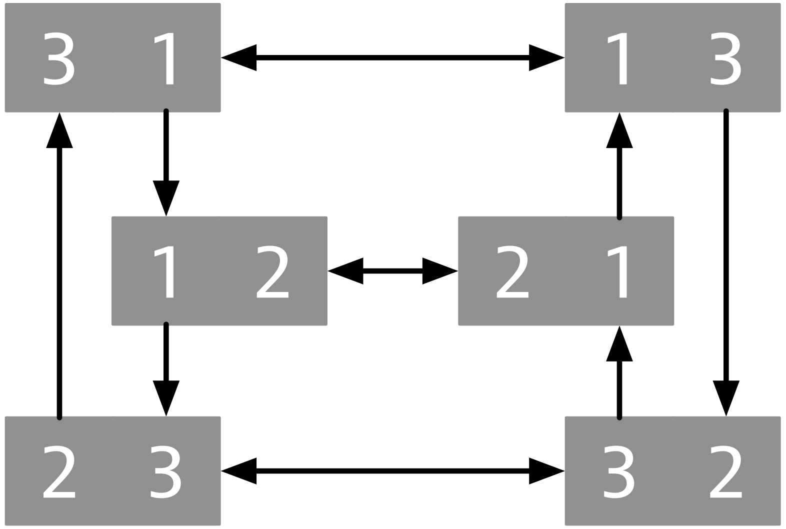

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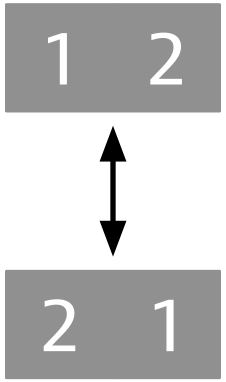

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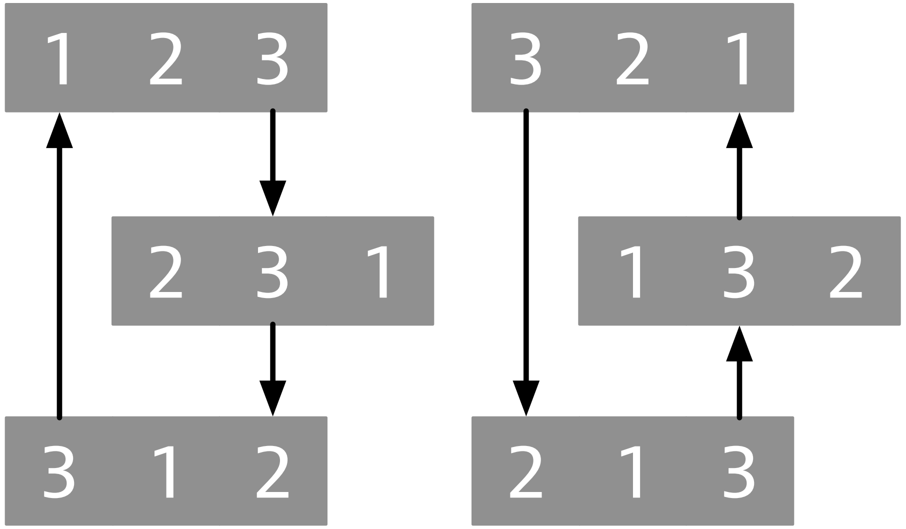

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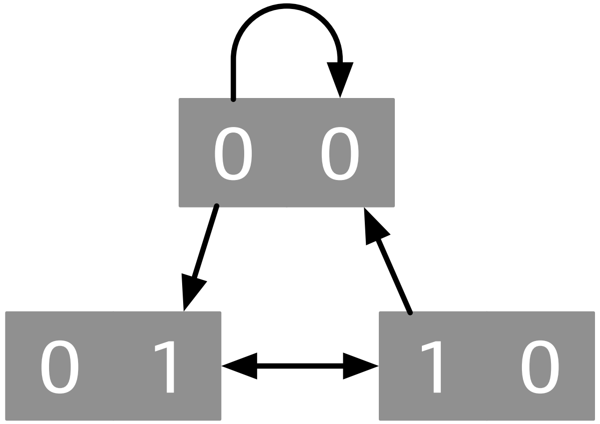

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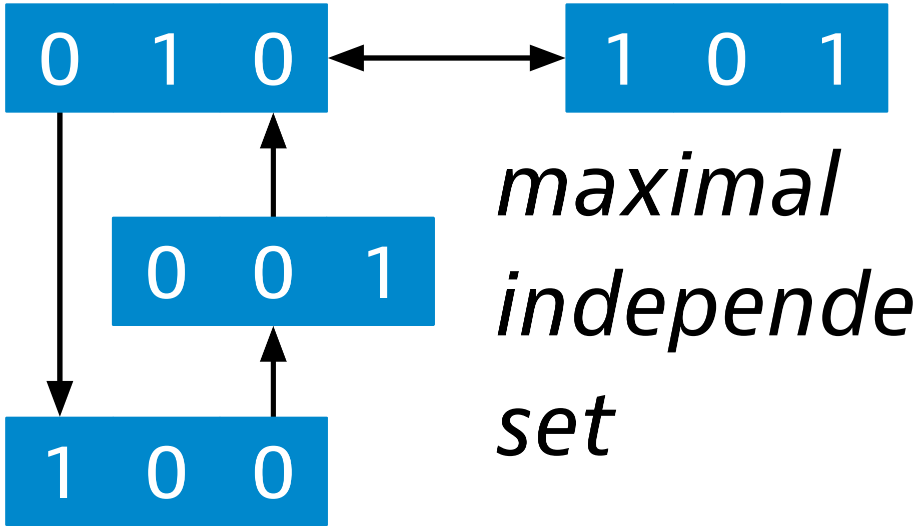

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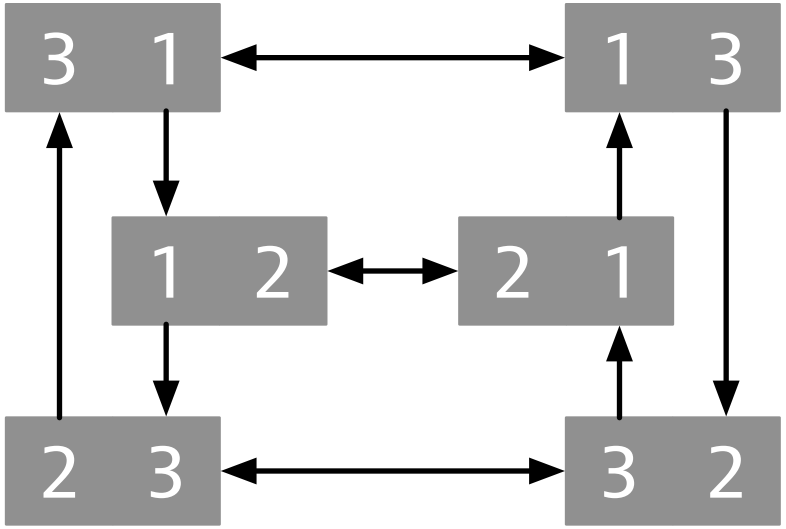
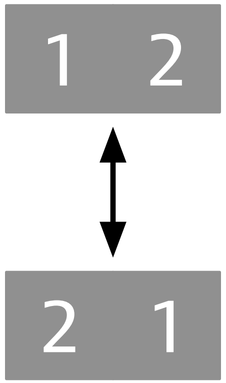
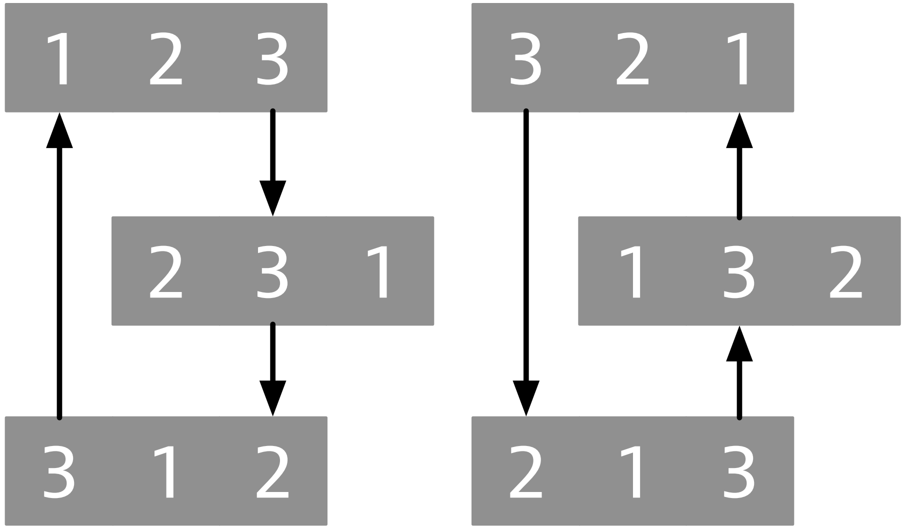


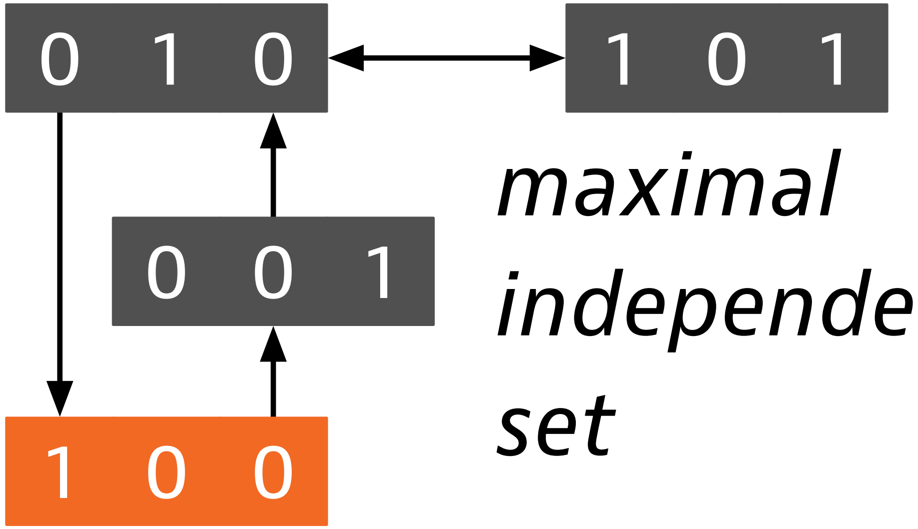
3-coloring



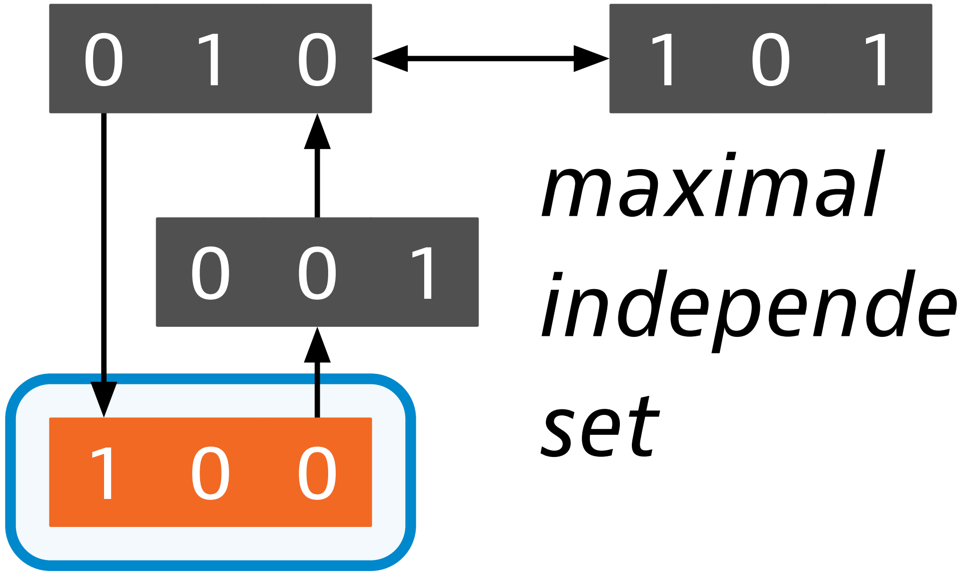
2-coloring



distance-2 coloring

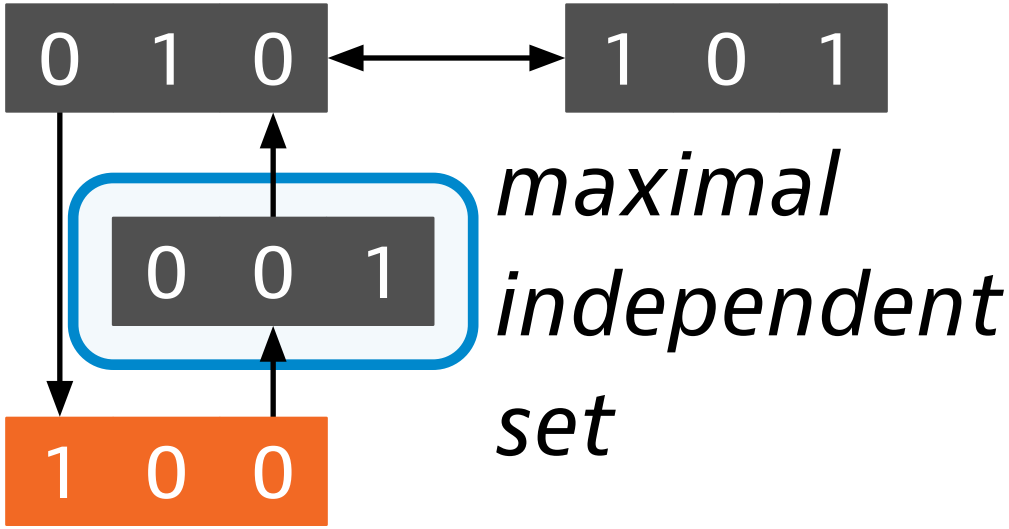


maximal independent set



maximal independent set

0



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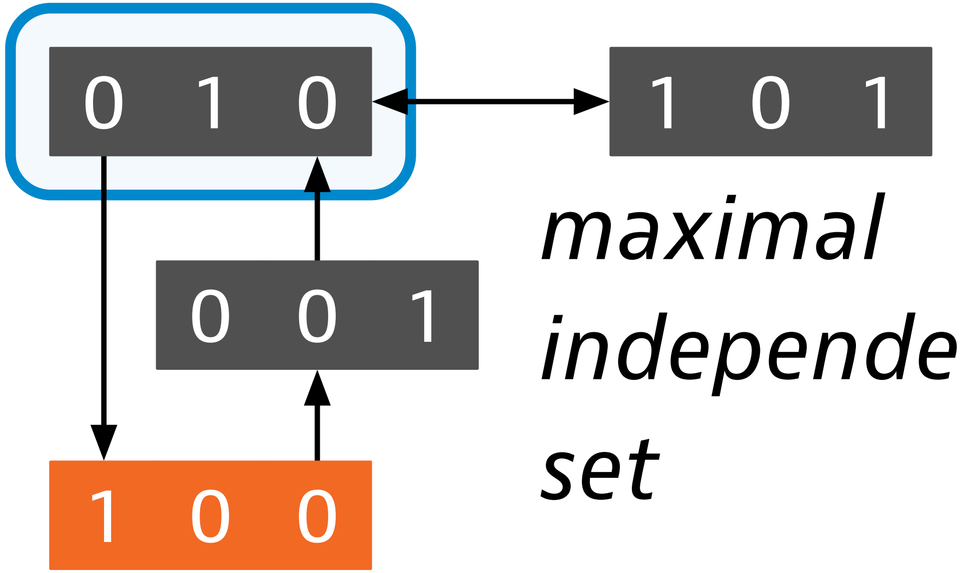
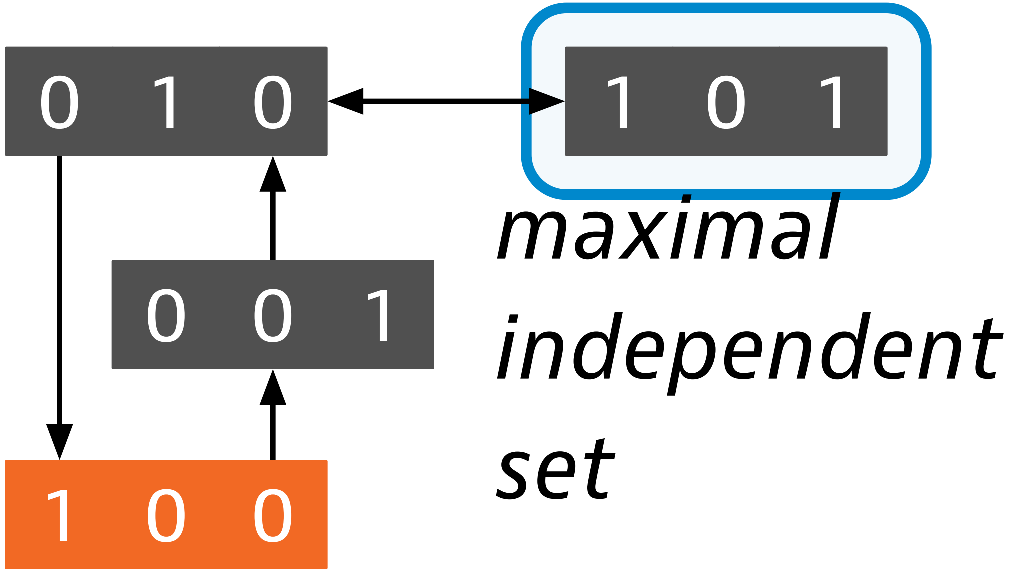


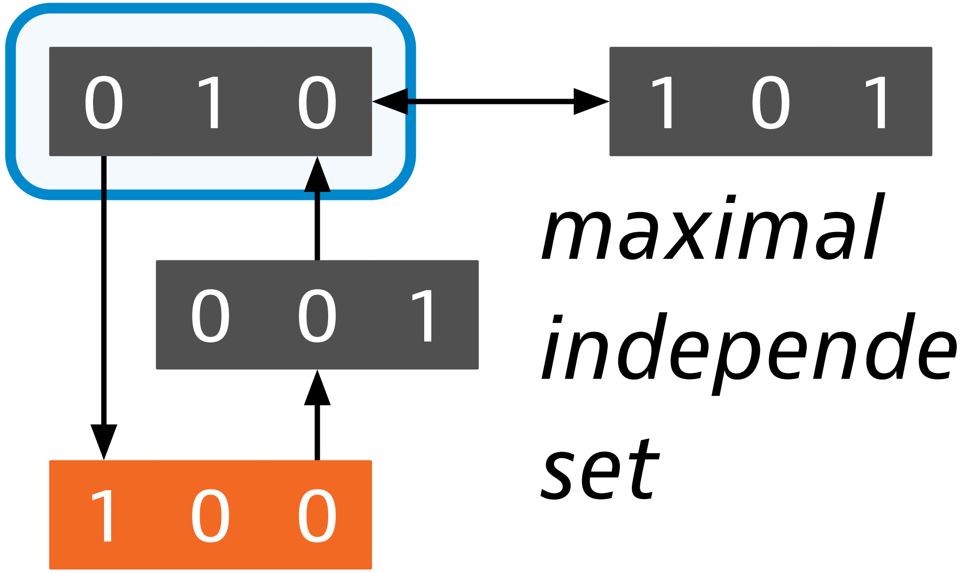
maximal independent set

2



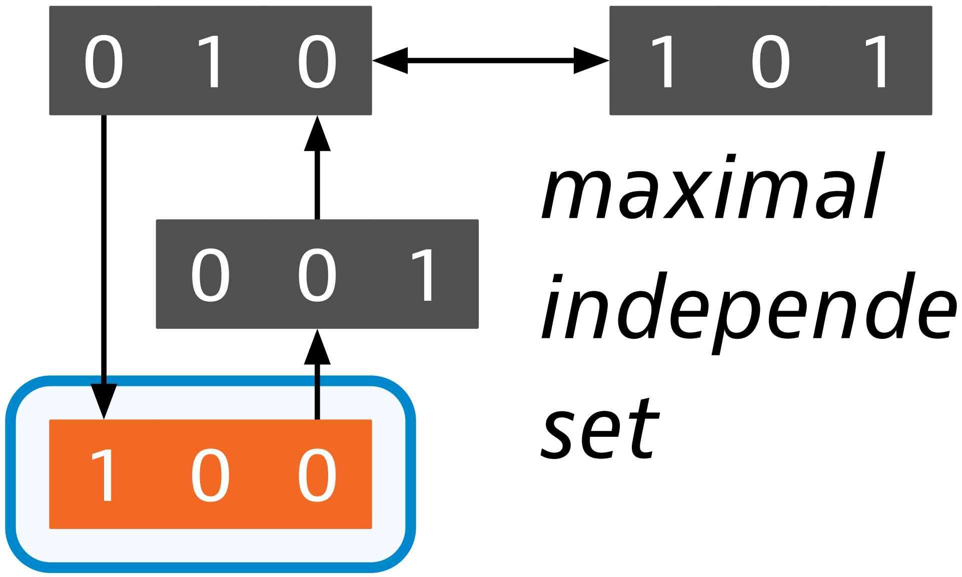
maximal independent set

3



maximal independent set

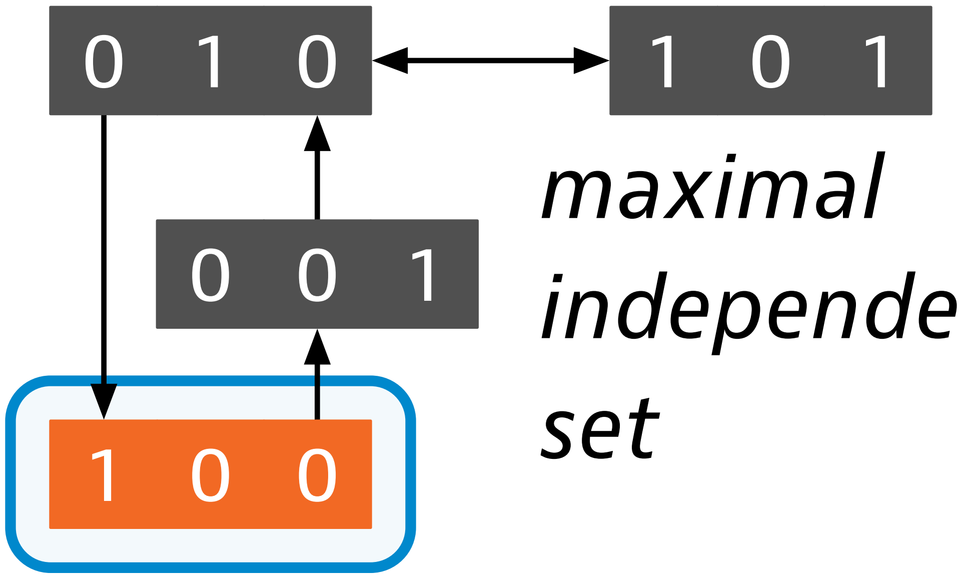
4



maximal independent set

Self-returning walk of length 5

5



0 1 0

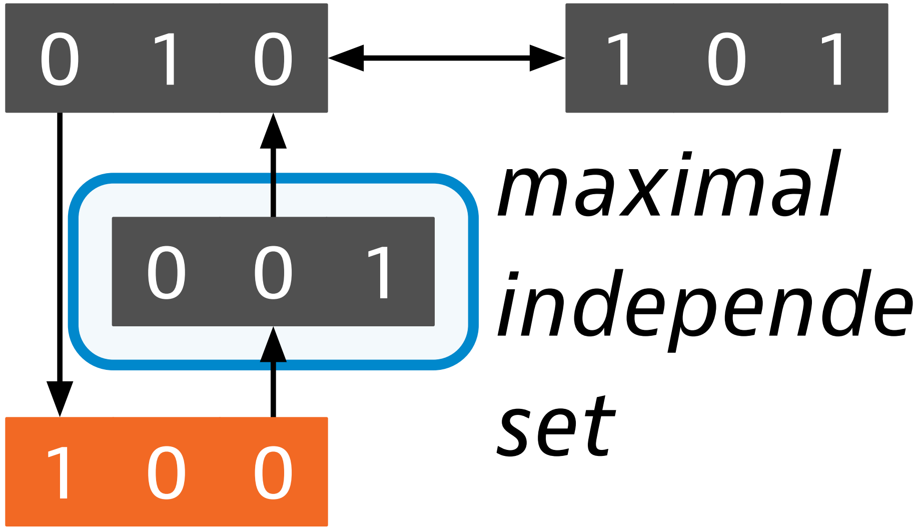
1 0 1

0 0 1

1 0 0

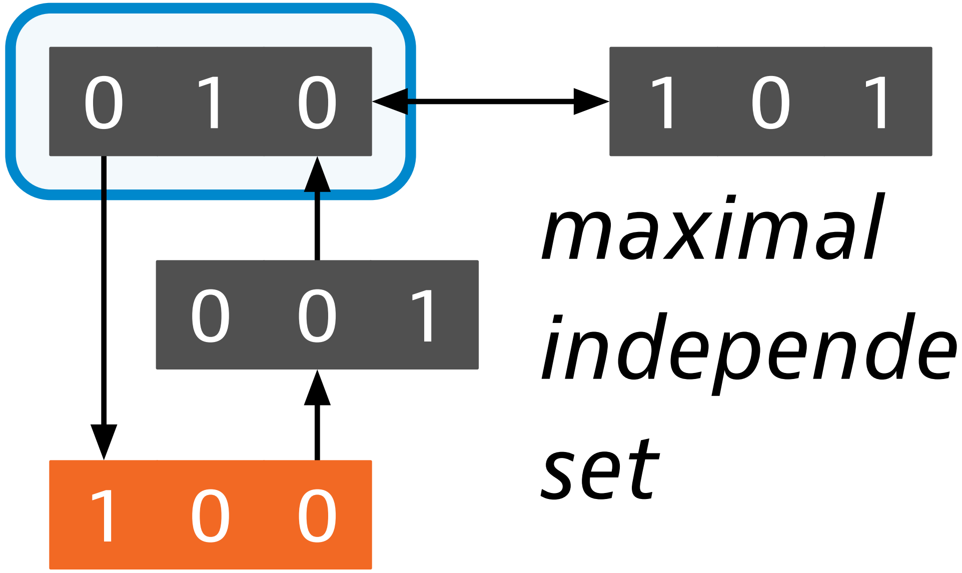
maximal independent set

0



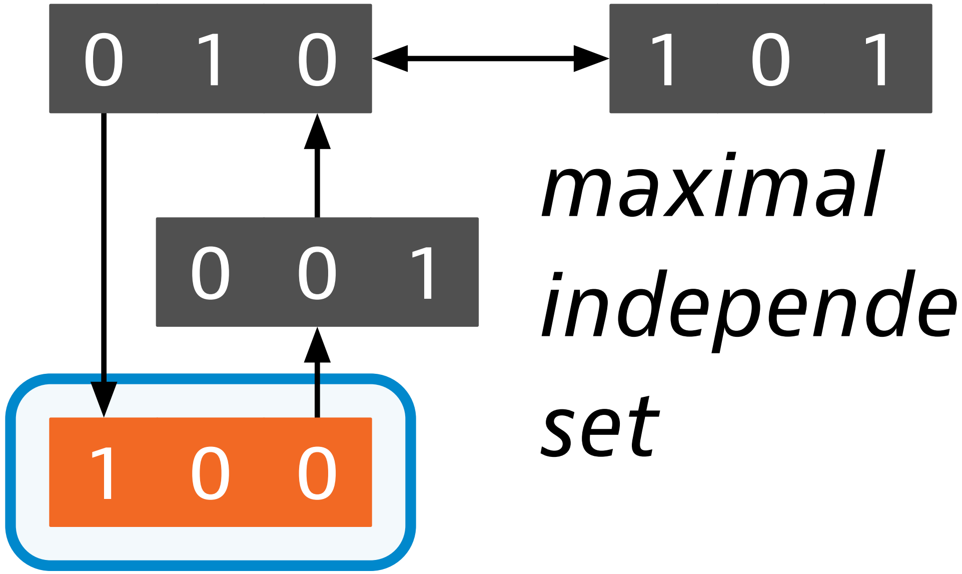
maximal independent set

1



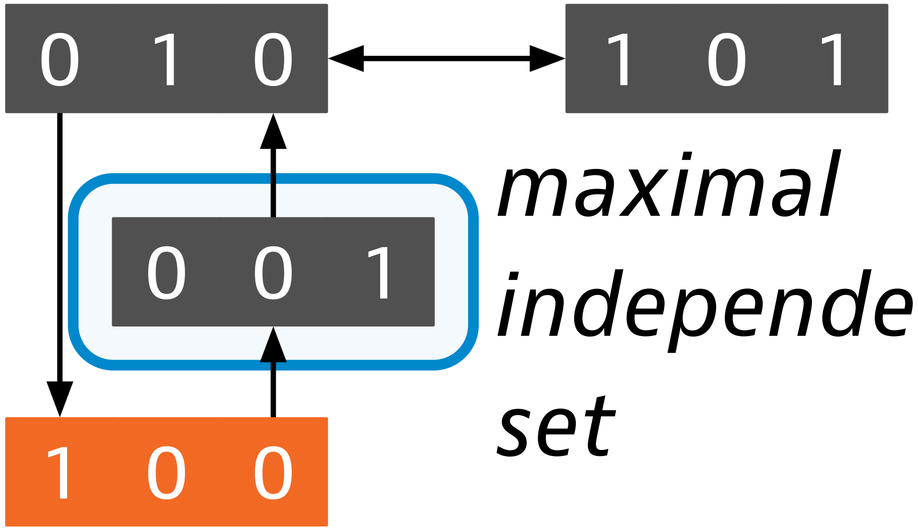
maximal independent set

2



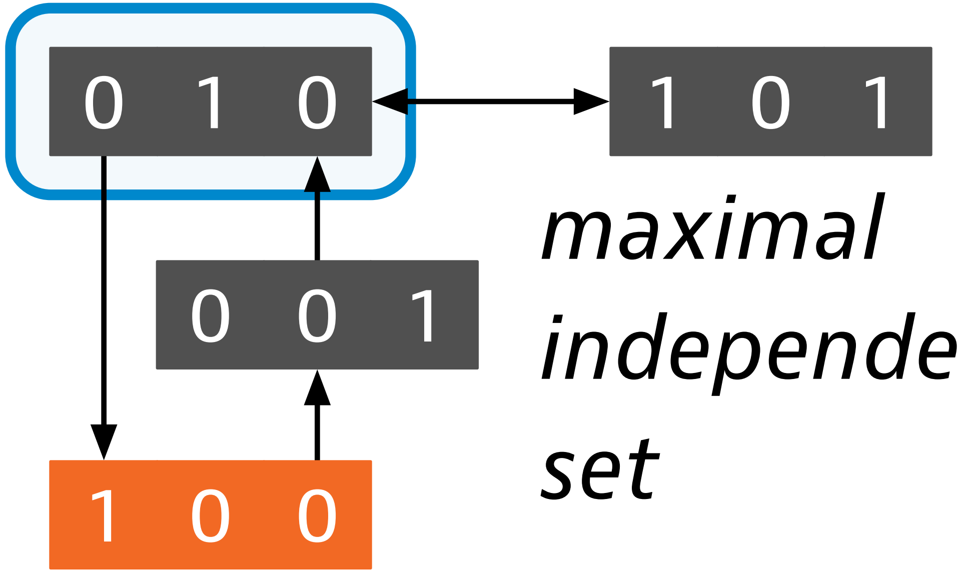
maximal independent set

3



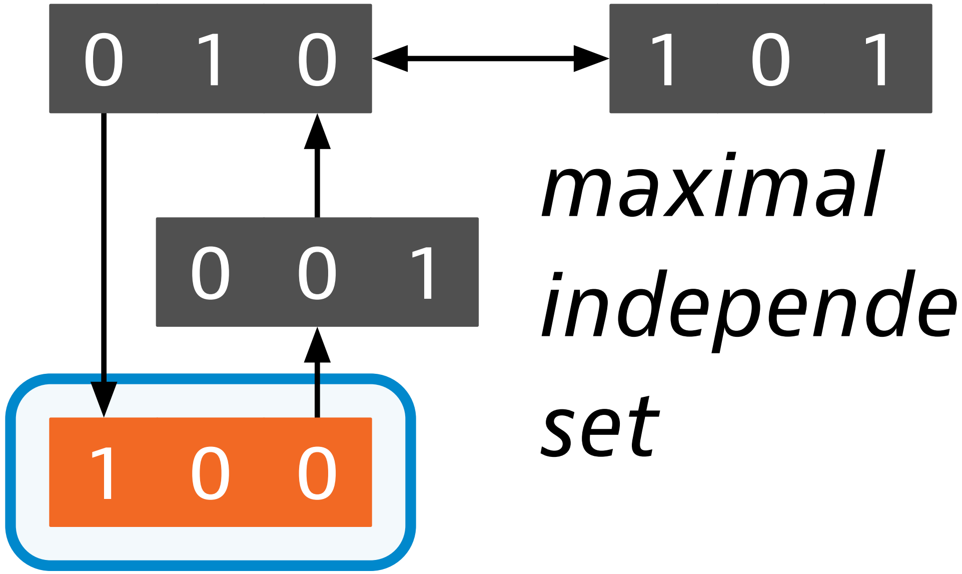
maximal independent set

4



maximal independent set

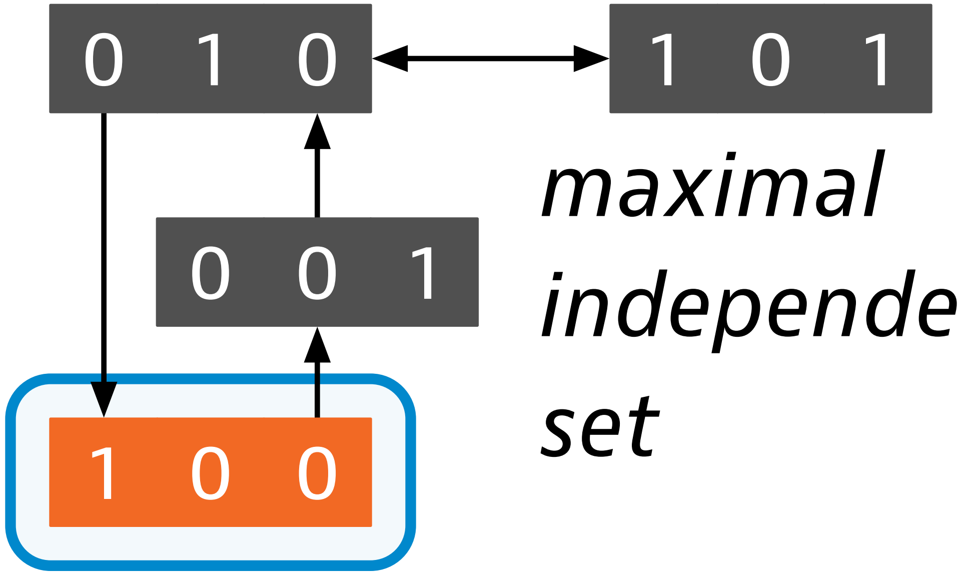
5



maximal independent set

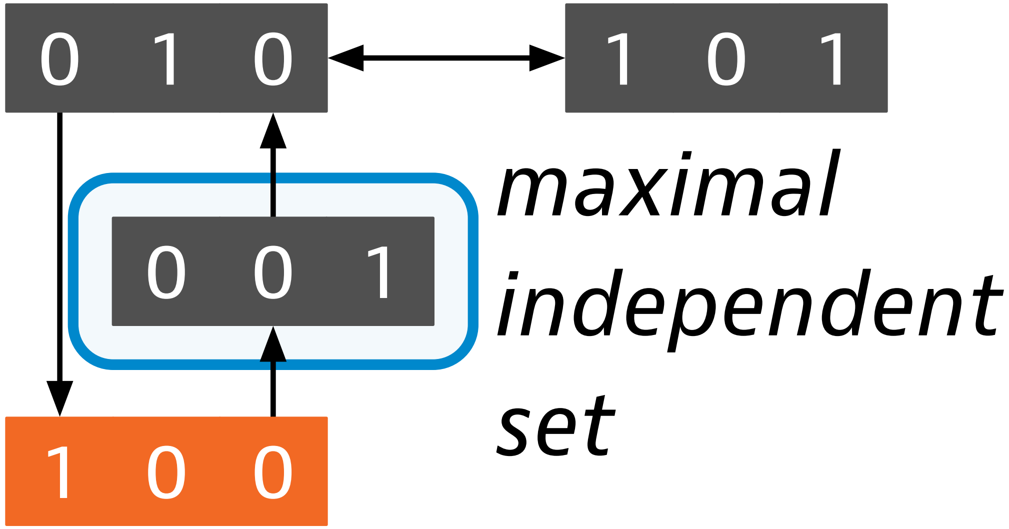
Self-returning walk of length 6

6

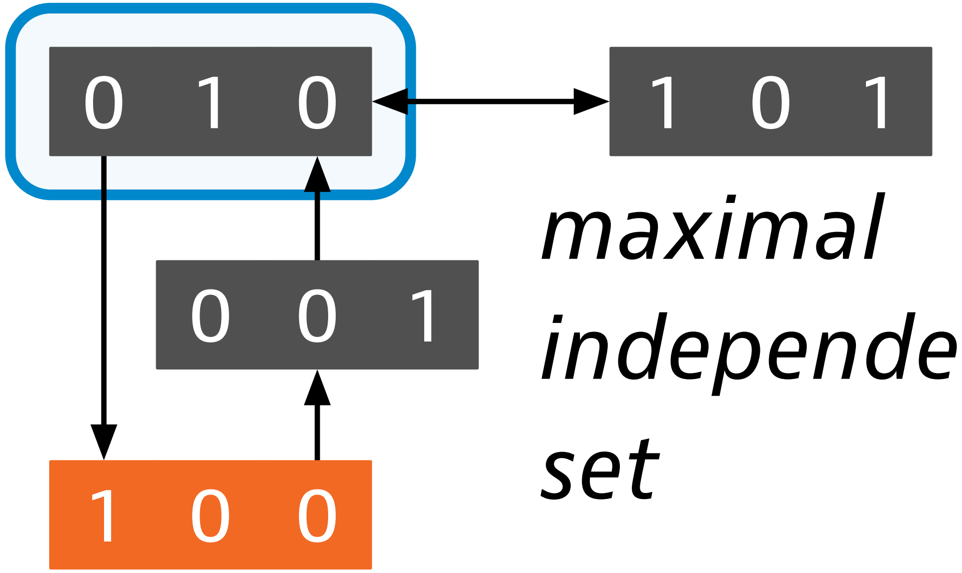


maximal independent set

0

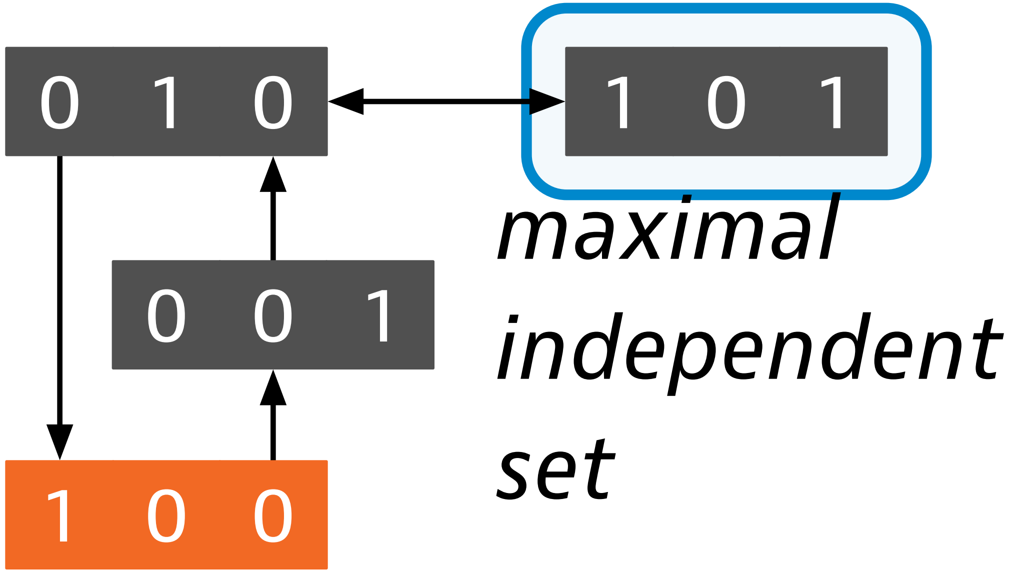


1



maximal independent set

2



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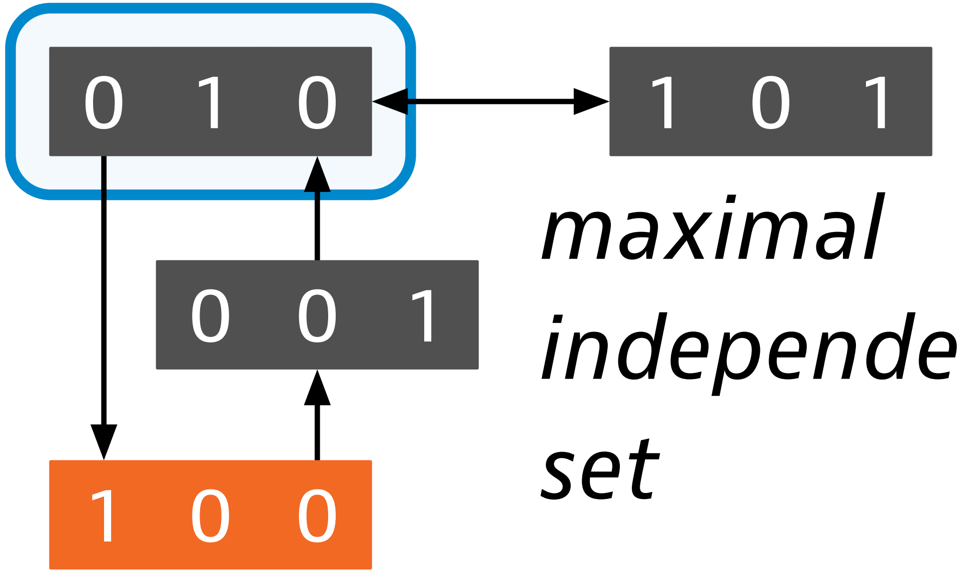
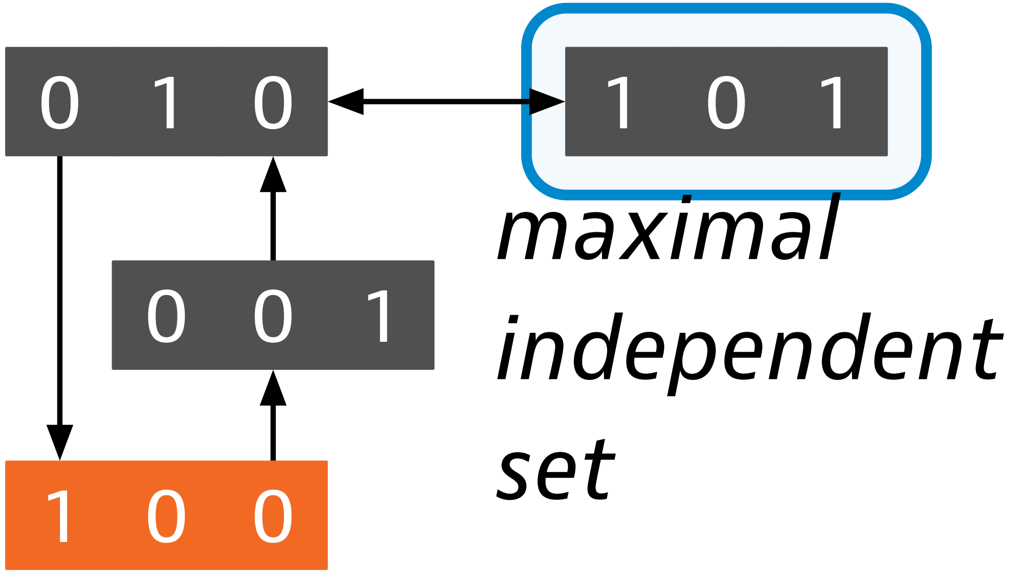


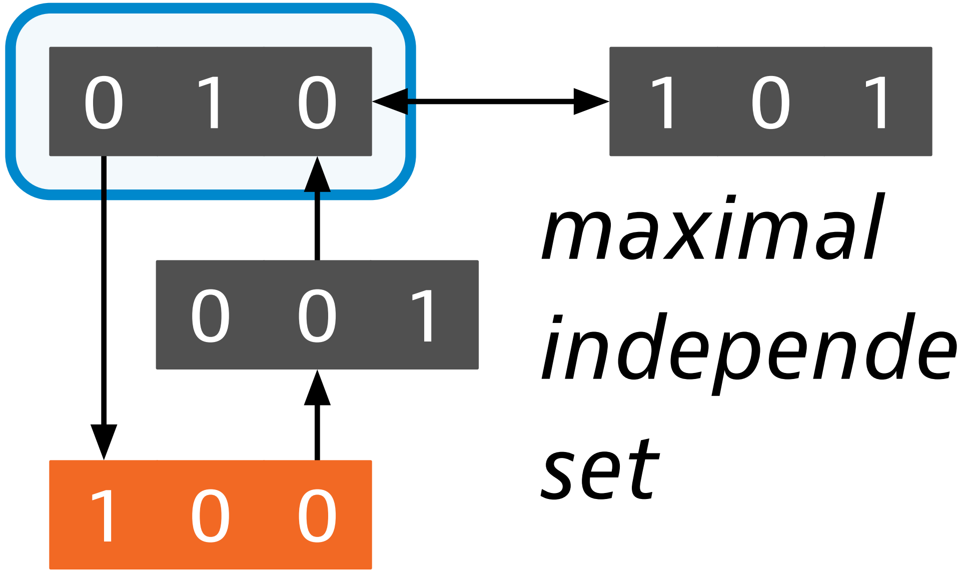
maximal independent set

4



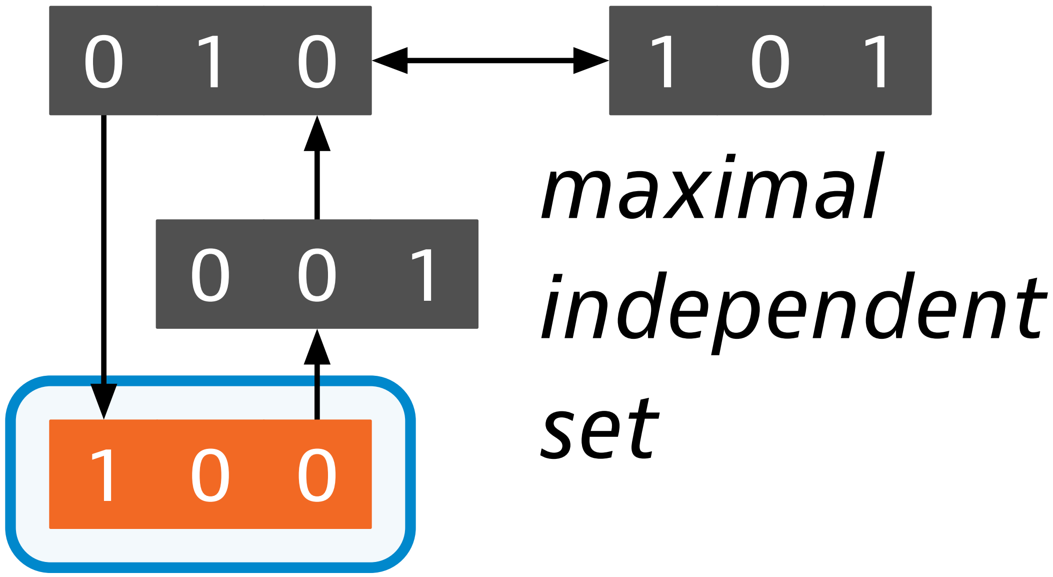
maximal independent set

5



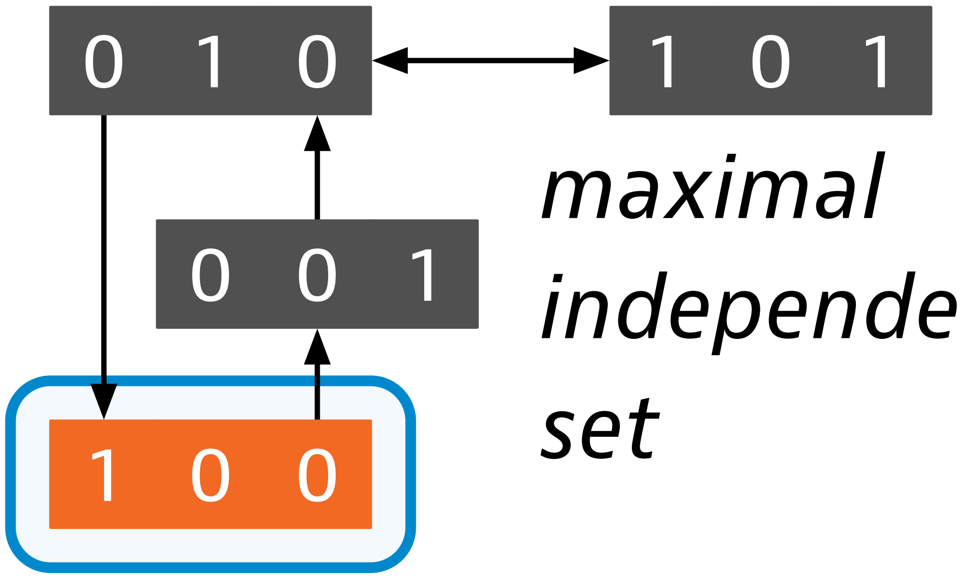
maximal independent set

6



Self-returning walk of length 7

7

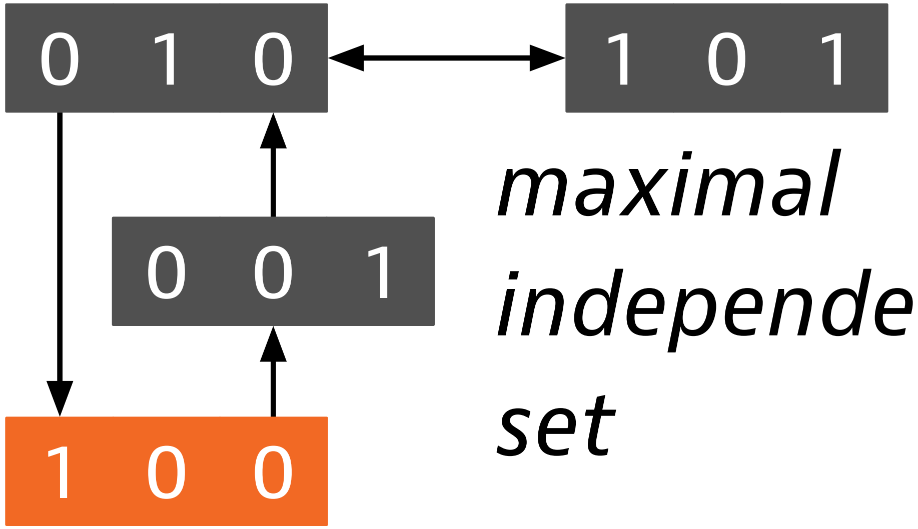


maximal independent set

Self-returning walk of length *k*

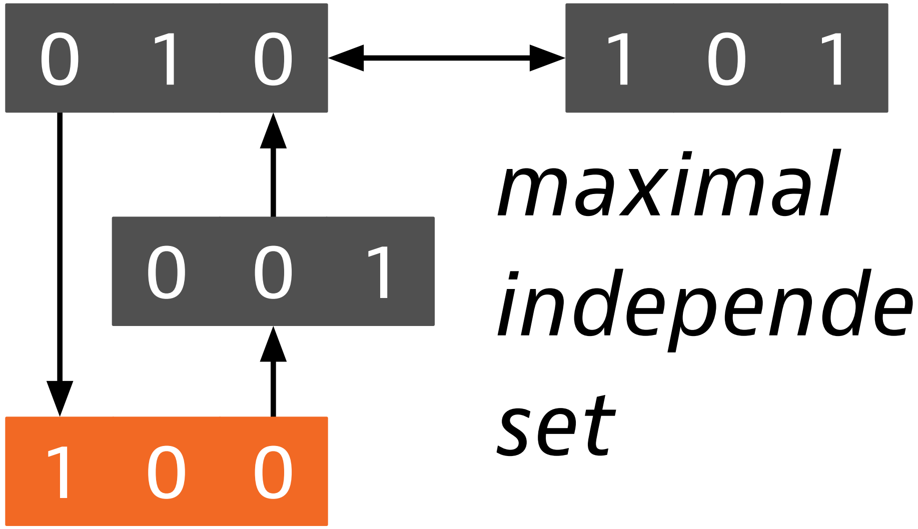
$$k = 5, 6, 7, 8, \ldots$$

“Flexible”: for all *k* ≥ k_0 there is a self-returning walk of length *k*



maximal independent set

“Flexible”: for all $k \geq k_0$ there is a self-returning walk of length k



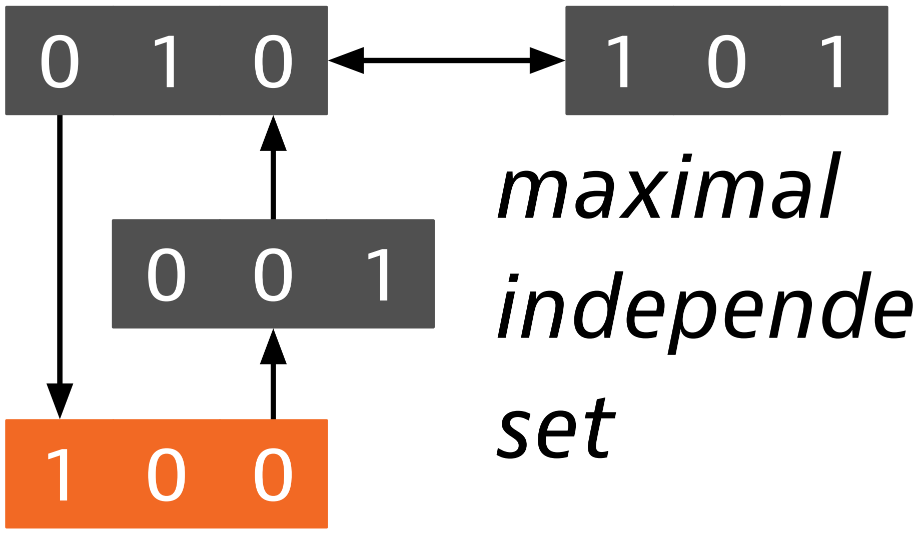
maximal independent set

Decidable in polynomial time

"Flexible": for all $k \geq k_0$ there is a self-returning walk of length k

↓

solvable in $O(\log^* n)$ rounds



maximal independent set

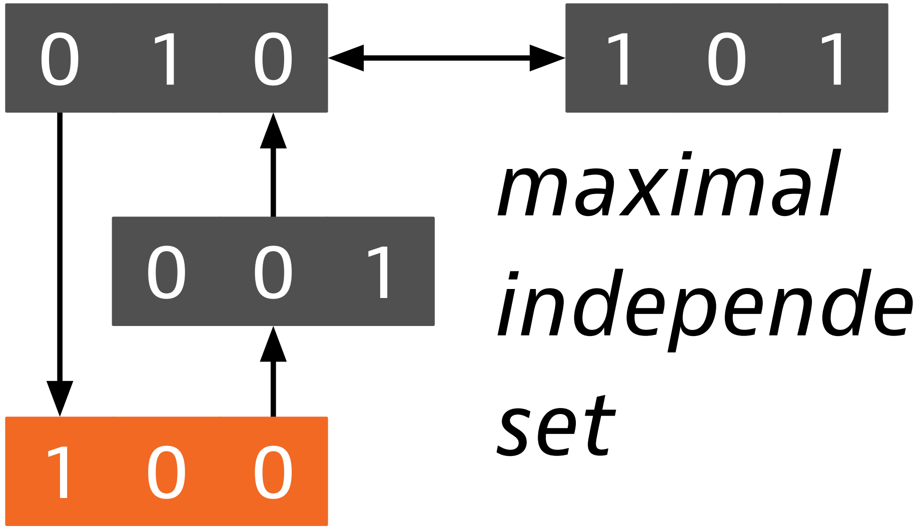
Algorithm:

- split in blocks of length ≥ k_0
- use the flexible configuration at each block boundary
- fill in between boundaries by following a self-returning walk

“Flexible”: for all $k \geq k_0$ there is a self-returning walk of length k

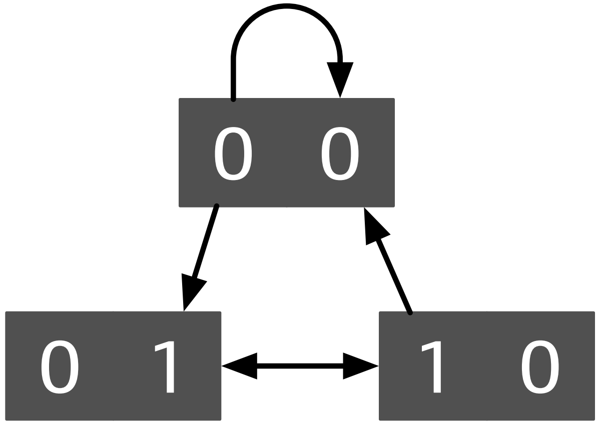
↓ ↑

solvable in $O(\log^* n)$ rounds

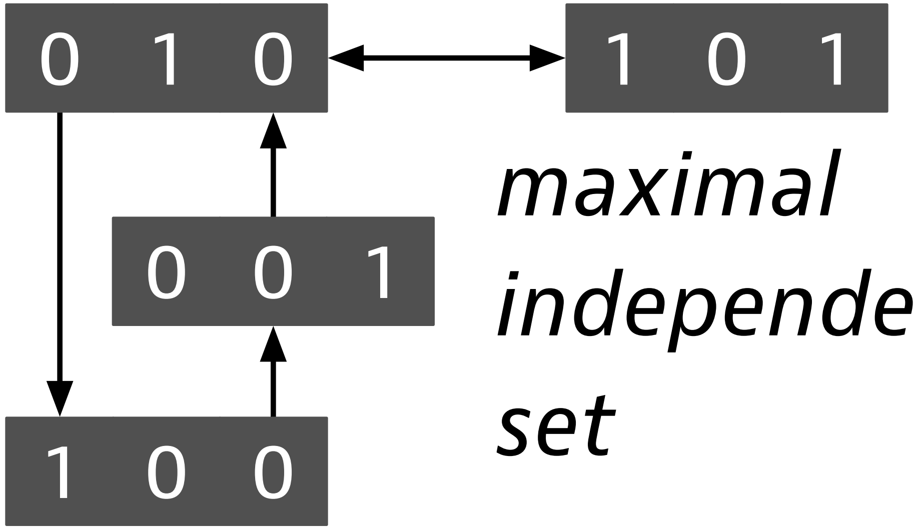


maximal independent set

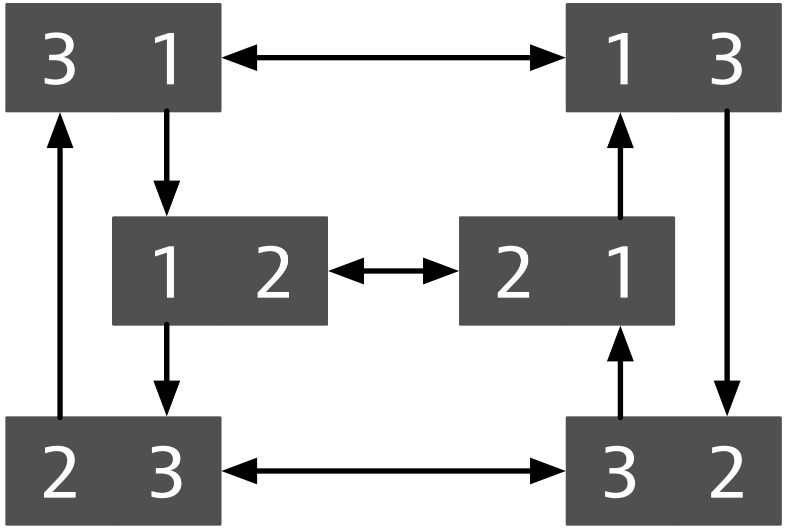
Proof: Not flexible → must use the same non-flexible configuration at least twice far from each other; not compatible for all distances
→ global coordination needed
→ not possible in $\boldsymbol{o(n)}$ rounds



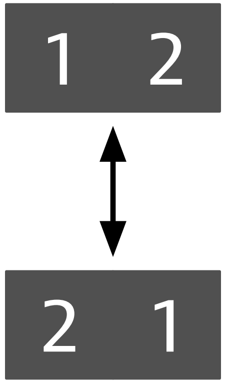
independent set



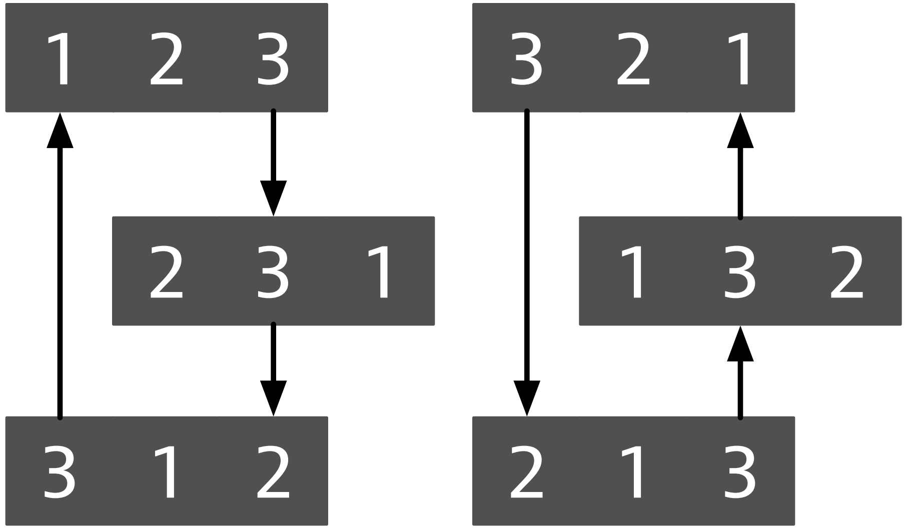
maximal independent set



3-coloring

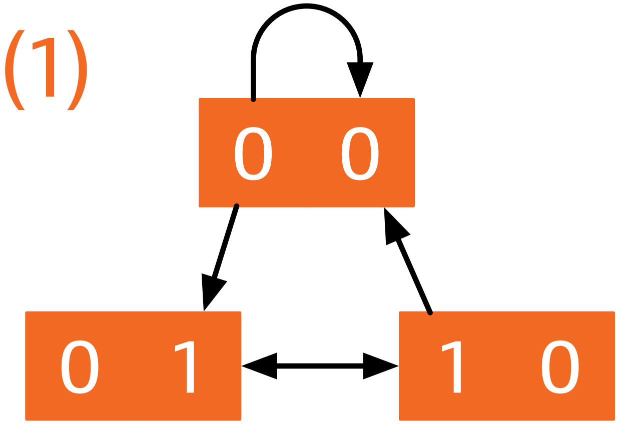


2-coloring

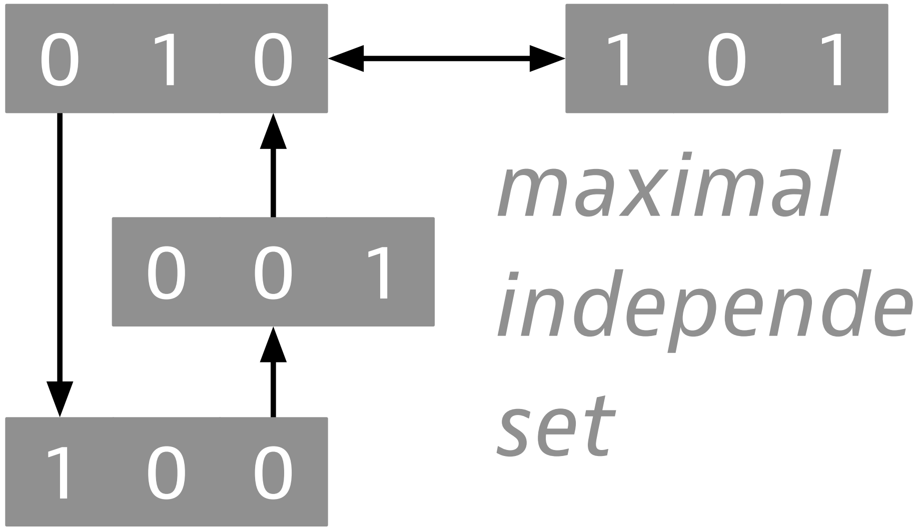


distance-2 coloring

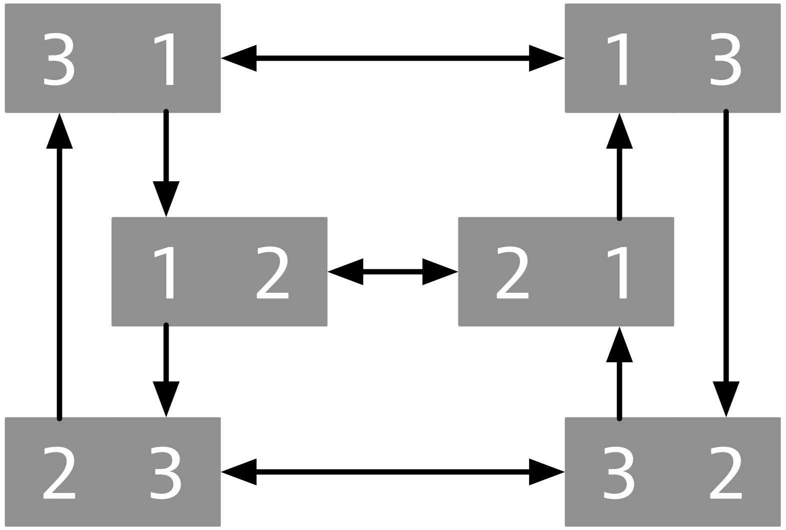
$O(1)$



independent set



maximal independent set



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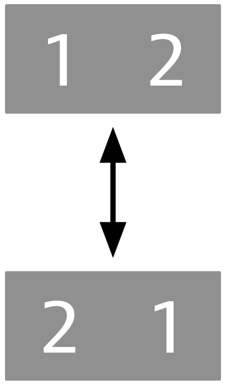

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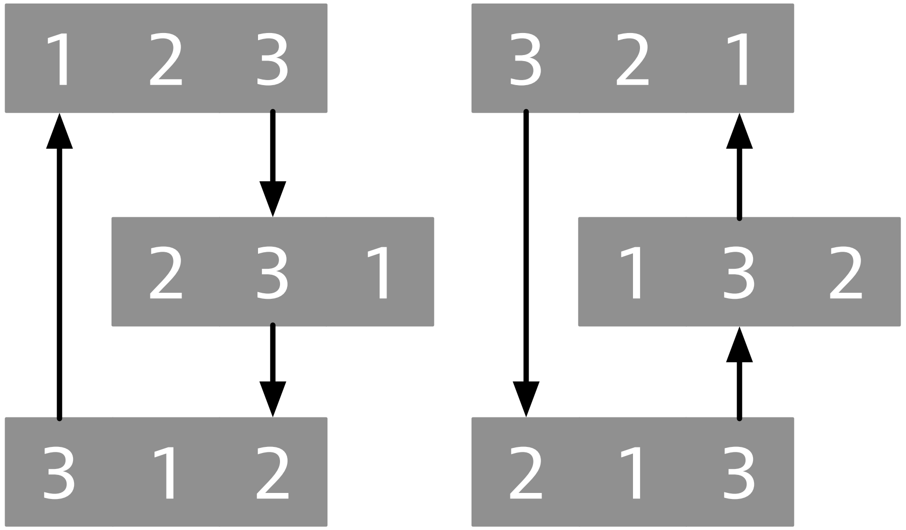

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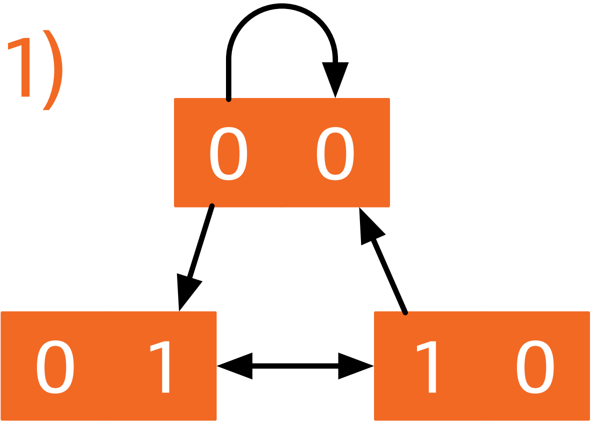
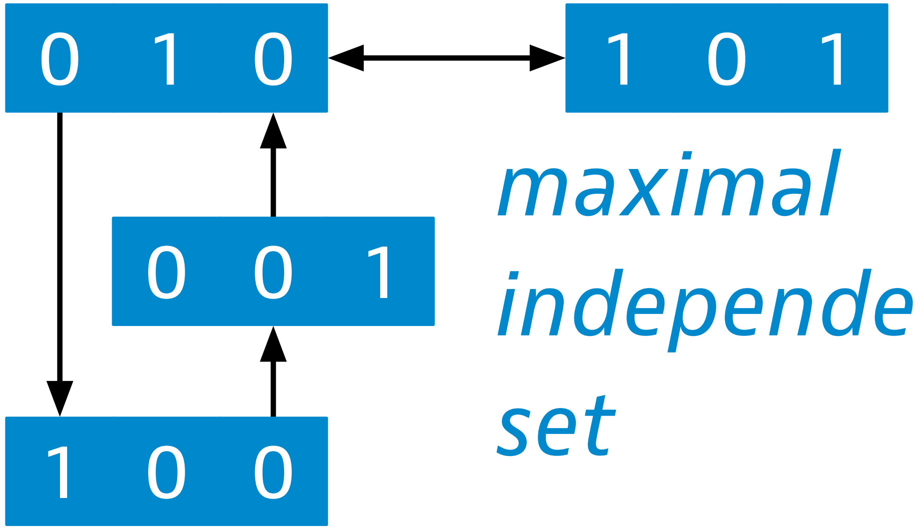
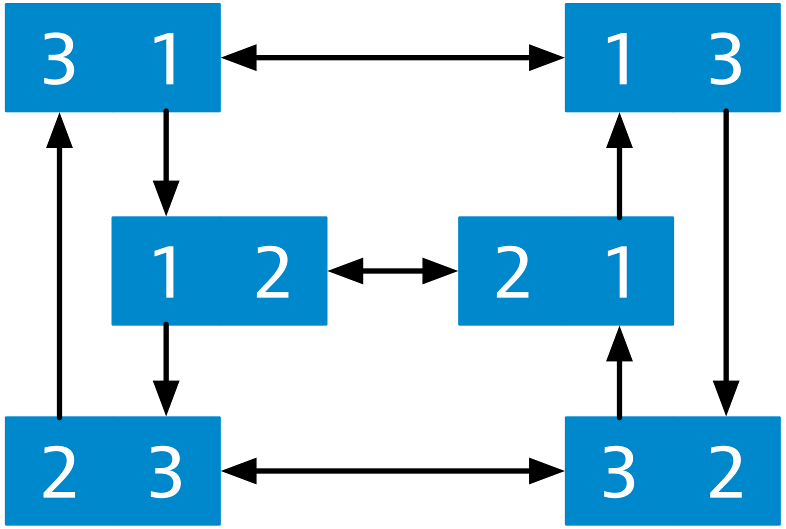


independent set

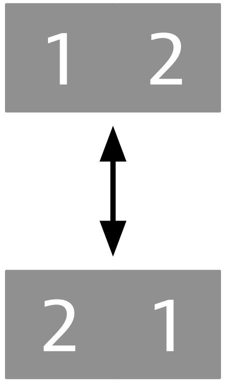


maximal independent set

$O(\log^* n)$



3-coloring



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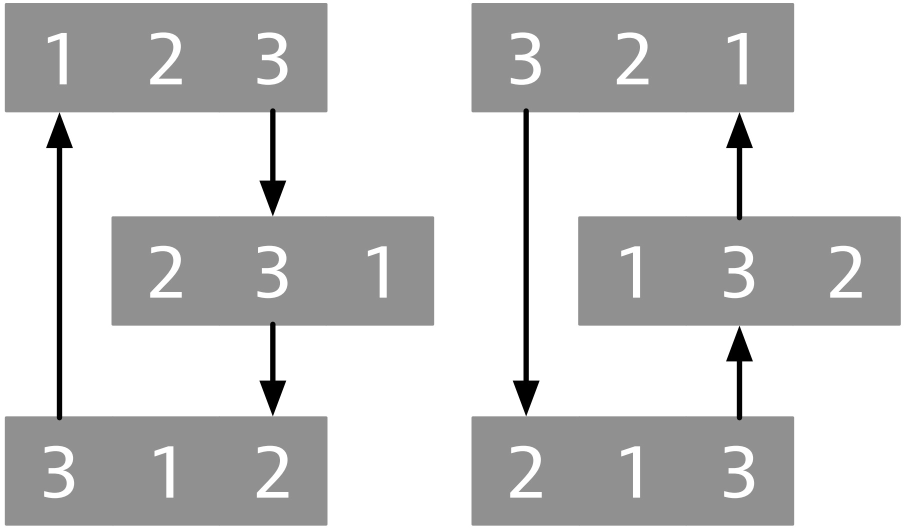

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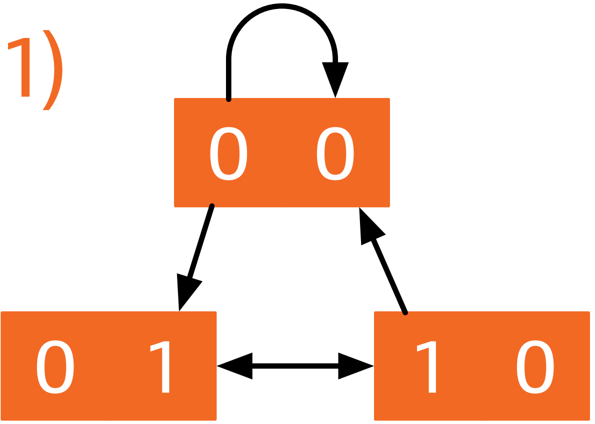
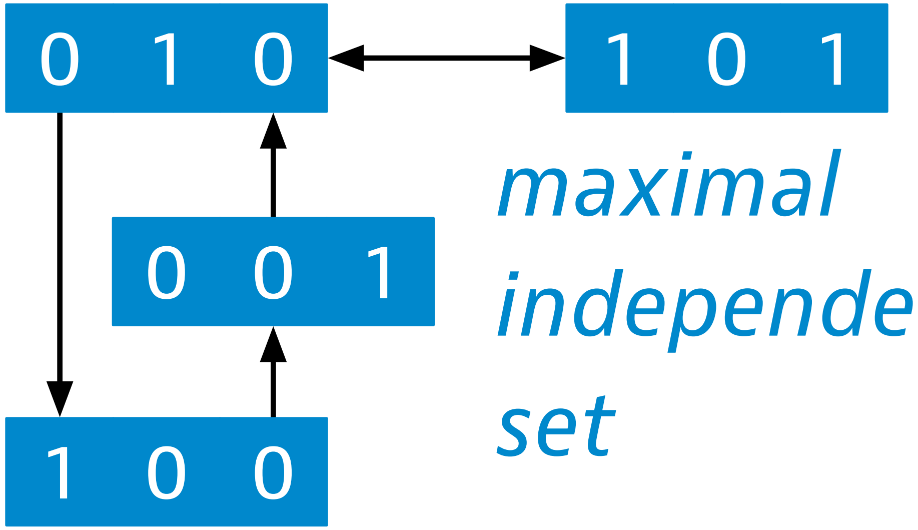


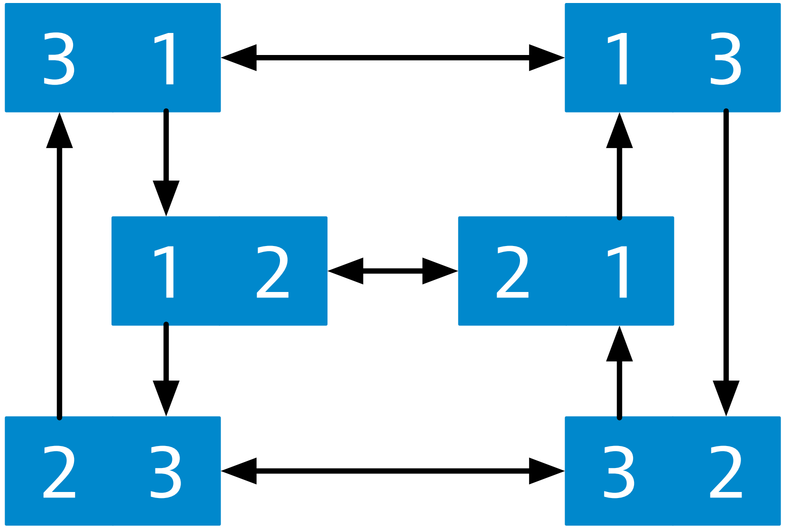
independent set



maximal independent set

$O(n)$

$O(\log^* n)$



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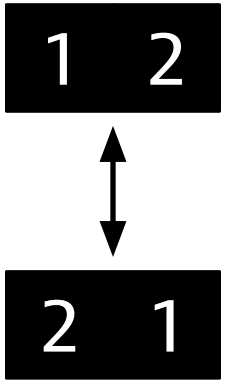

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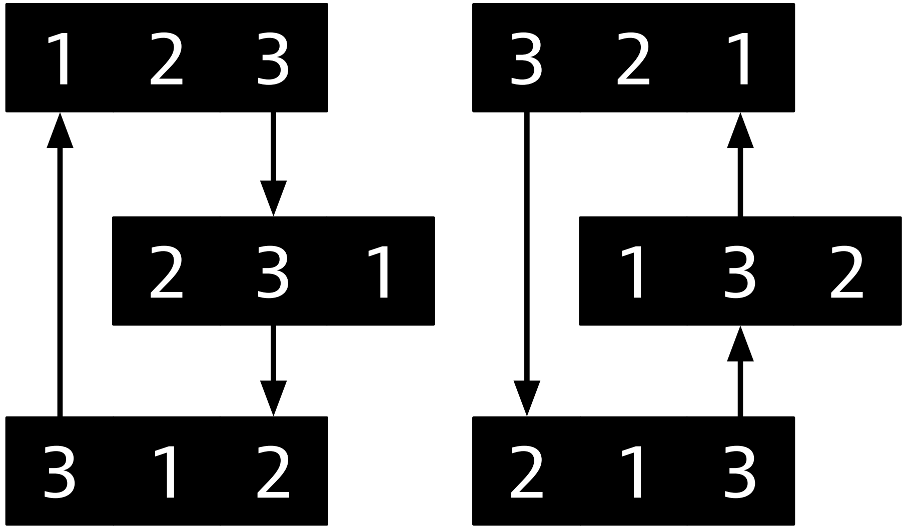
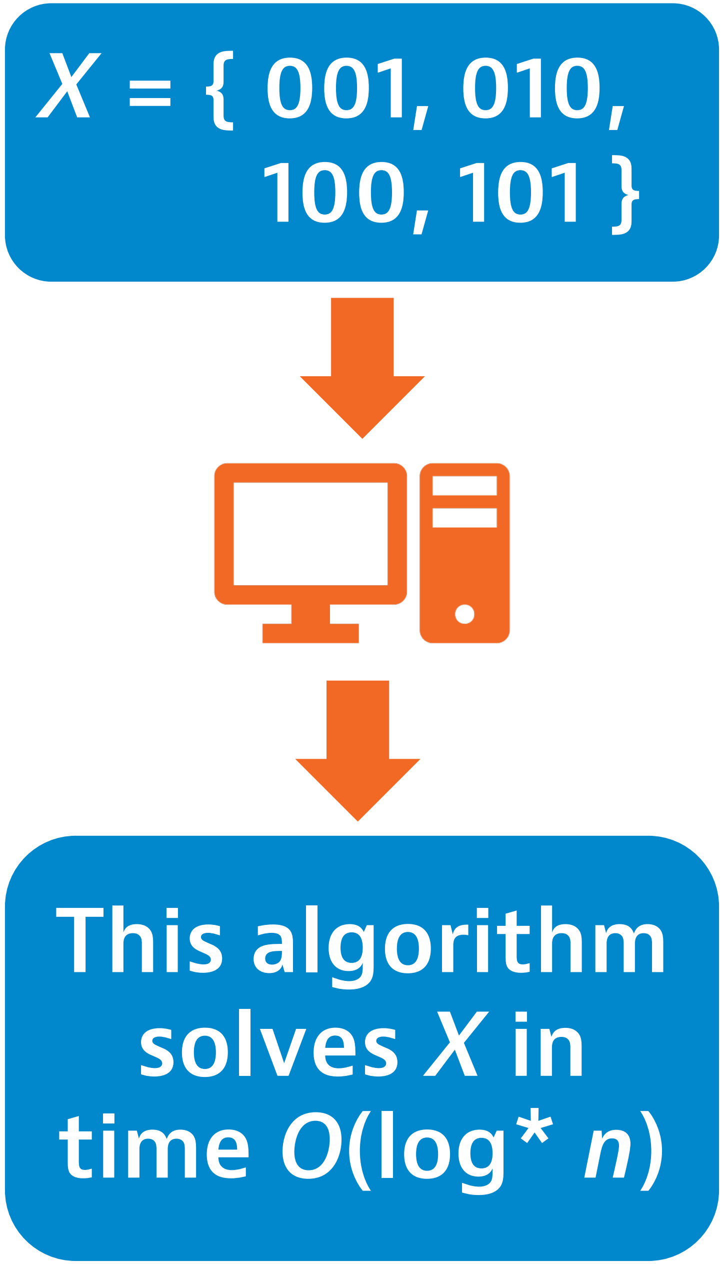


distance-2 coloring

Fully automatic

- Write down the specification of ***any locally checkable problem X***
- Then you can ***find efficiently***
  - distributed round complexity of *X*
  - asymptotically optimal distributed algorithm for *X*



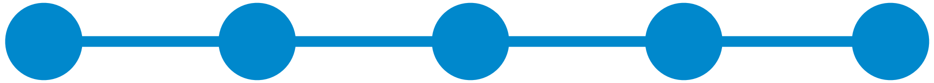
X = { 001, 010, 100, 101 }

This algorithm solves *X* in time *O*(log* *n*)

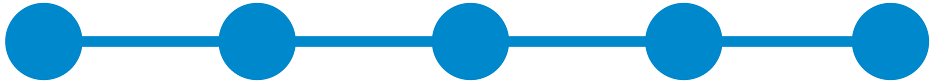
“Oh but doing it for ***this*** *case is of course trivial…”*

But what are **other cases** in which algorithm design & lower-bound proofs can be automated?

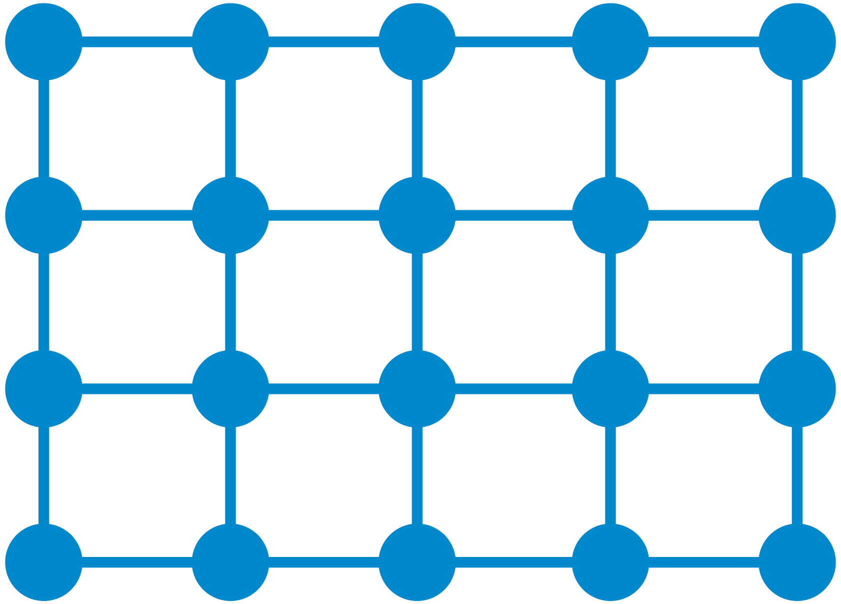
Cycles, paths



Cycles, paths

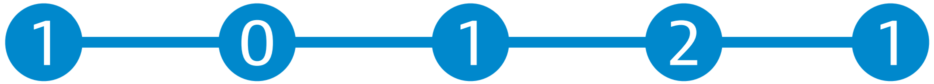


Grids



Cycles, paths

solution ≈
execution history of
a **finite automaton**



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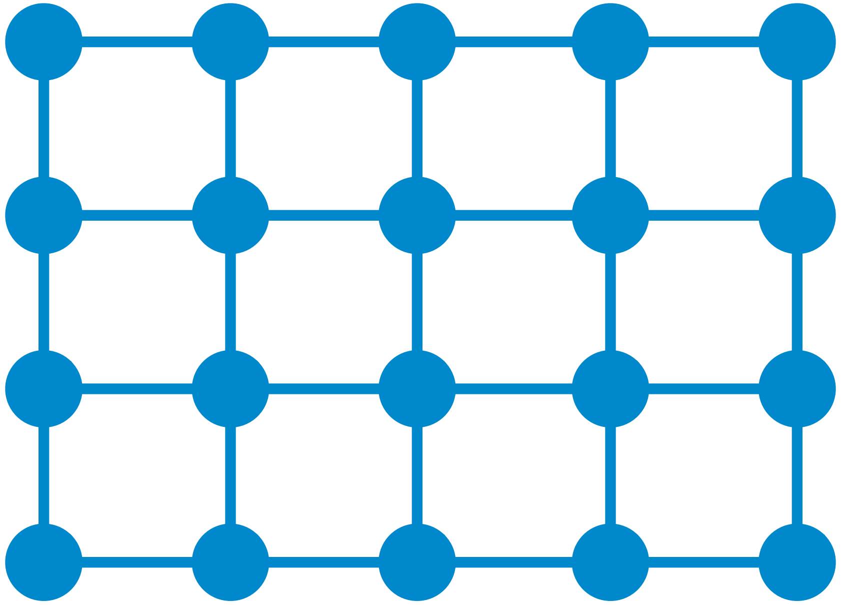

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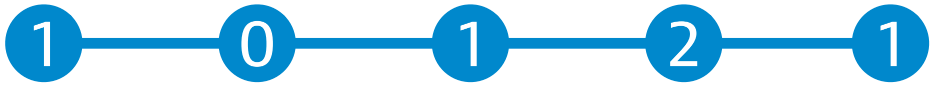
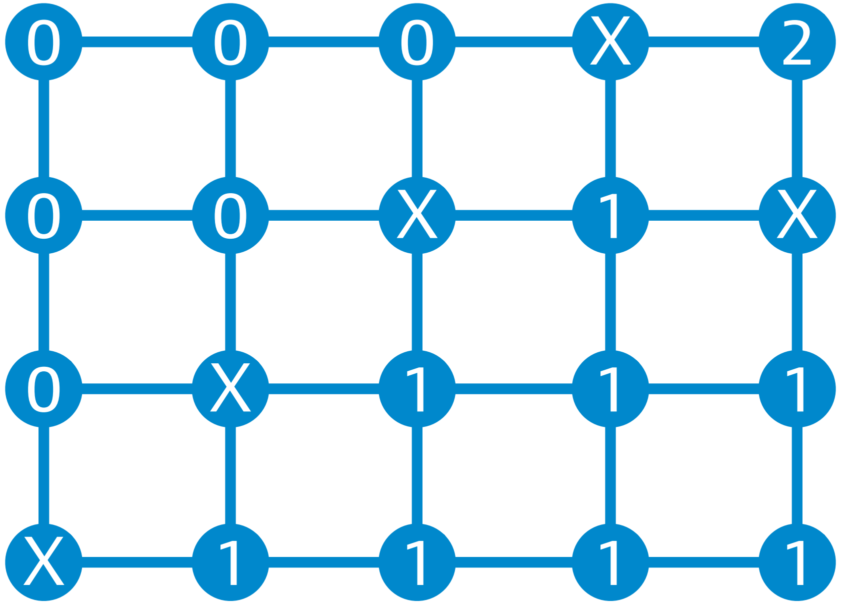


Grids

solution ≈
execution history of
a **Turing machine**



Cycles, paths

solution ≈
execution history of
a **finite automaton**

Many questions (efficiently) decidable

Grids

solution ≈
execution history of
a **Turing machine**

Cycles, paths

solution ≈
execution history of
a **finite automaton**

Many questions (efficiently) decidable

Grids

solution ≈
execution history of
a **Turing machine**

Many questions undecidable

Undecidable

$\neq$

hopeless

Normal forms

Any algorithm $\boldsymbol{A}$ that solves a locally checkable problem X fast can be written as $\boldsymbol{A} = \boldsymbol{B} \circ \boldsymbol{C_k}$

- $\boldsymbol{C_k}$ = distance-k coloring
- $\boldsymbol{B}$ = finite function that maps colored neighborhoods to local outputs

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"Fast" = e.g. $O(\log^* n)$

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Proof idea: Coloring ≈ locally unique identifiers. If A fails with such fake identifiers, it also fails in some small graph with some real identifiers.

Normal forms

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For each k = 1, 2, 3, …:

- check all possible candidate functions $\boldsymbol{B}$
- if any of them is good → fast algorithm found!

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Normal forms

Any algorithm ***A*** that solves a locally checkable probler … as ***A*** = ***B*** ∘ C_k

- C_k =
- ***B*** = … plored neig … s

For eac … 2, 3, ….

- check all p … sible candidate functions ***B***
- if any of them is good → fast algorithm found!

Finite computation for a given candidate *B*:
no worries about the halting problem

Normal forms

Undecidability:
don’t know when to stop if fast algorithms don’t exist

ves a locally checkable
ritten as $\boldsymbol{A} = B \circ C_k$

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nei orhoods to local outputs

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- $\boldsymbol{C}_k$ = distance-k coloring
- $\boldsymbol{B}$ = finite func
  neighborhoods

Computational complexity:
typically doubly-exponential in k

For each $\boldsymbol{k}$ = 1, 2, 3, ...

- check all possible candidate functions $\boldsymbol{B}$
- if any of them is good → fast algorithm found!

Sometimes doable!

- Natural problems often solvable with a ***small k***

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- We can make it more feasible in practice:
  - more ***"compact" normal forms***,
    e.g. distance-*k* coloring → ruling set

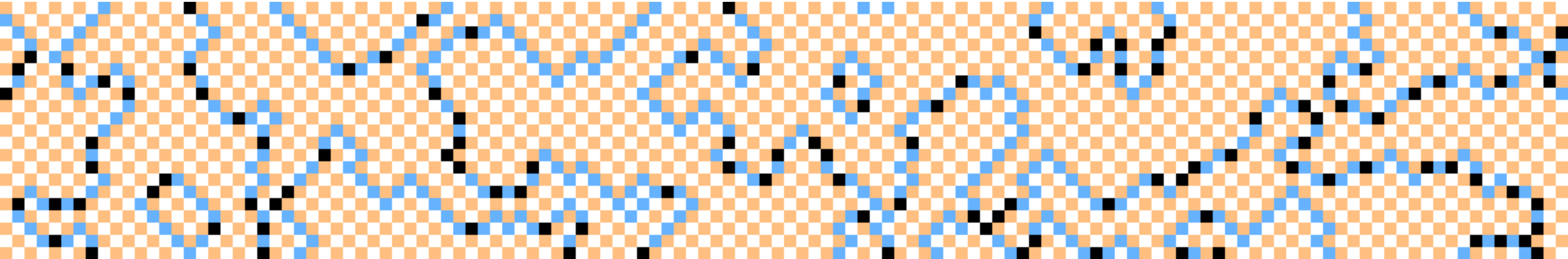
Sometimes doable!

- Natural problems often solvable with a ***small k***
- We can make it more feasible in practice:
    - more ***“compact” normal forms***,
      e.g. distance-k coloring → ruling set
    - represent *“candidate B is good for this value of k”*
      as a Boolean formula and use modern ***SAT solvers***
      to find such a B

Sometimes doable!

- Example: ***4-coloring in grids***
- Computers were much faster than human beings in figuring out that this is solvable in $O(\log^* n)$ rounds

[Brandt et al., PODC 2017]



Cycles, paths

solution ≈
execution history of
a **finite automaton**

Many questions (efficiently) decidable

Grids

solution ≈
execution history of
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Many questions undecidable (but there is hope!)

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Grids + beyond

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Bad news apply to
any graph family that
contains large grids

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What is here between paths and grids?

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Trees
Bounded treewidth
High girth

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lots of open questions,
no known obstacles!

- **Trees**
- **Bounded treewidth**
- **High girth**

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some positive results
already known
(ask me, happy to tell more!)
{

Trees
Bounded treewidth
High girth

Big picture: **towards meta-computational research questions**

Meta questions

- **Traditional questions:** what is the best distributed algorithm for solving problem *X* ?
- **Meta-computational questions:** can we design an (efficient) ***meta-algorithm*** that finds the best distributed algorithm for ***any problem X*** in some problem family *F* ?

Classification

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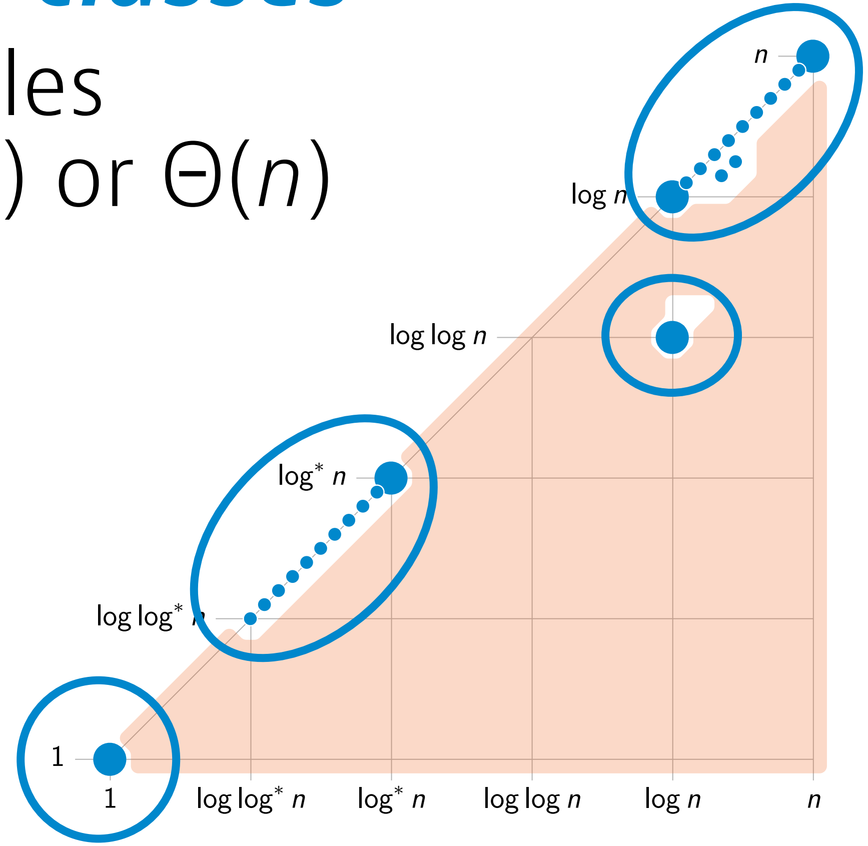
  - locally checkable problems in general graphs belong to one of four broad classes



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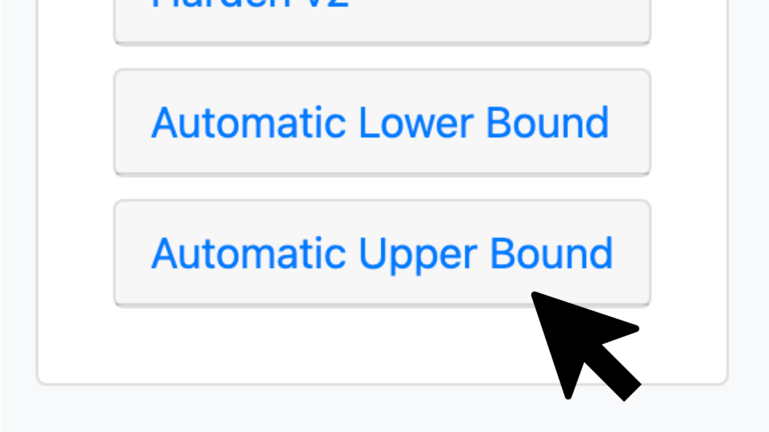
How? *Are there general techniques we can apply without much thinking?*

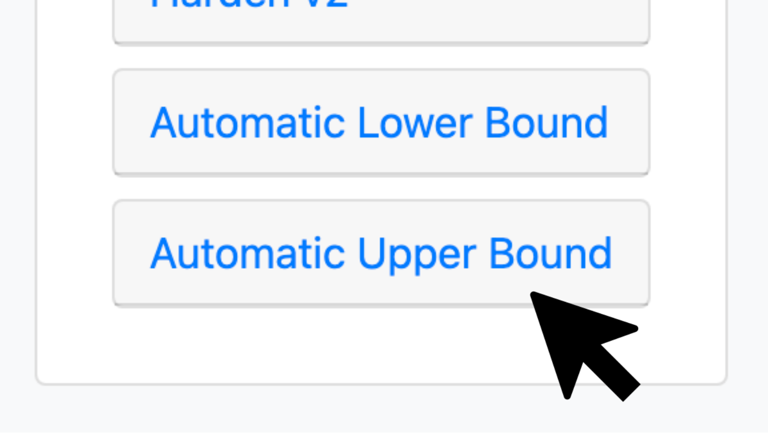
General techniques



- Example: ***round elimination*** technique
  - github.com/olidennis/round-eliminator
  - applicable to any locally checkable problem

[Brandt, PODC 2019]
[Olivetti, PODC 2020]

General techniques



- Example: ***round elimination*** technique
  - github.com/olidennis/round-eliminator
  - applicable to any locally checkable problem
- Does not always work — but when it works, you get algorithms and/or lower bound proofs for free!

[Brandt, PODC 2019]
[Olivetti, PODC 2020]

Success stories

- Lower bound for maximal matching and maximal independent set
- ***Six people and one computer program***
  - enabled rapid hypothesis testing and exploration of possible proof strategies

[Brandt et al., FOCS 2019]

Conclusions

Take-home messages

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  - ***yes*** — some questions on theory of distributed computing can be solved automatically!
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- ***Opportunities for human–computer collaboration!***
  - theory researchers who can write programs are going to have a competitive edge!