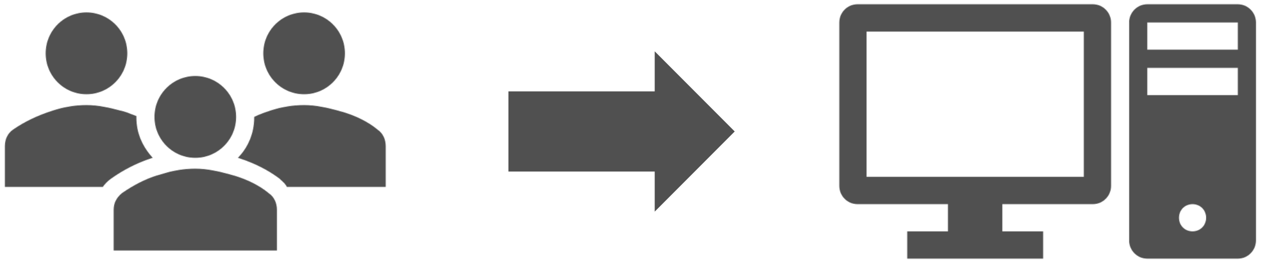
Jukka Suomela
Aalto University

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 OPODIS, PODC, DISC…

Abstract

While the relationship of time and space is an estab
plexity theory, this is not the case in distributed com
the time and space complexity of algorithms in a weal
puting. While a constant number of communication
visited during the execution, the other direction is n
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of only cycle and path graphs. Our work provides us
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and space complexity.

1998 ACM Subject Classification F.1.1 Models of
and Classes

Keywords and phrases distributed computing, spa
weak models, Thue–Morse sequence

Digital Object Identifier 10.4230/LIPIcs.OPODIS.2

1 Introduction

In the classical centralised theory of computing, th
helped us with understanding computability and c

1. Constant-space models (finite-state machines) p
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2. Space-limited complexity classes (e.g., PSPAC
limited complexity classes (e.g., NP ⊆ PSPACE

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How much of the work is done with computers?

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How much of it could be done with computers?

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Standard process

- **Question:** is there an efficient distributed algorithm for solving task X in model M?

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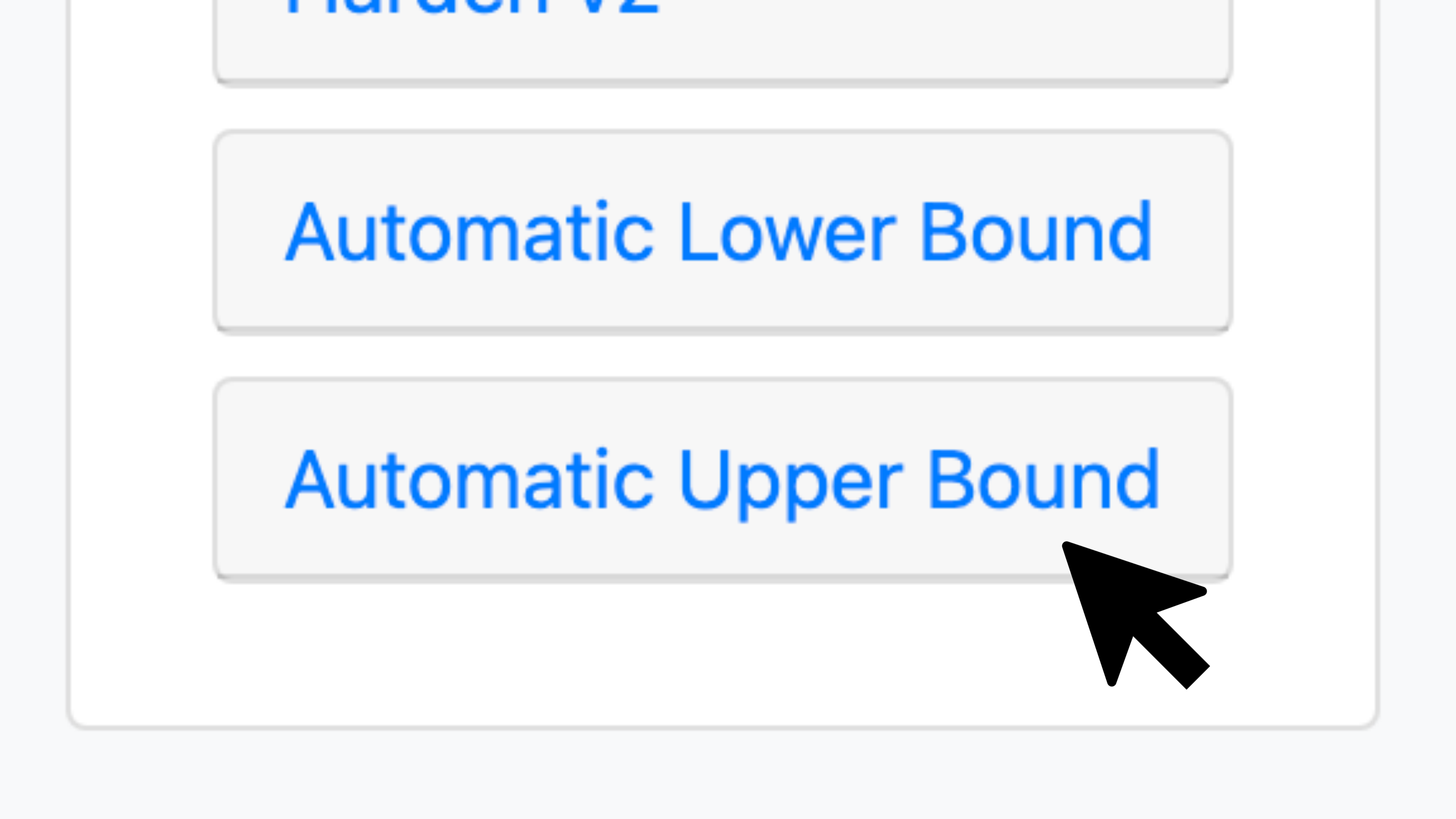
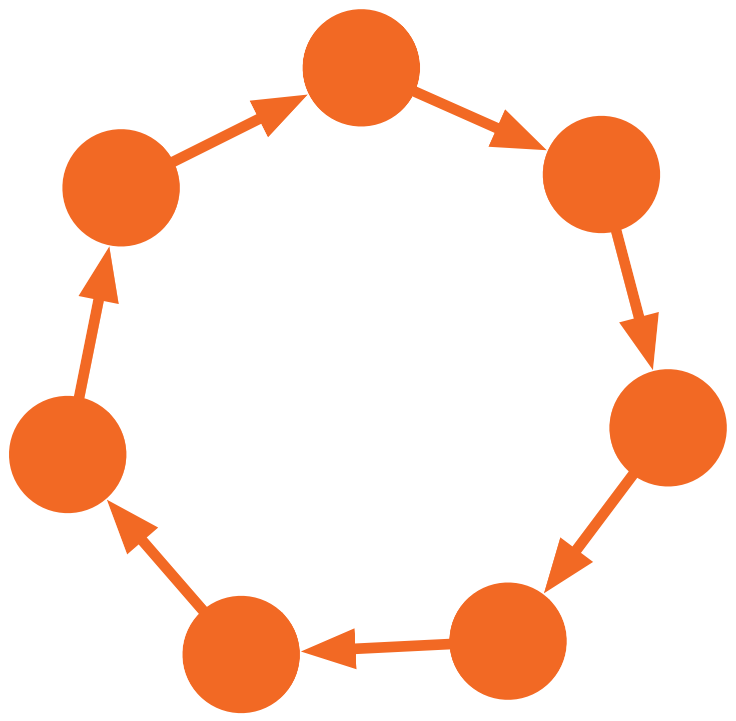

Automatic Lower Bound
Automatic Upper Bound

Lost sanity?

Toy example:
Locally checkable problems in cycles

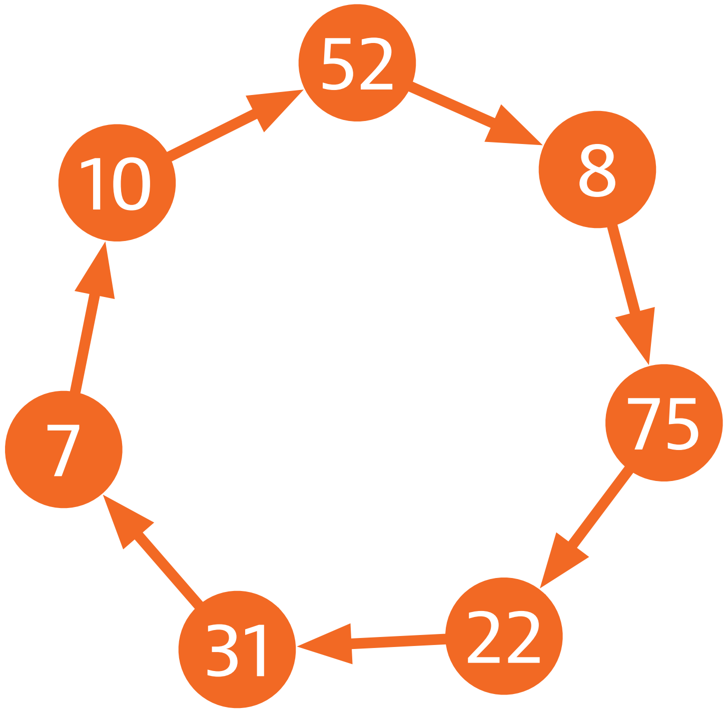
Setting

- ***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

Setting

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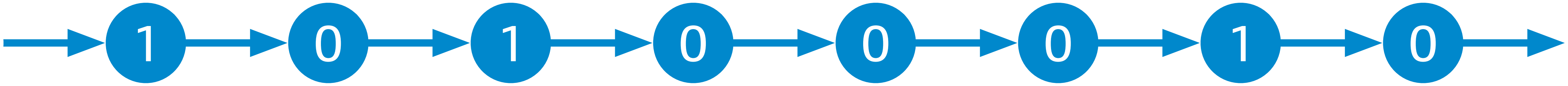
Example: maximal independent set



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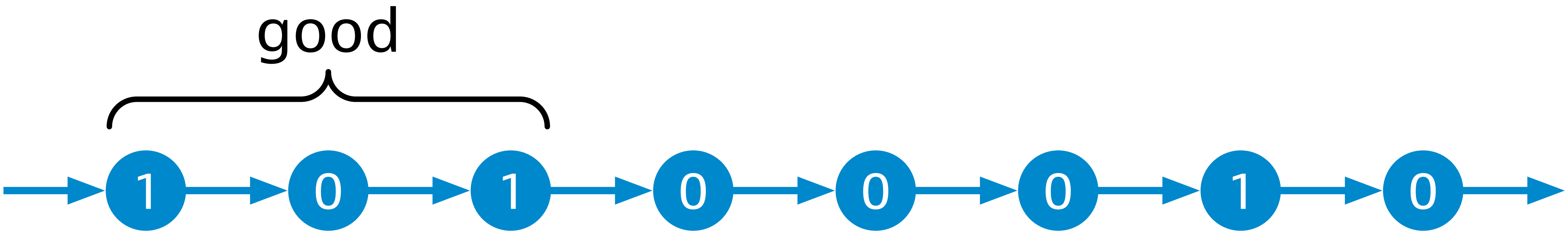

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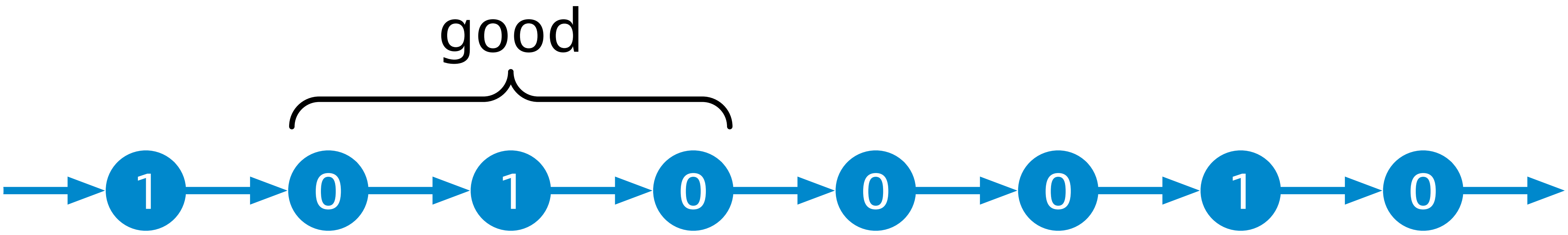

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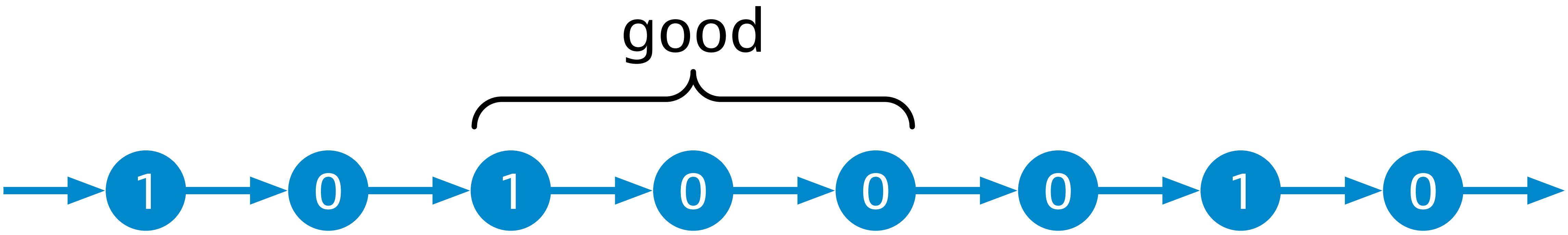

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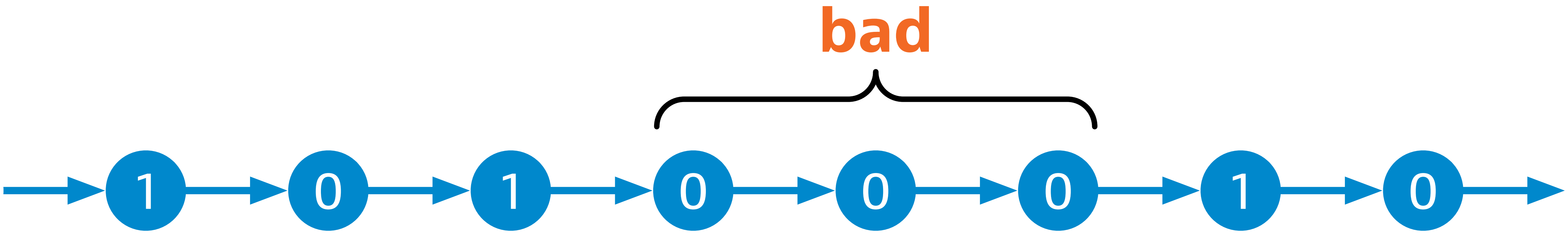

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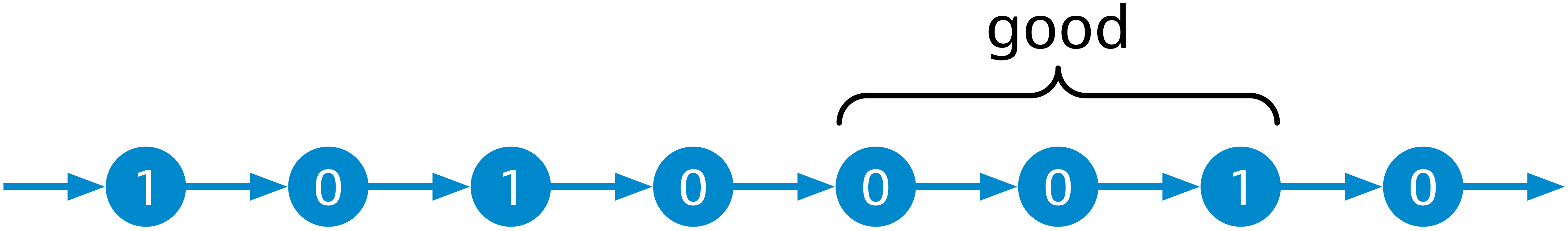

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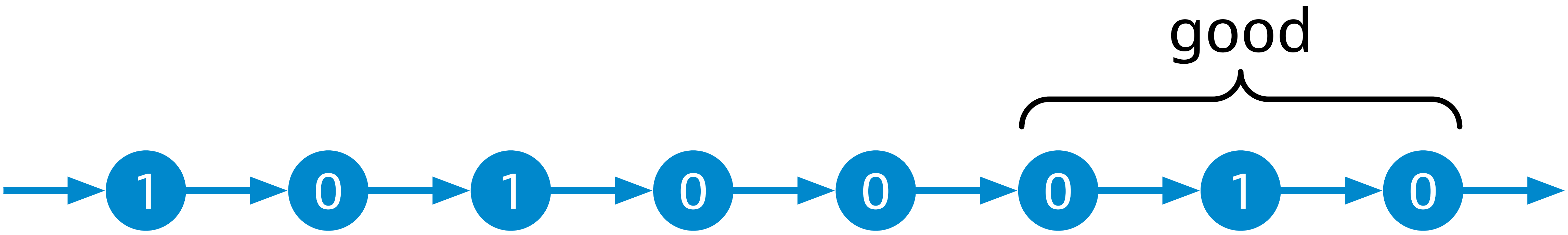

Valid label sequences

- *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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All possible output labelings in a window of size *k*

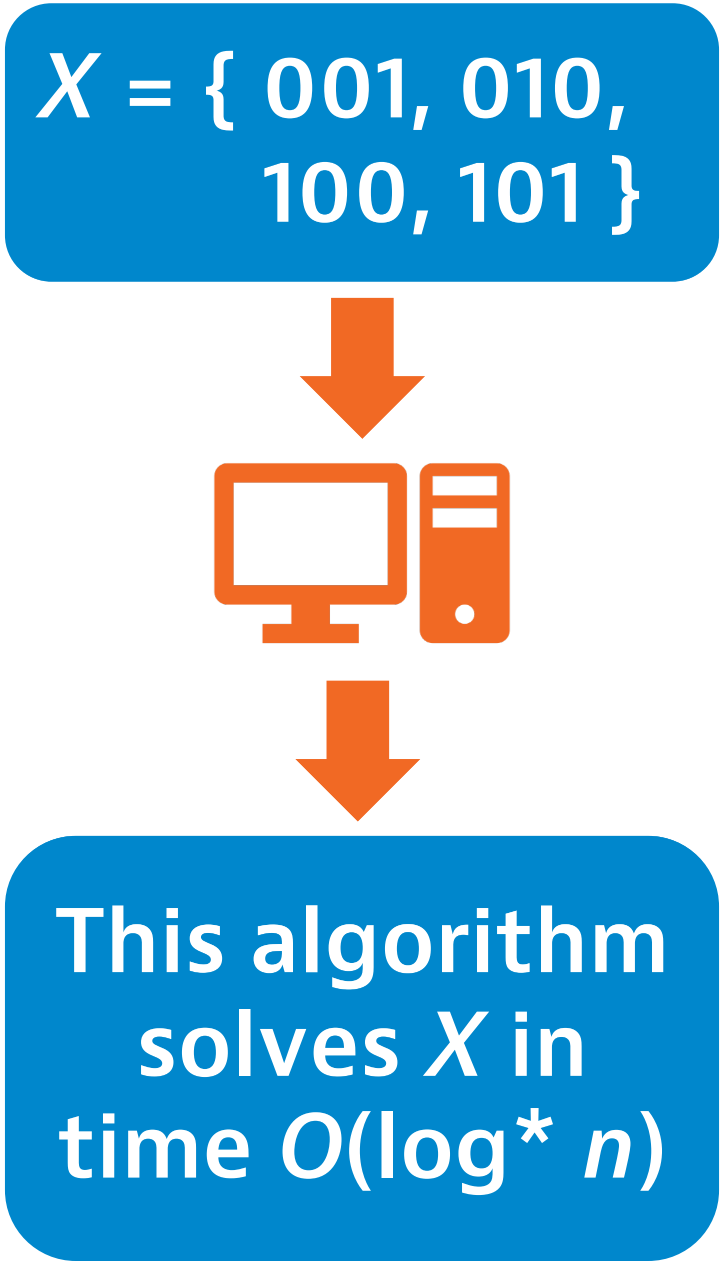
Fully automatic

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



Fully automatic

- Write down the specification of ***any locally checkable problem X***
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  - asymptotically optimal distributed algorithm for X

Polynomial time (in the size of problem description)

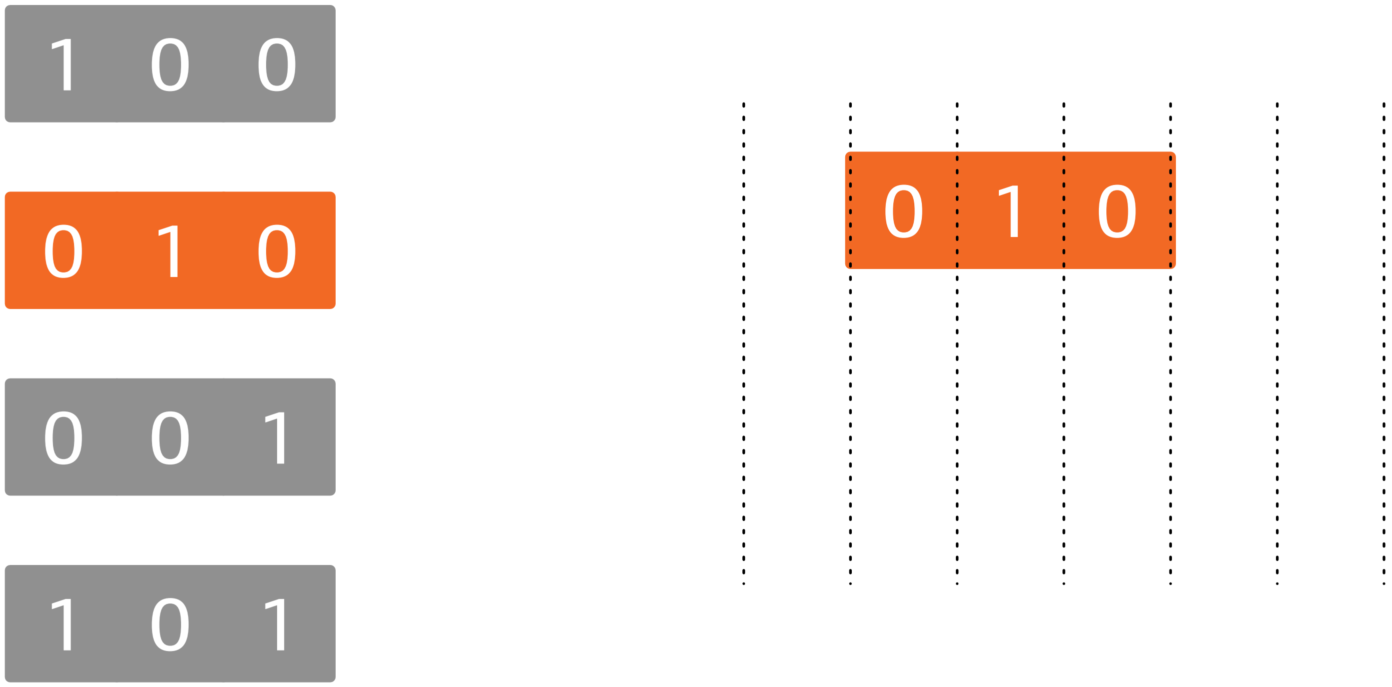
1 0 0

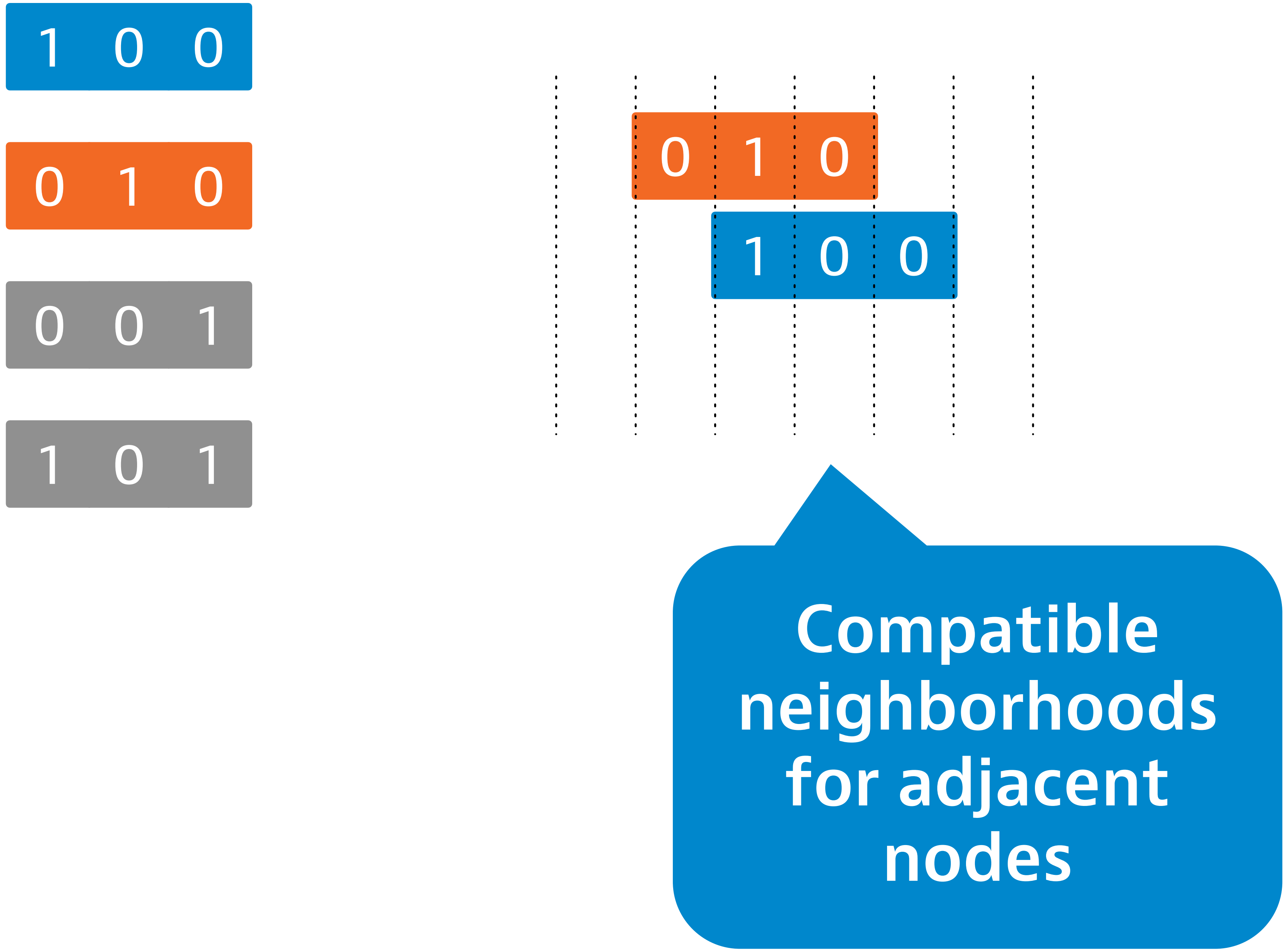
0 1 0

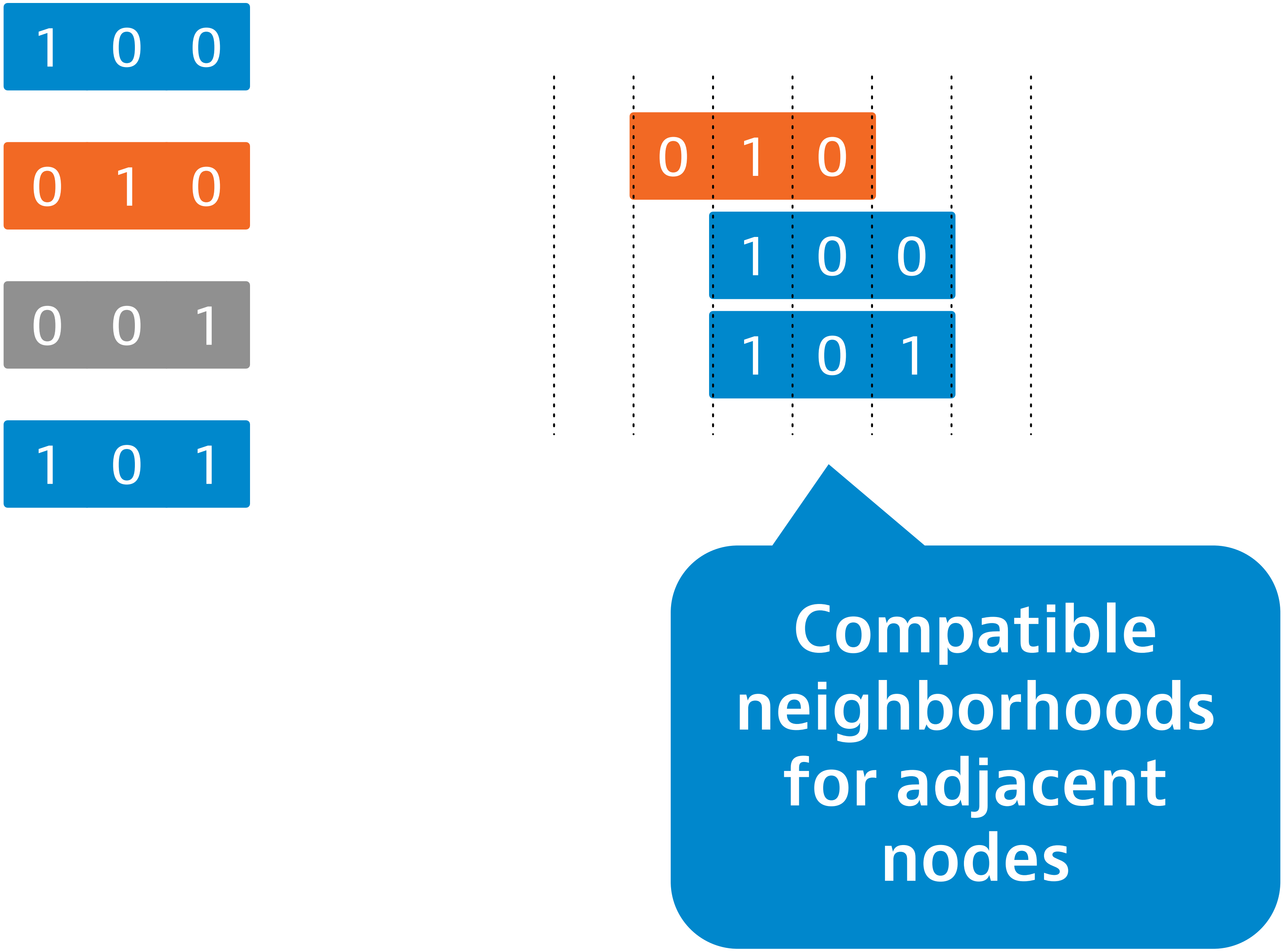
0 0 1

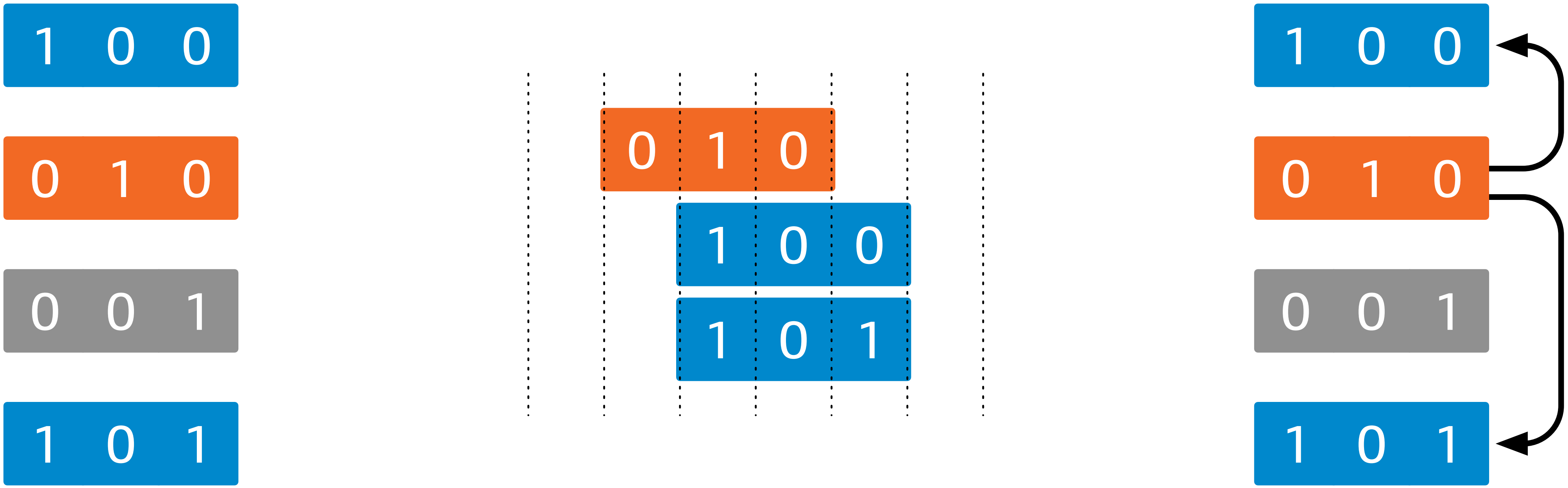
1 0 1

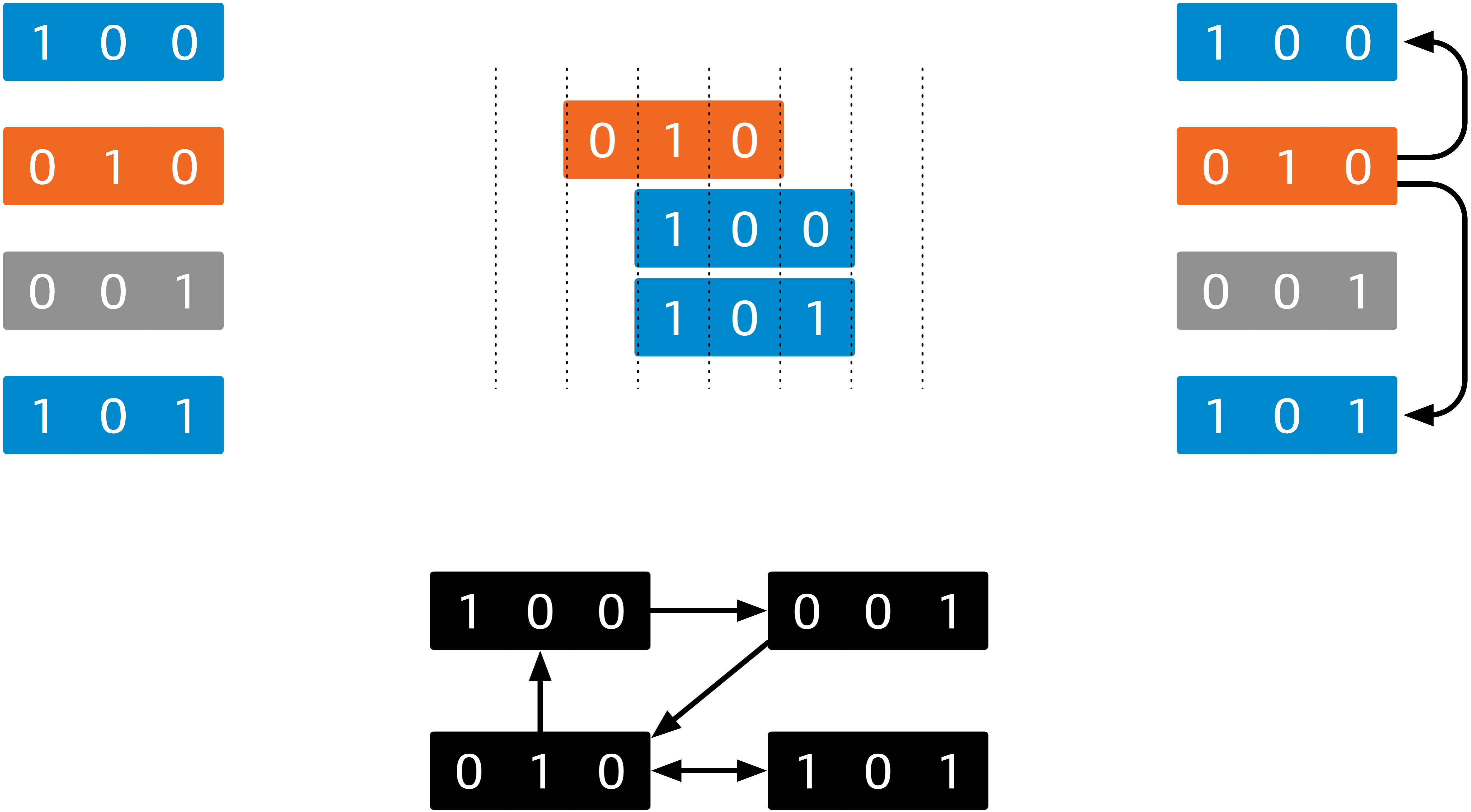
Example:
X = maximal independent set problem

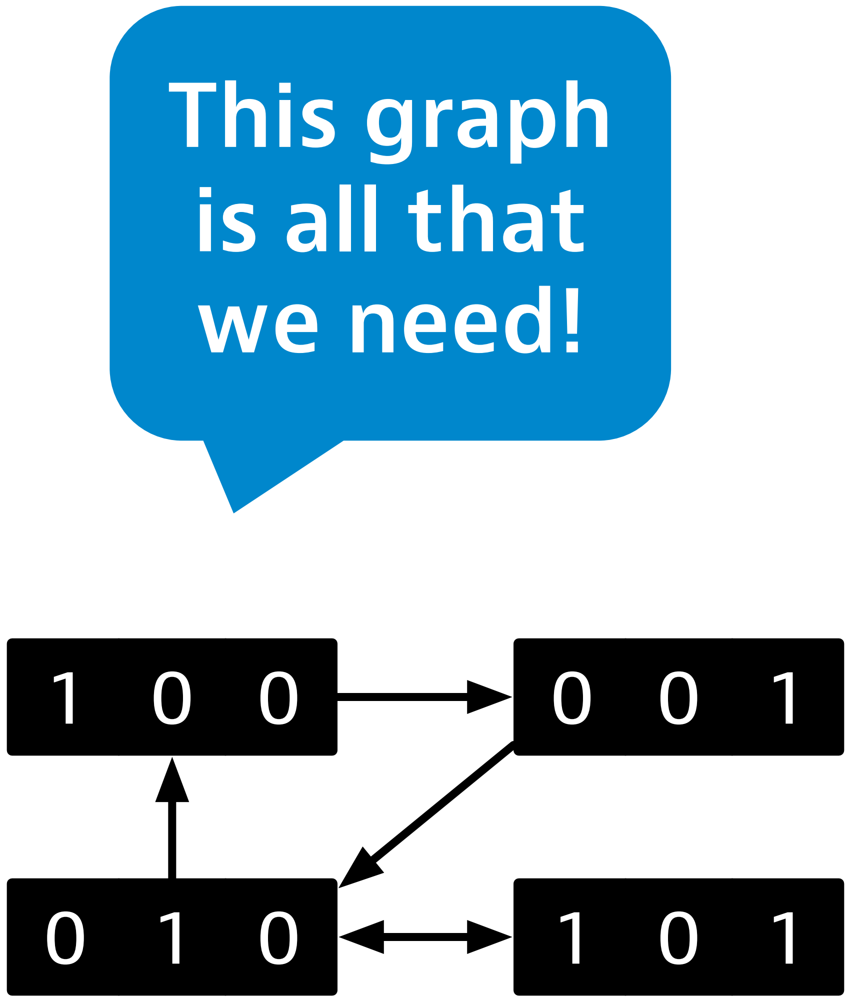

1 0 0
0 1 0
0 0 1
1 0 1
0 1 0

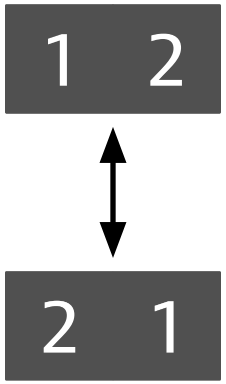

1 0 0
0 1 0
0 0 1
1 0 1
0 1 0
1 0 0
Compatible neighborhoods for adjacent nodes


1 0 0
0 1 0
0 0 1
1 0 1
0 1 0
1 0 0
1 0 1
Compatible neighborhoods for adjacent nodes

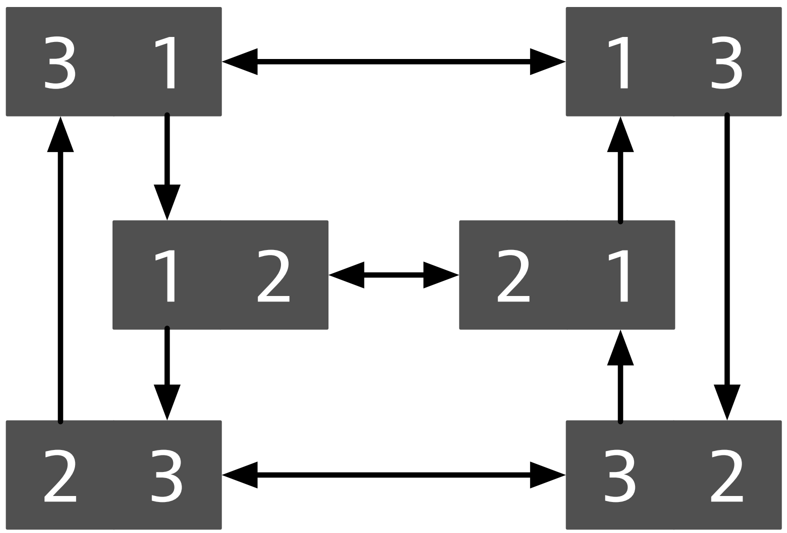

1 0 0
0 1 0
0 0 1
1 0 1
0 1 0
1 0 0
1 0 1
1 0 0
0 1 0
0 0 1
1 0 1


1 0 0
0 1 0
0 0 1
1 0 1
0 1 0
1 0 0
1 0 1
1 0 0
0 1 0
0 0 1
1 0 1
1 0 0
0 0 1
0 1 0
1 0 1

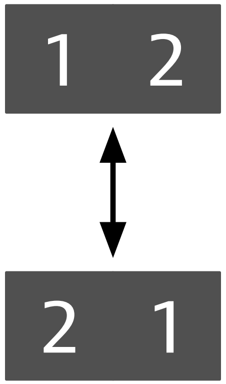

This graph is all that we need!
1 0 0
0 0 1
0 1 0
1 0 1



2-coloring



3-coloring



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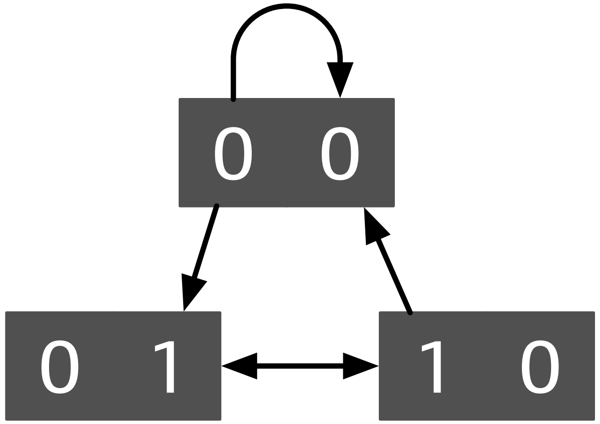
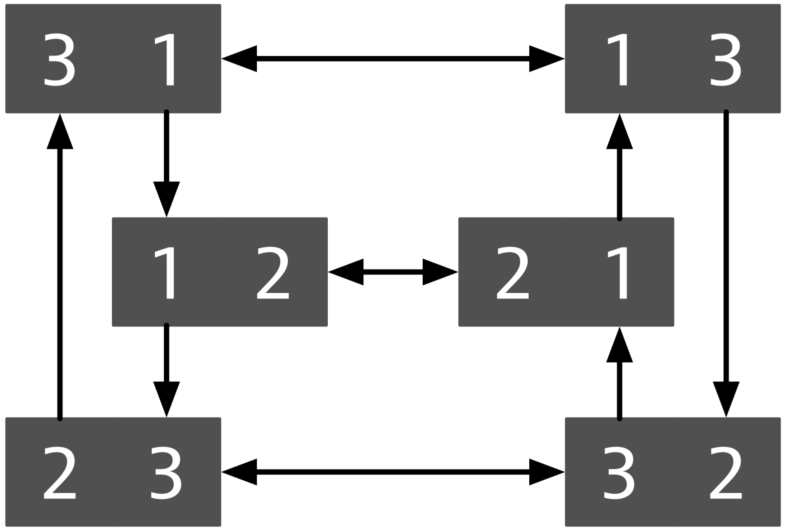


independent set



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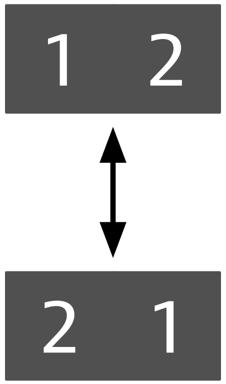

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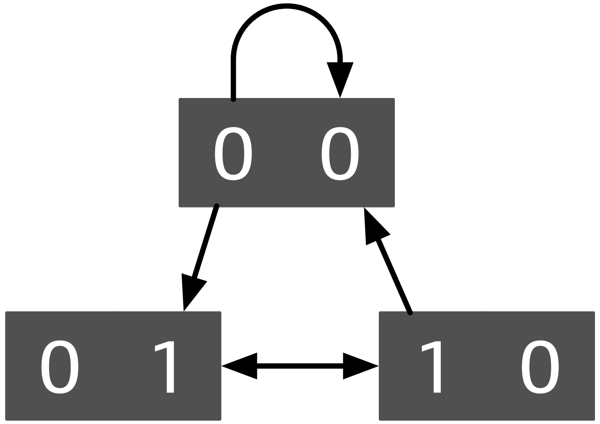

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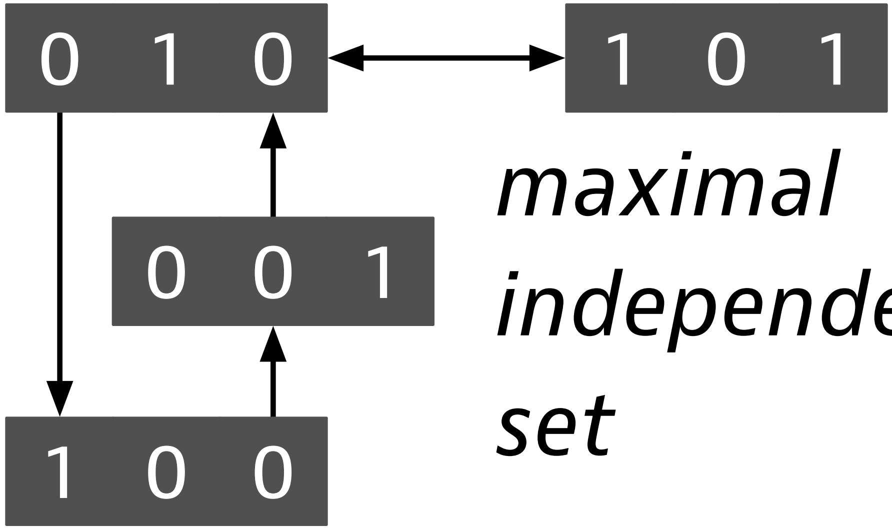
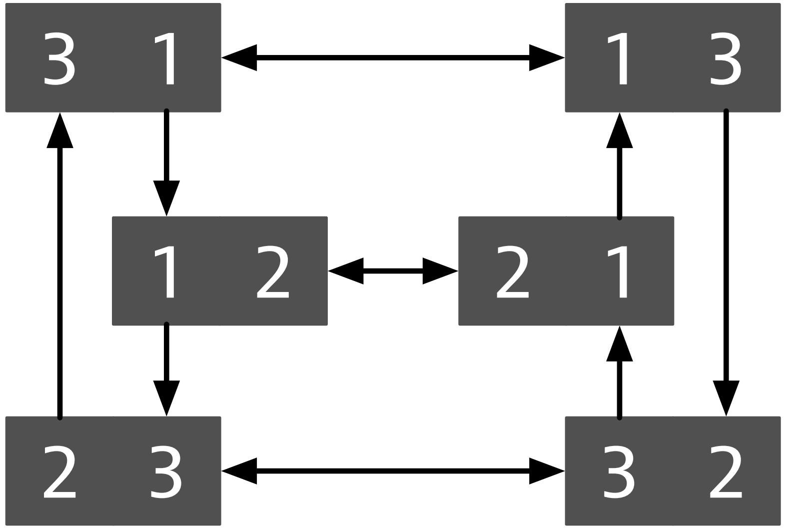


maximal independent set



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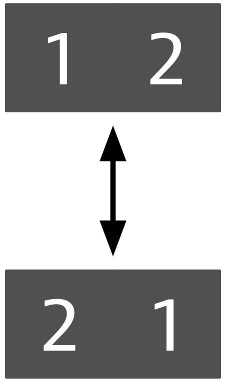
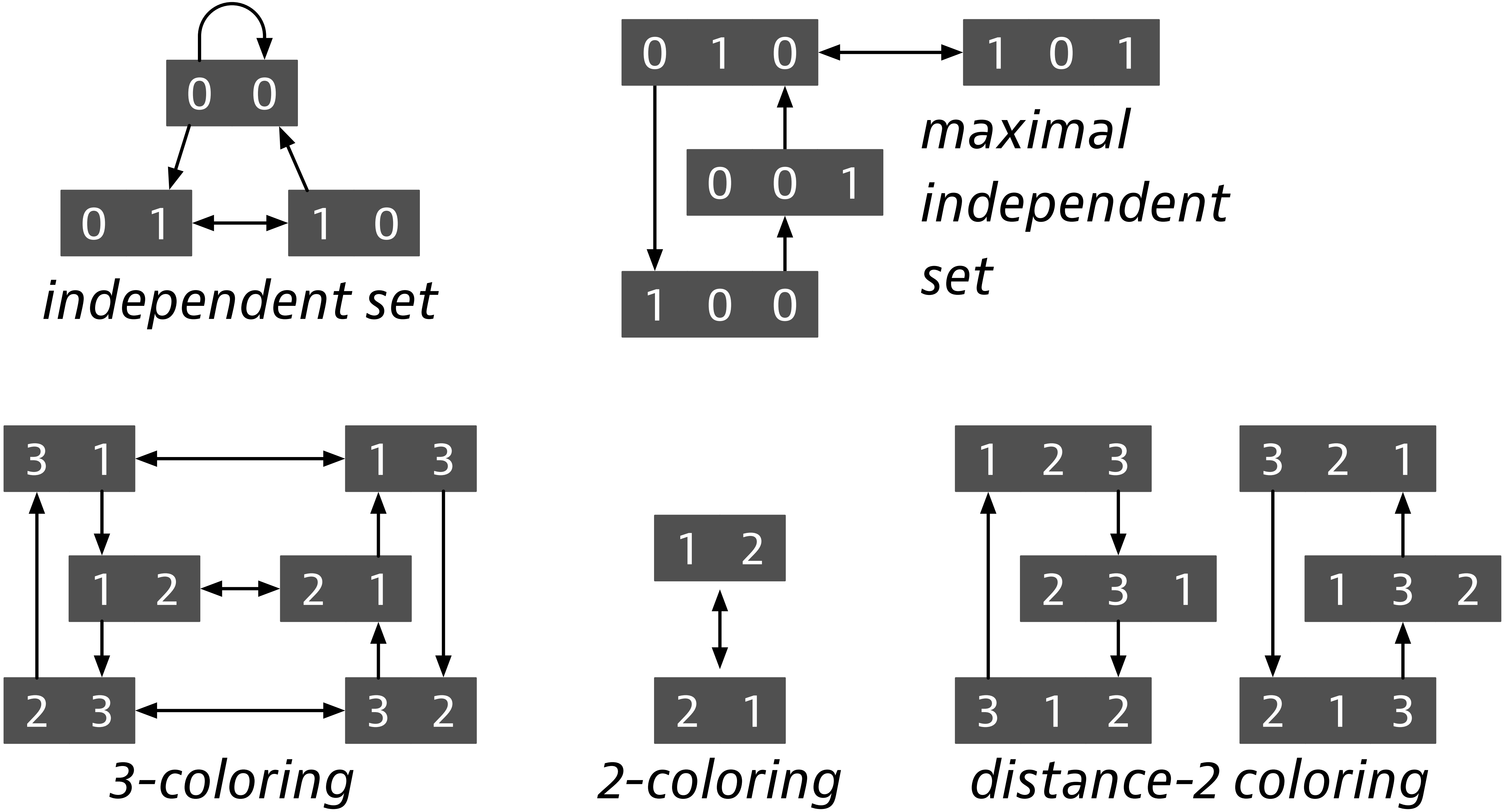
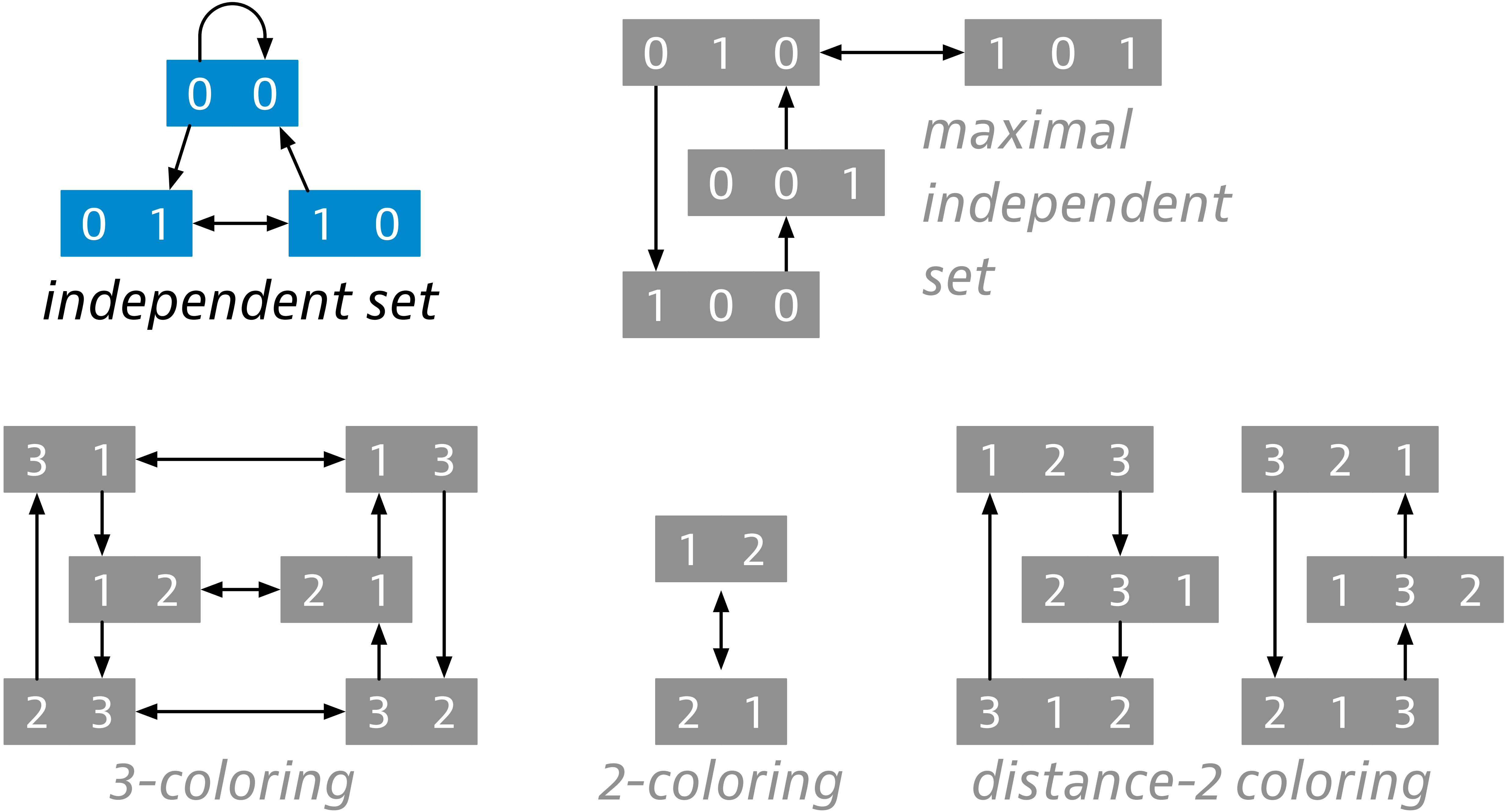


2-coloring



0 0
0 1
1 0
independent set
0 1 0
1 0 1
0 0 1
1 0 0
maximal independent set
3 1
1 3
1 2
2 1
2 3
3 2
3-coloring
1 2
2 1
2-coloring
1 2 3
3 2 1
2 3 1
1 3 2
3 1 2
2 1 3
distance-2 coloring



0 0
0 1
1 0
independent set
0 1 0
1 0 1
0 0 1
1 0 0
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3 1
1 3
1 2
2 1
2 3
3 2
3-coloring
1 2
2 1
2-coloring
1 2 3
3 2 1
2 3 1
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3 1 2
2 1 3
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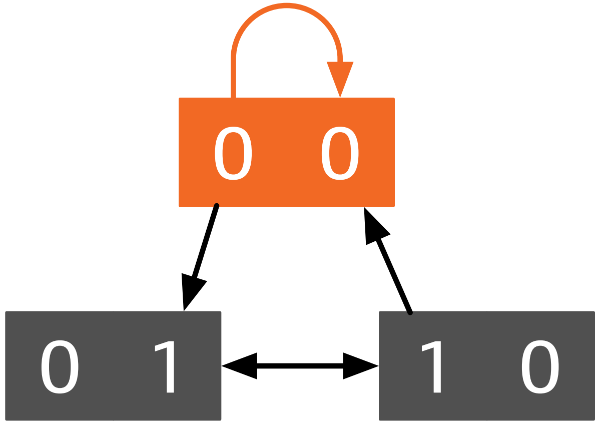
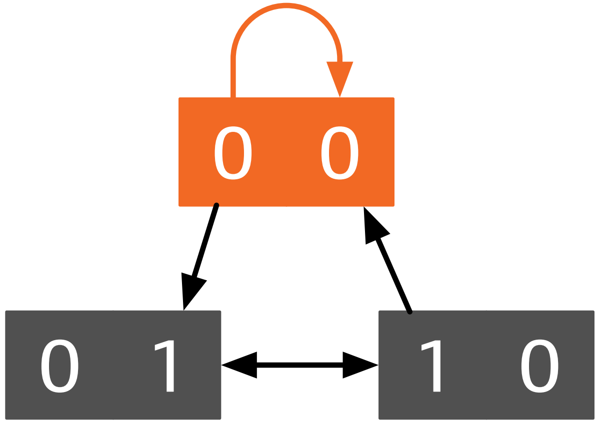


independent set

self-loop

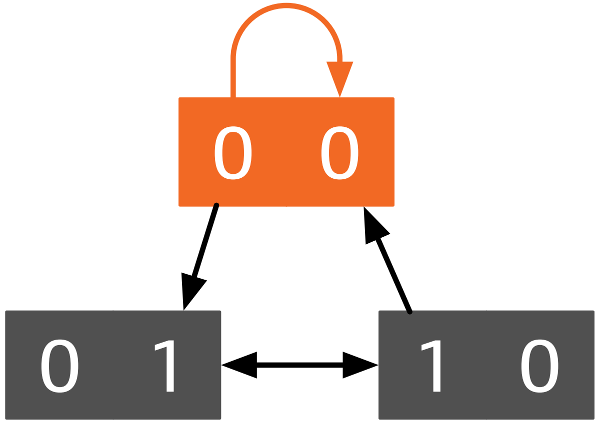


independent set

self-loop

solvable
in $O(1)$ rounds

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



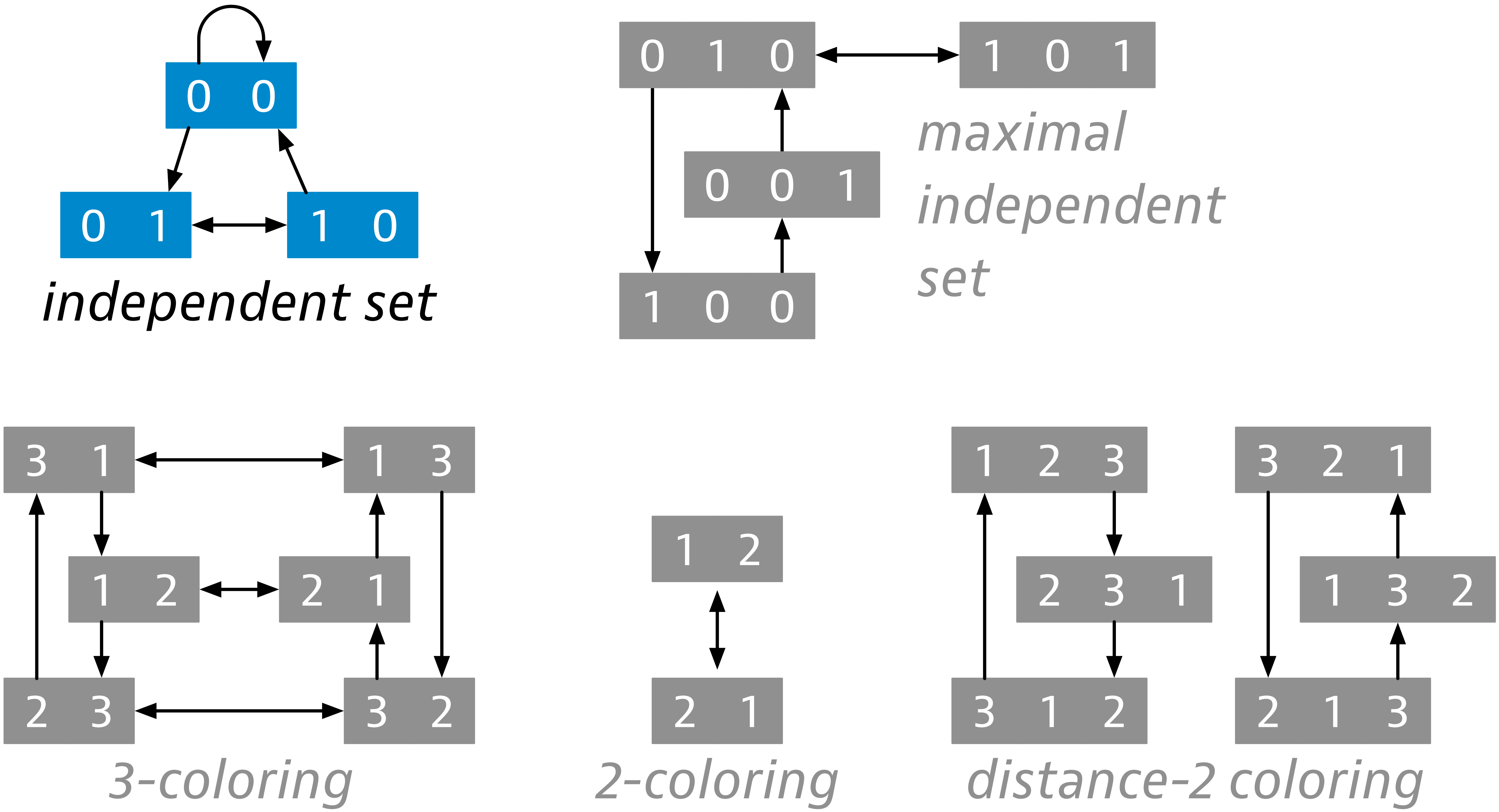
independent set

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



0 0
0 1
1 0
independent set
0 1 0
1 0 1
0 0 1
1 0 0
maximal independent set
3 1
1 3
1 2
2 1
2 3
3 2
3-coloring
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3 2 1
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3 1 2
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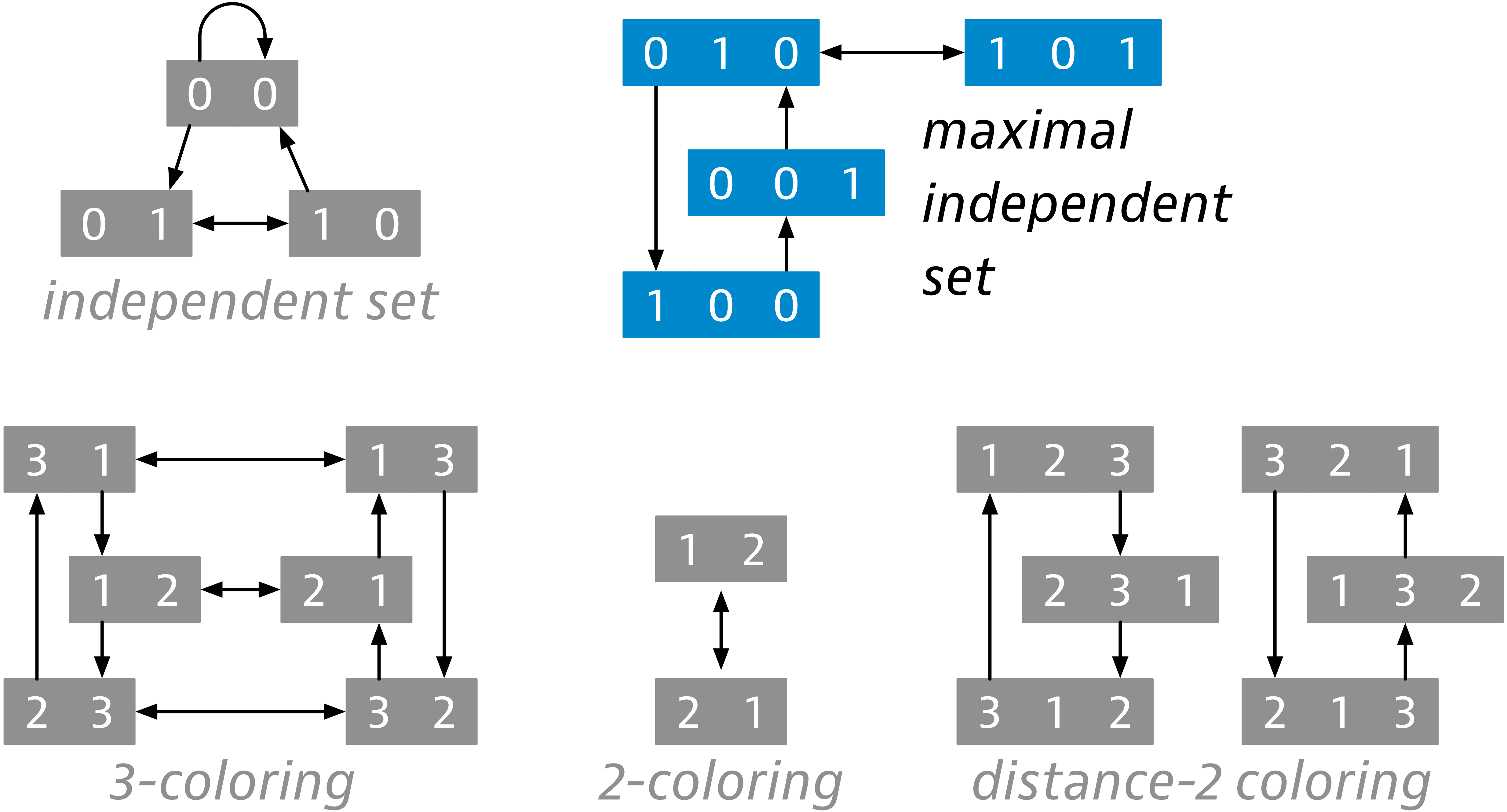
distance-2 coloring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1 2
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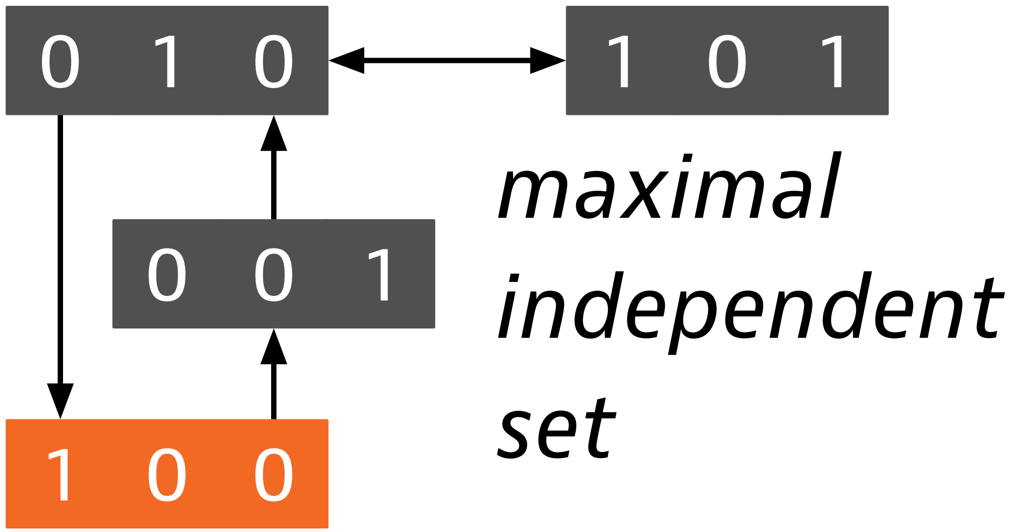
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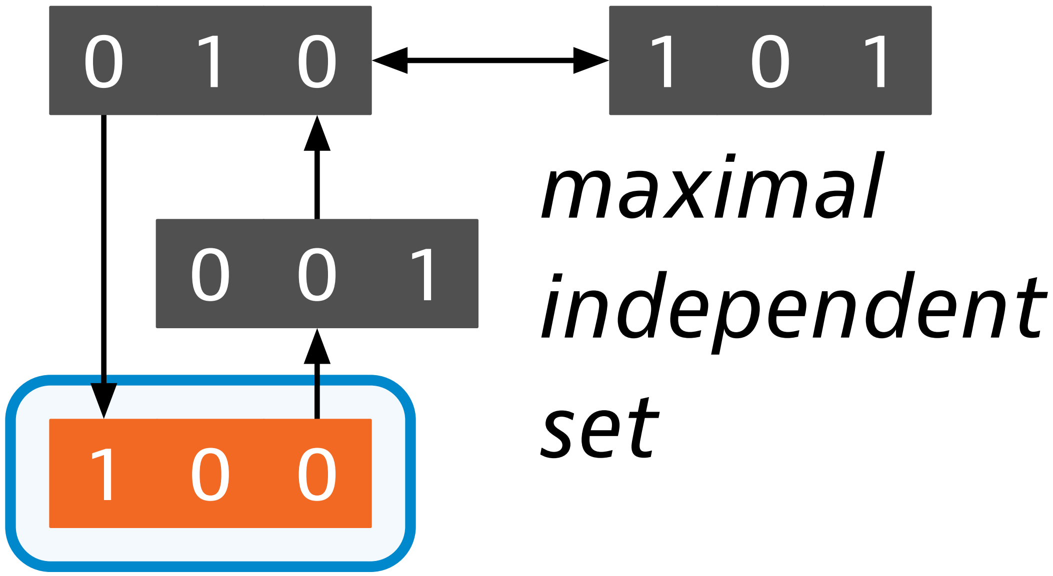

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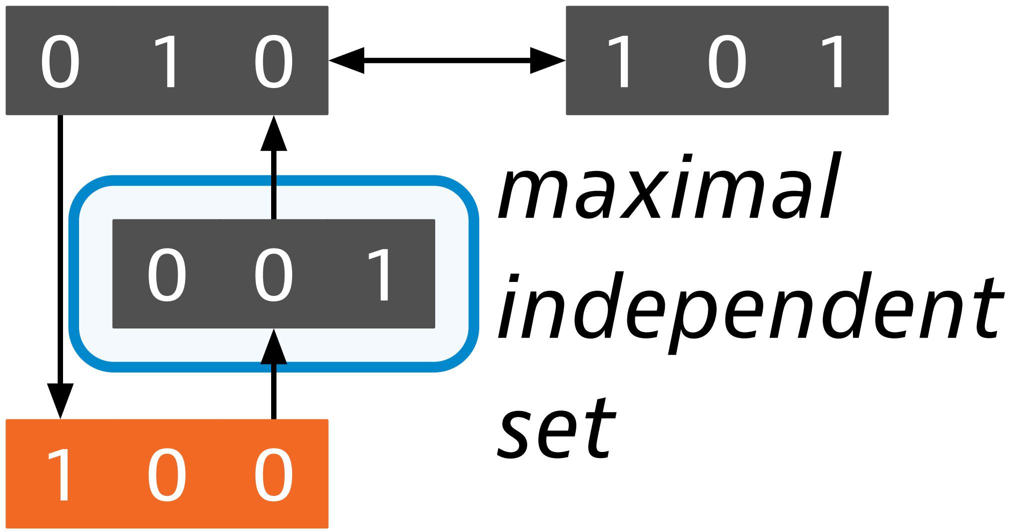

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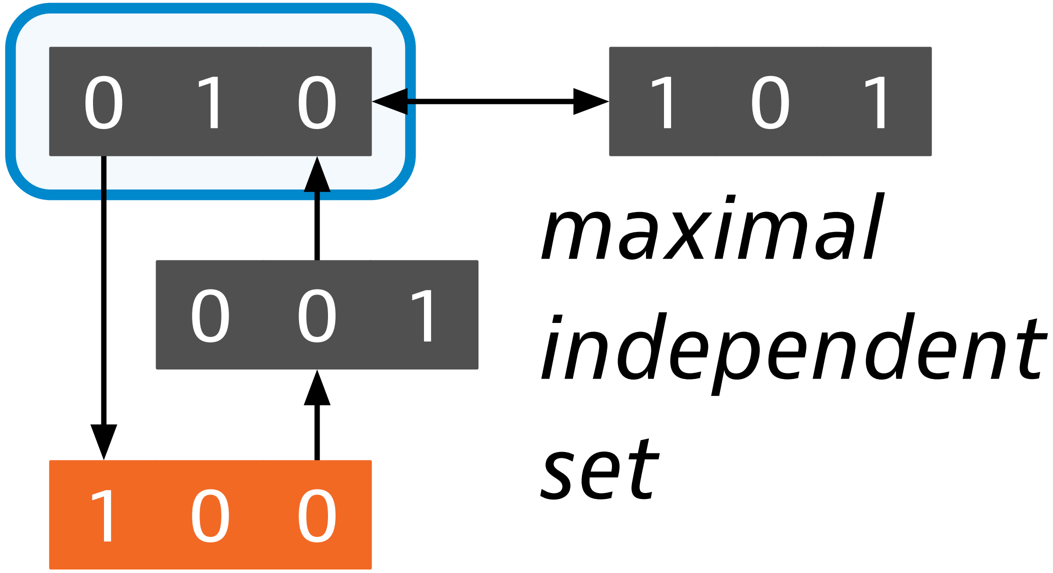

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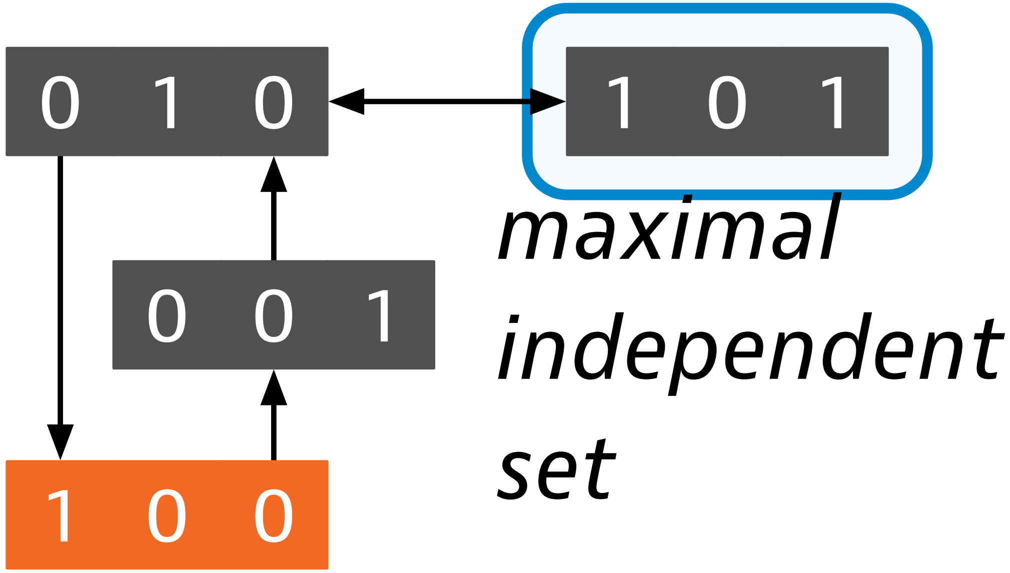

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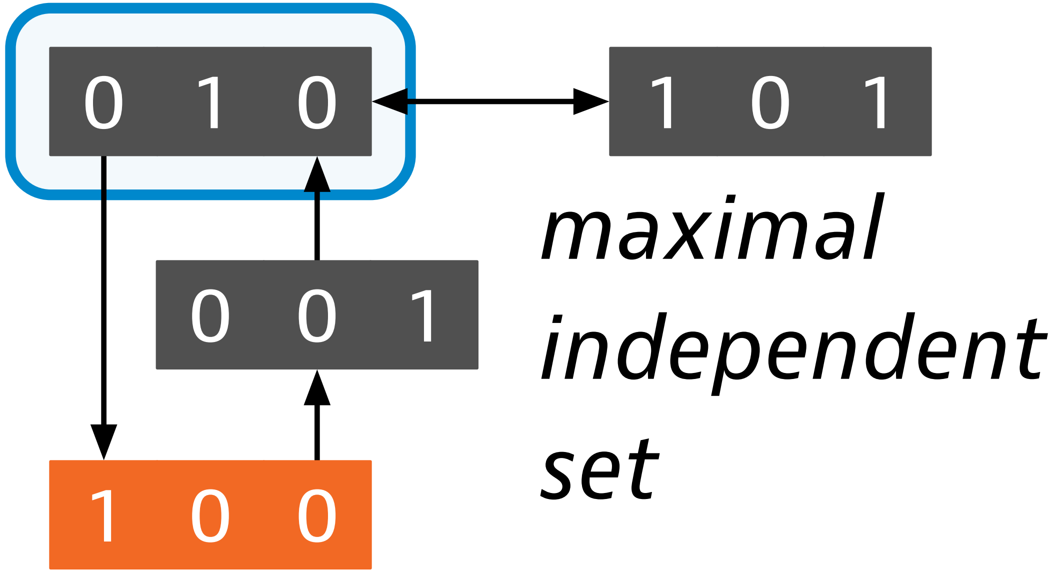
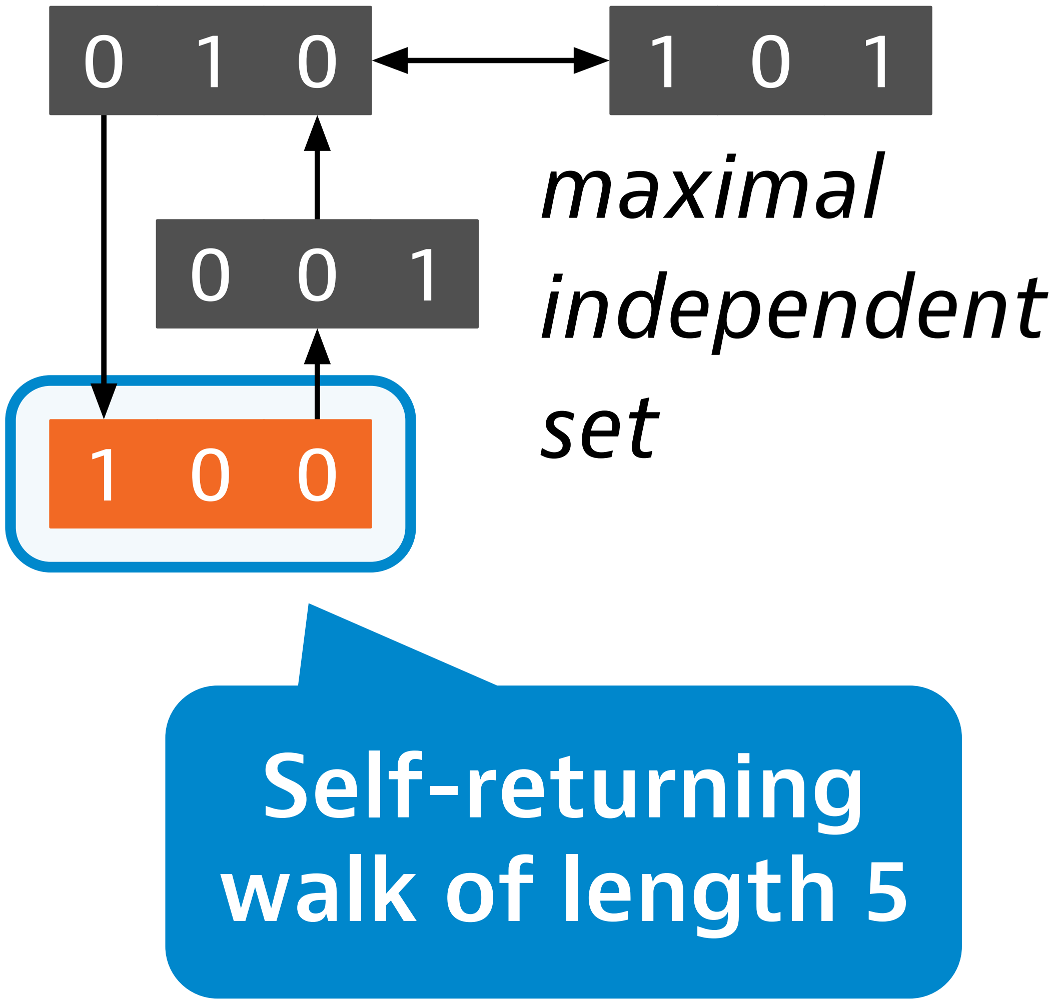
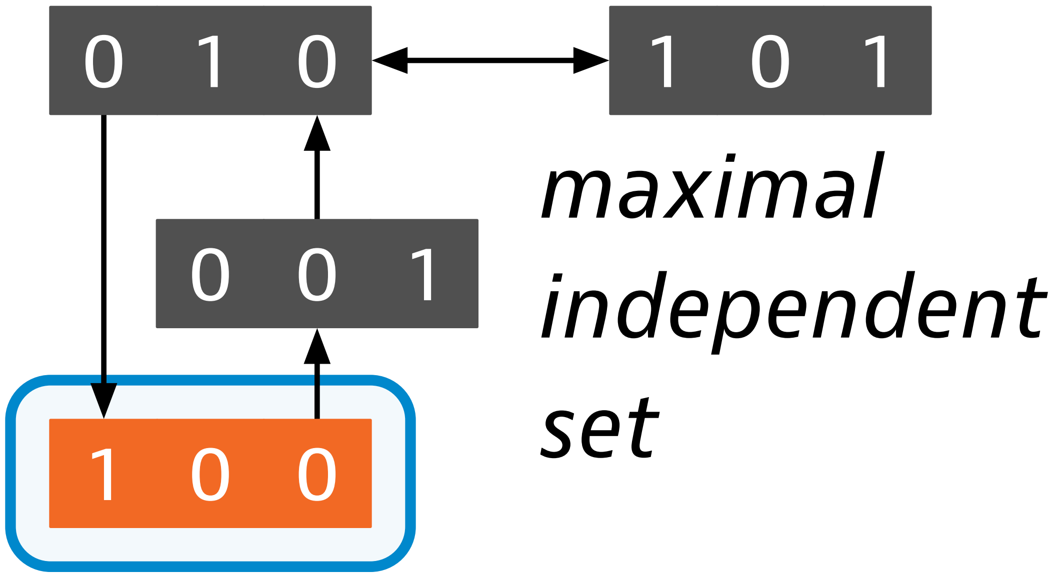


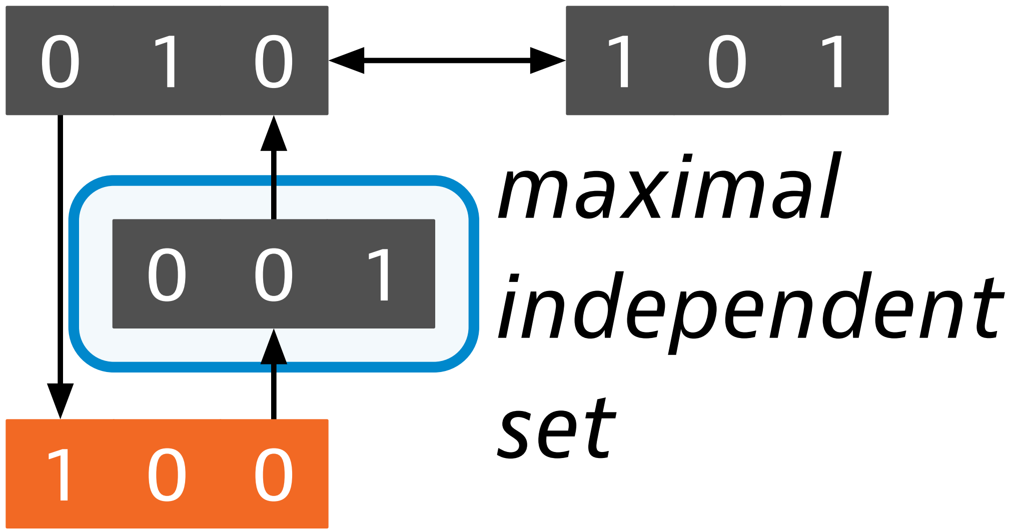
4

5


0 1 0
1 0 1
0 0 1
1 0 0
maximal independent set
Self-returning walk of length 5



0



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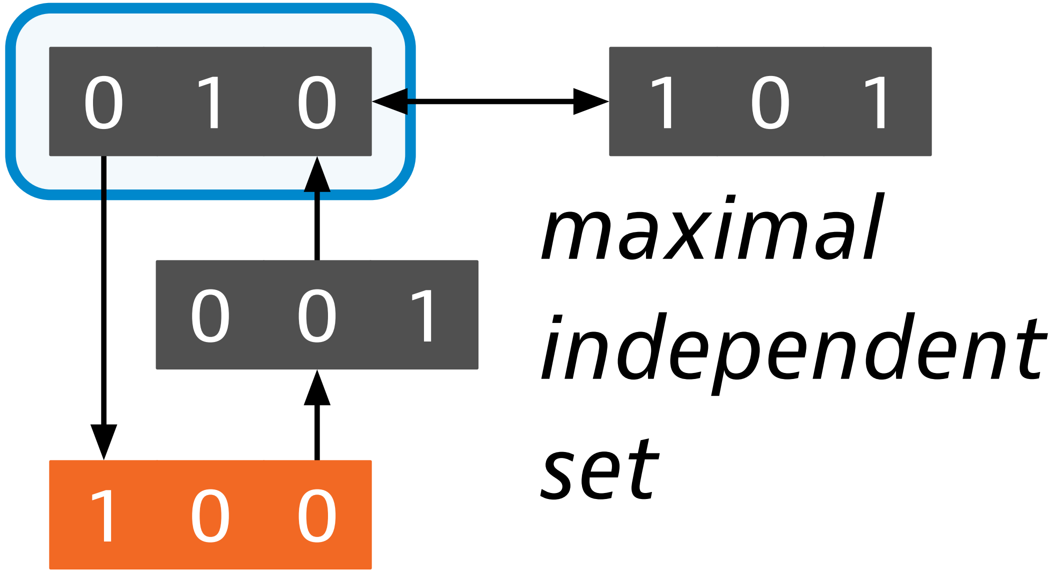

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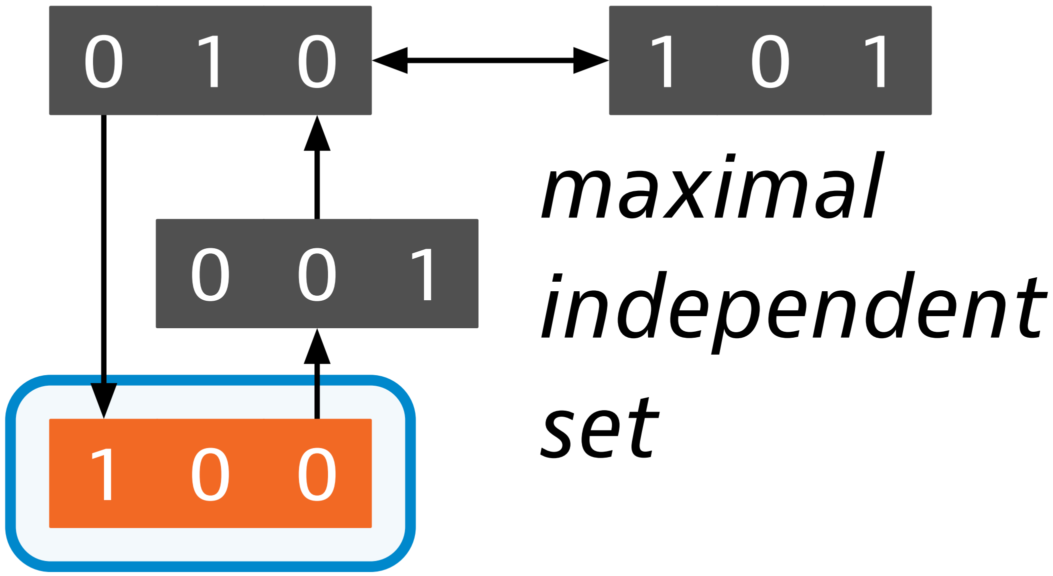
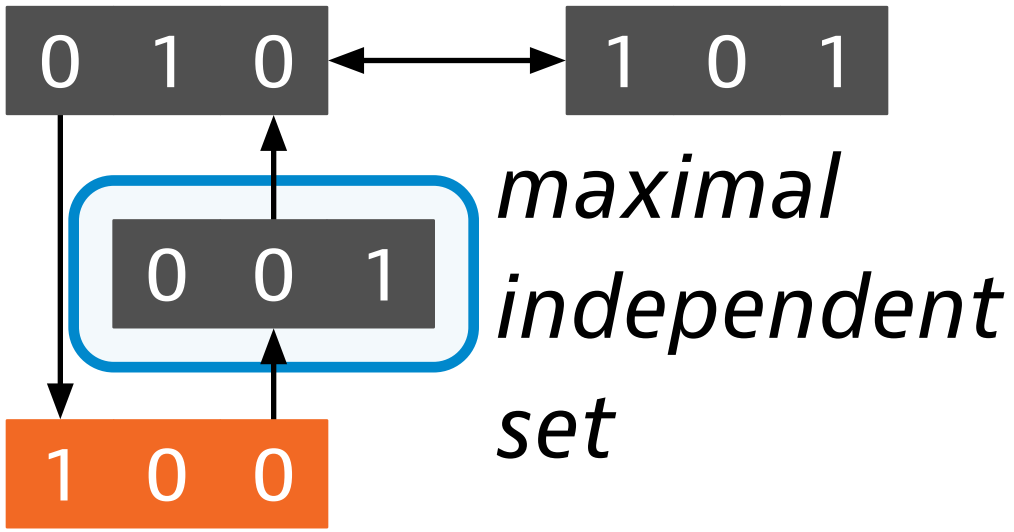


3



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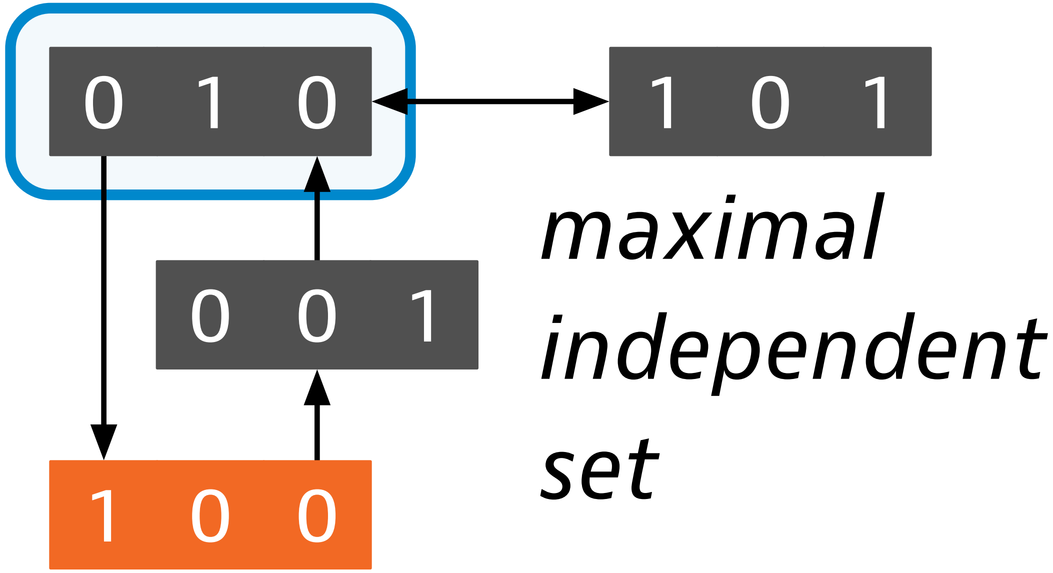
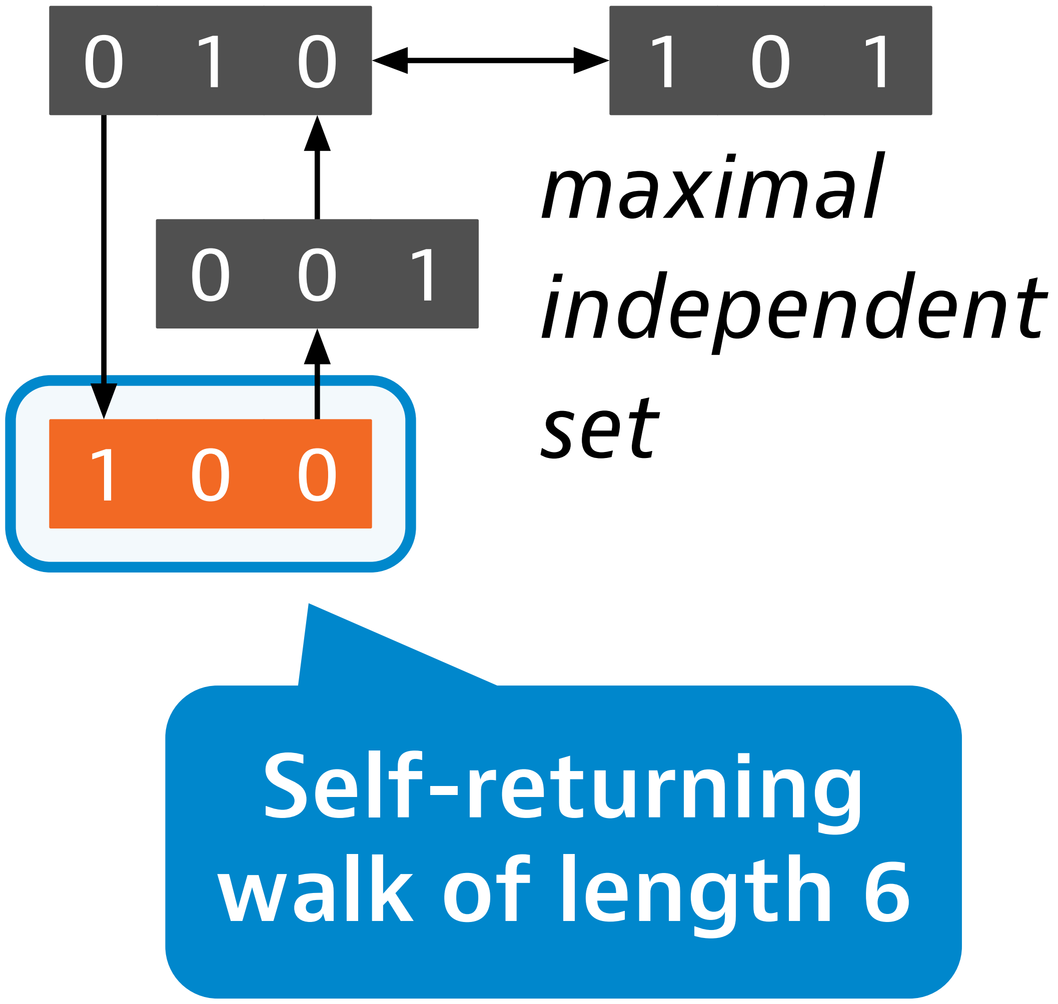
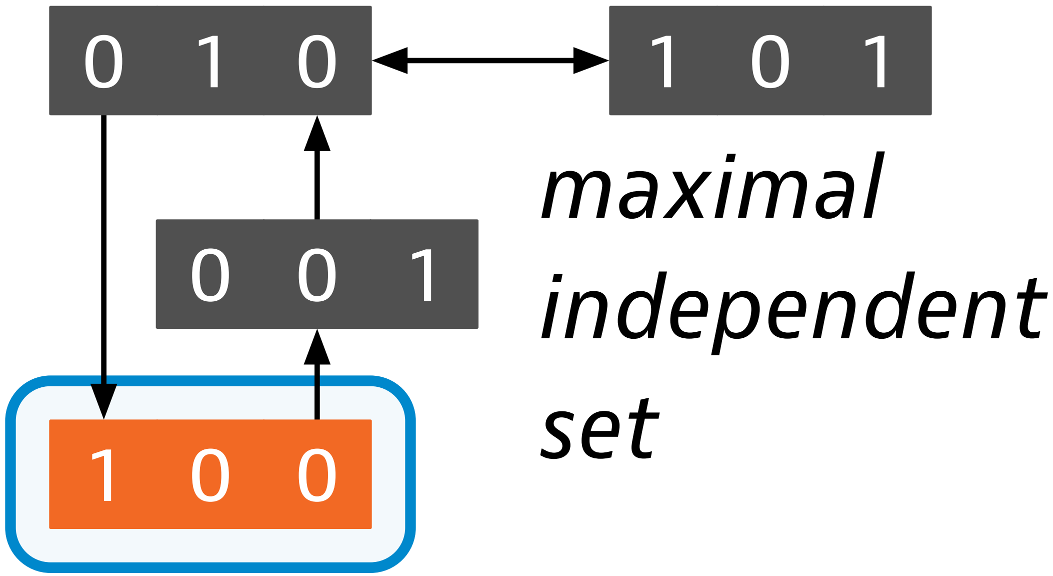


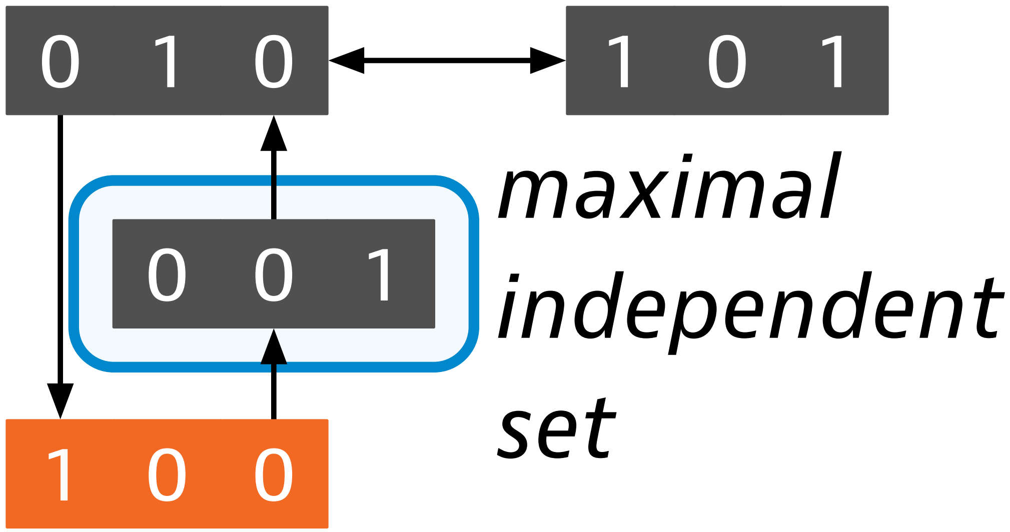
5


0 1 0
1 0 1
0 0 1
1 0 0
maximal independent set
Self-returning walk of length 6

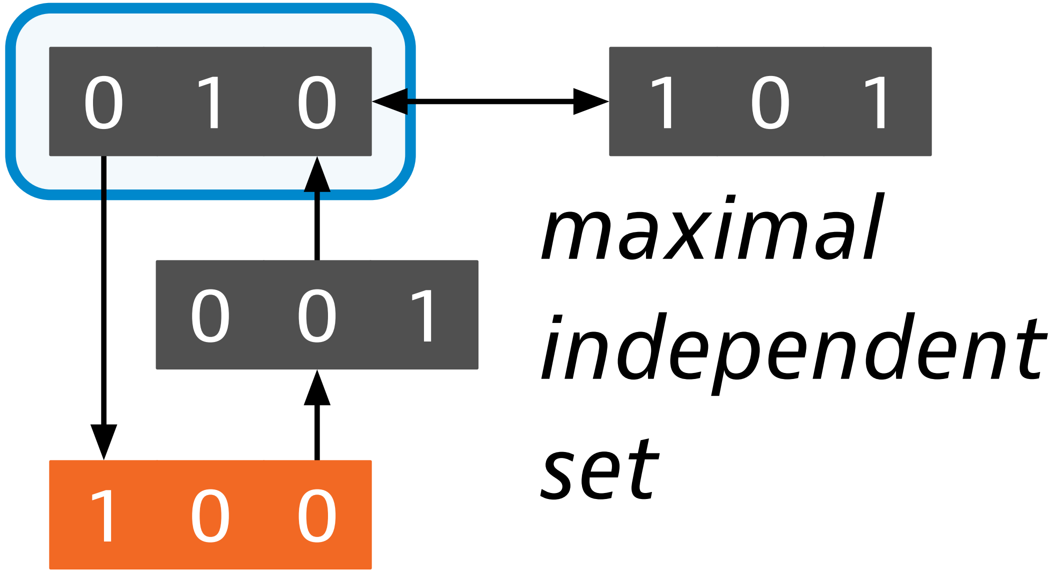
6



0



1



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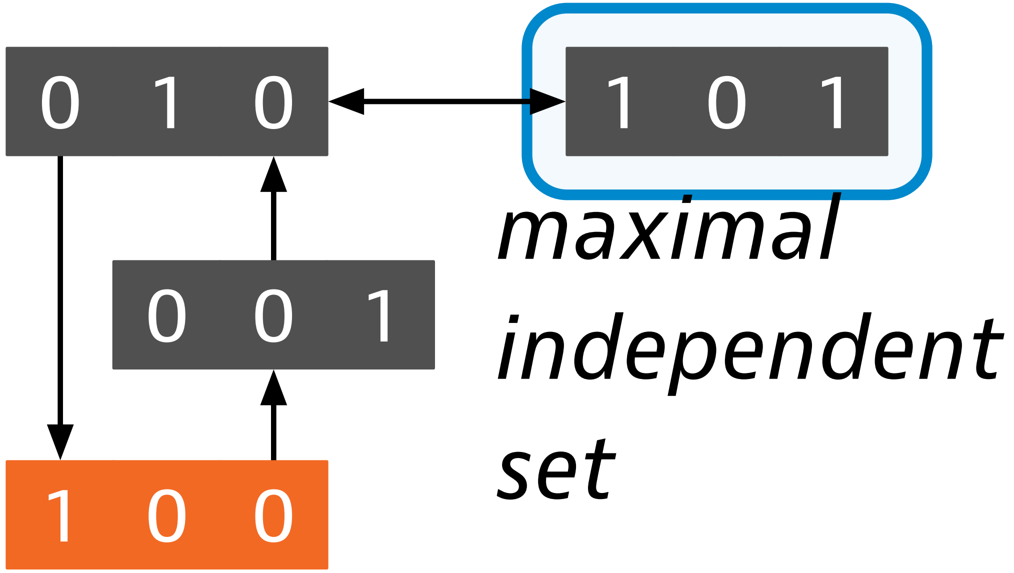

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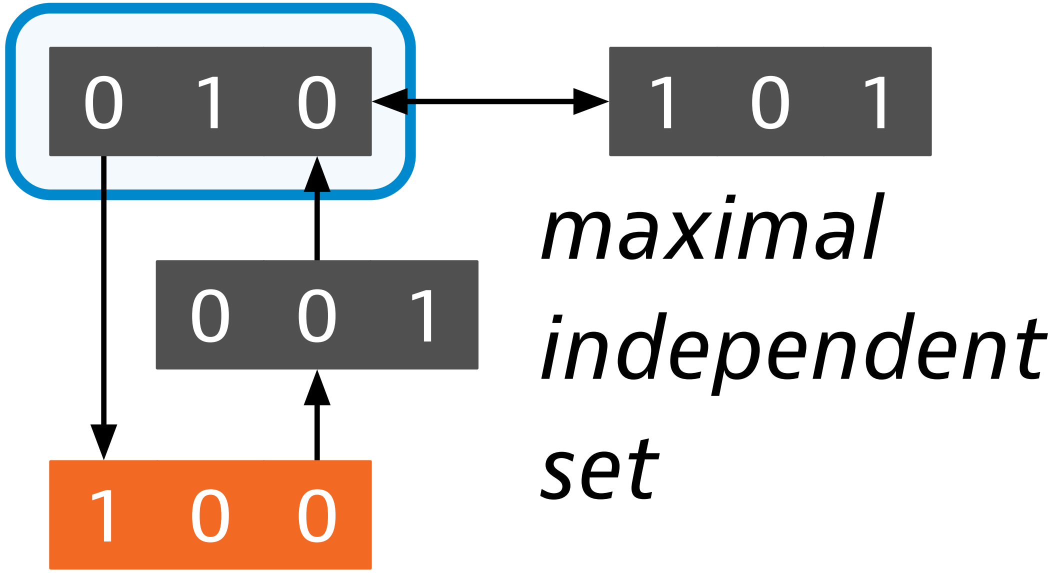

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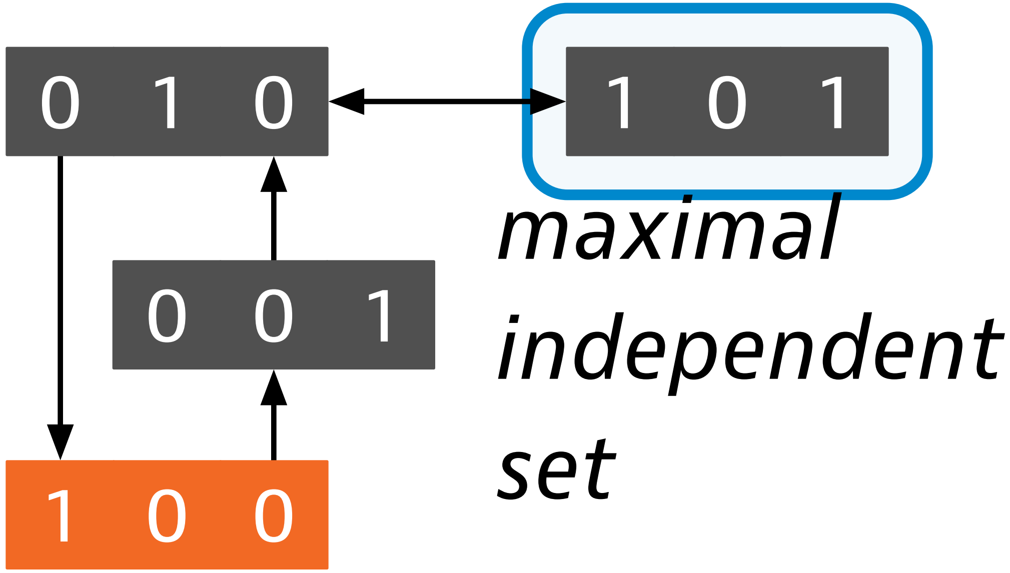

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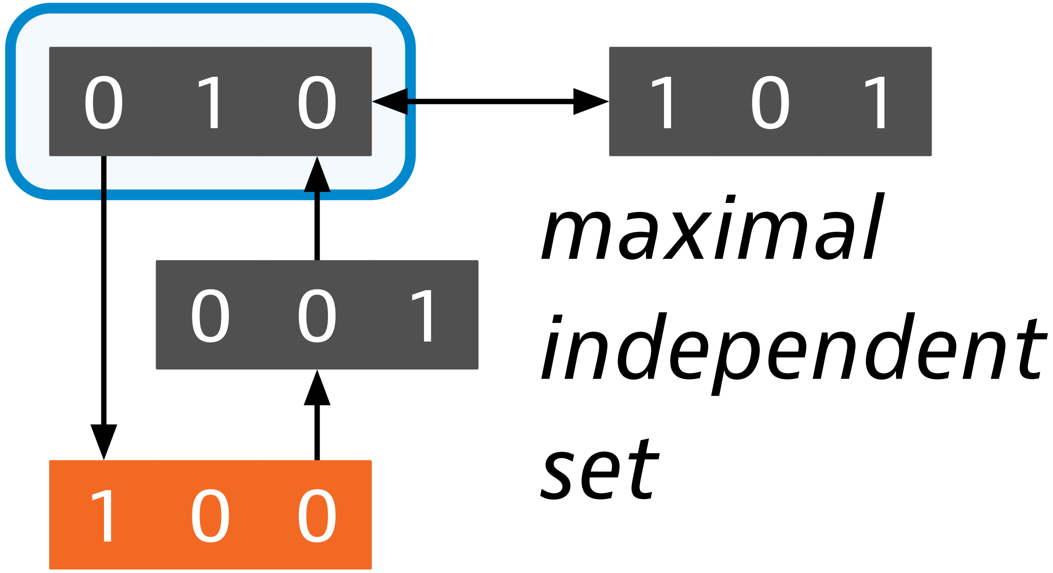

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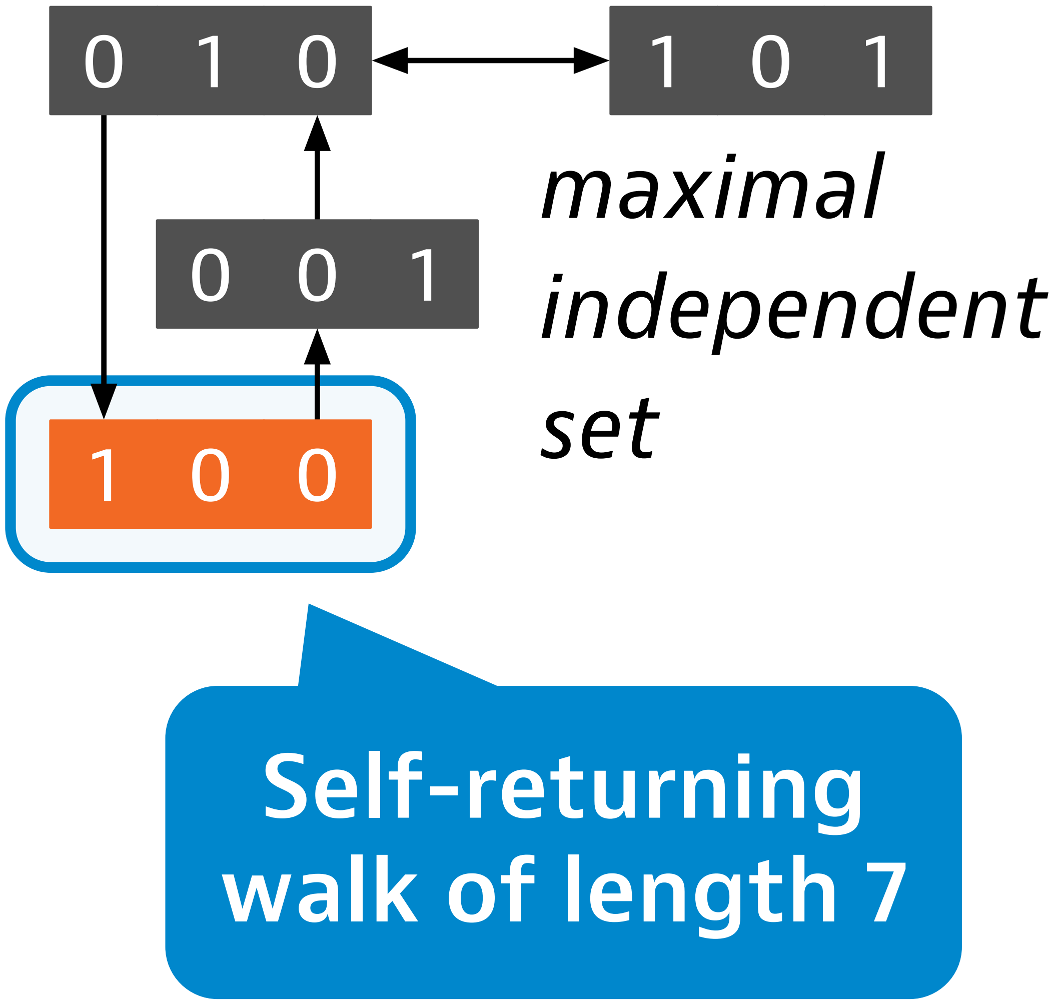
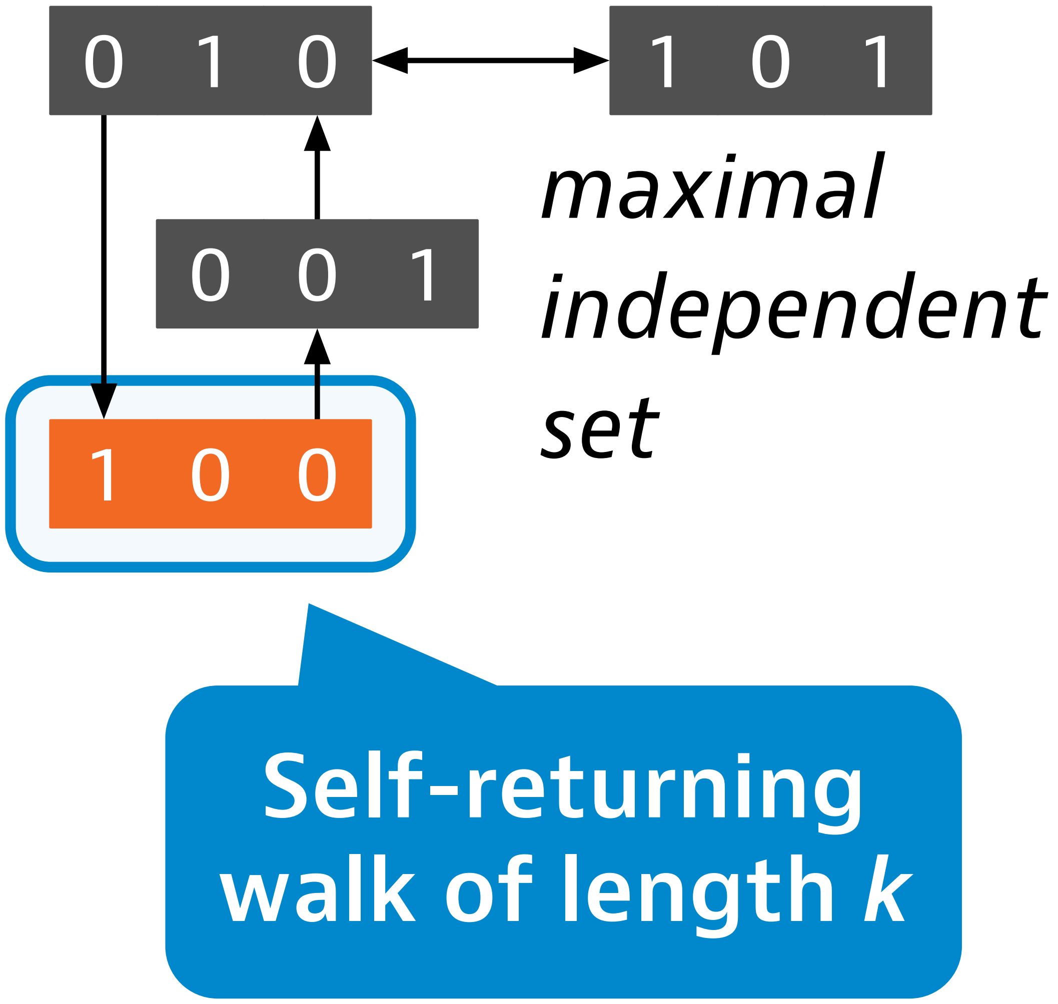
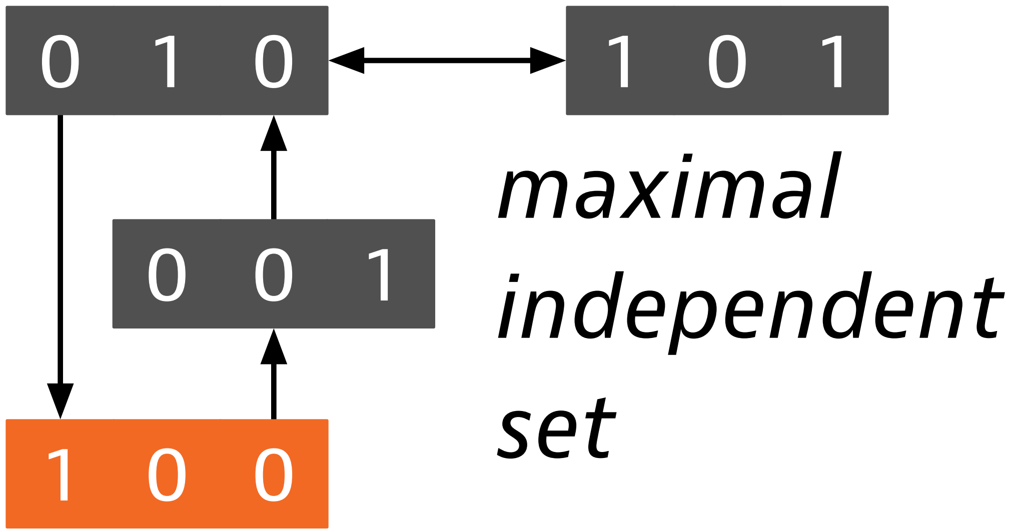

0 1 0
1 0 1
0 0 1
1 0 0
maximal independent set
Self-returning walk of length 7

7


0 1 0
1 0 1
0 0 1
1 0 0
maximal
independent
set
Self-returning
walk of length *k*

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

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



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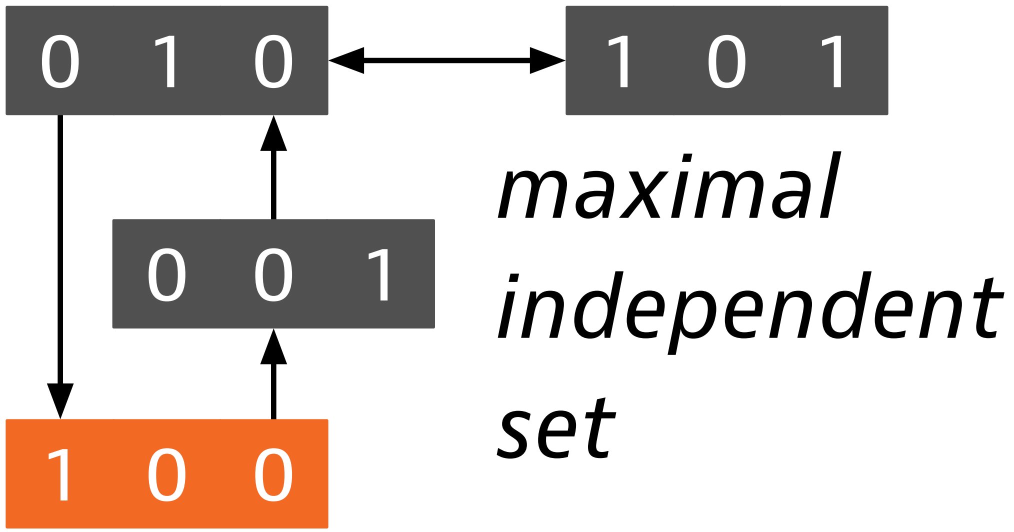
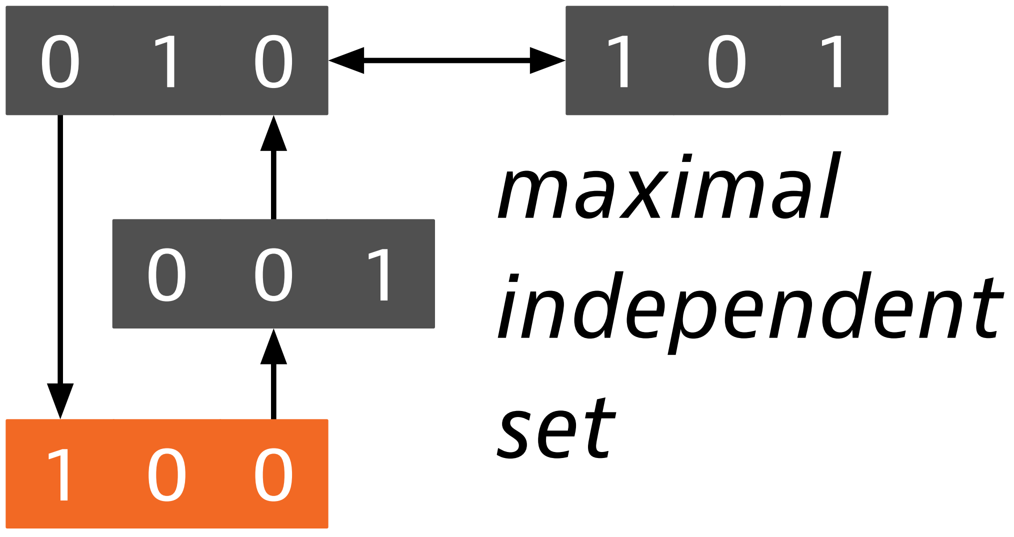


Decidable in polynomial time

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

↓

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



Algorithm:

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

"Flexible":
for all $k \geq k_0$
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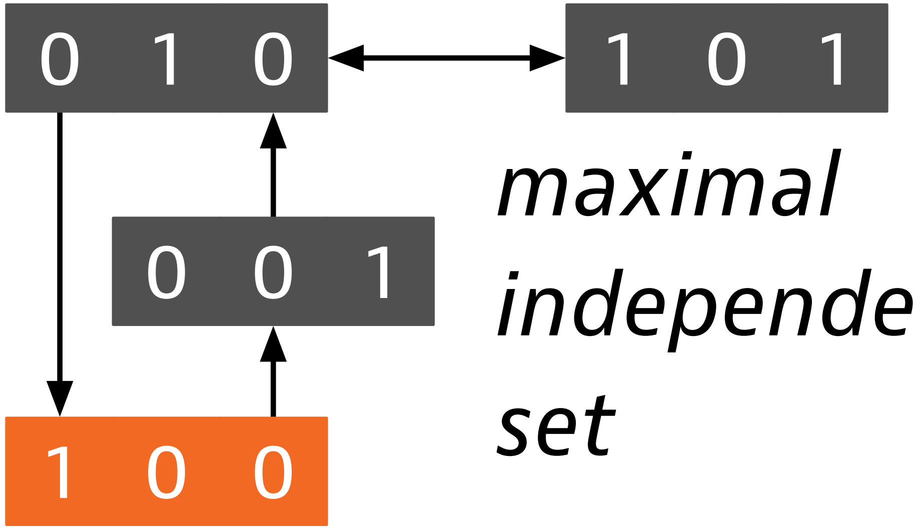
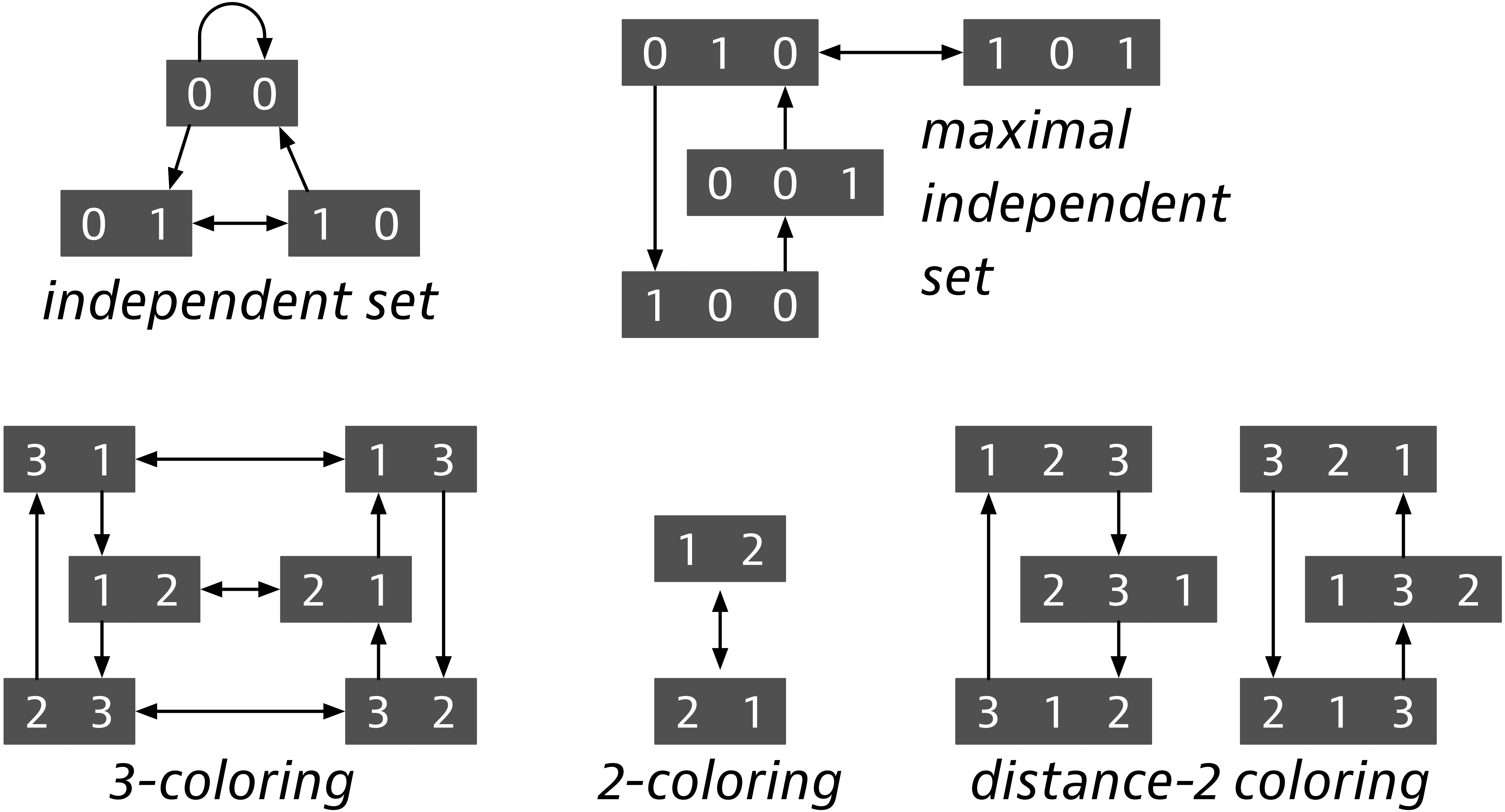


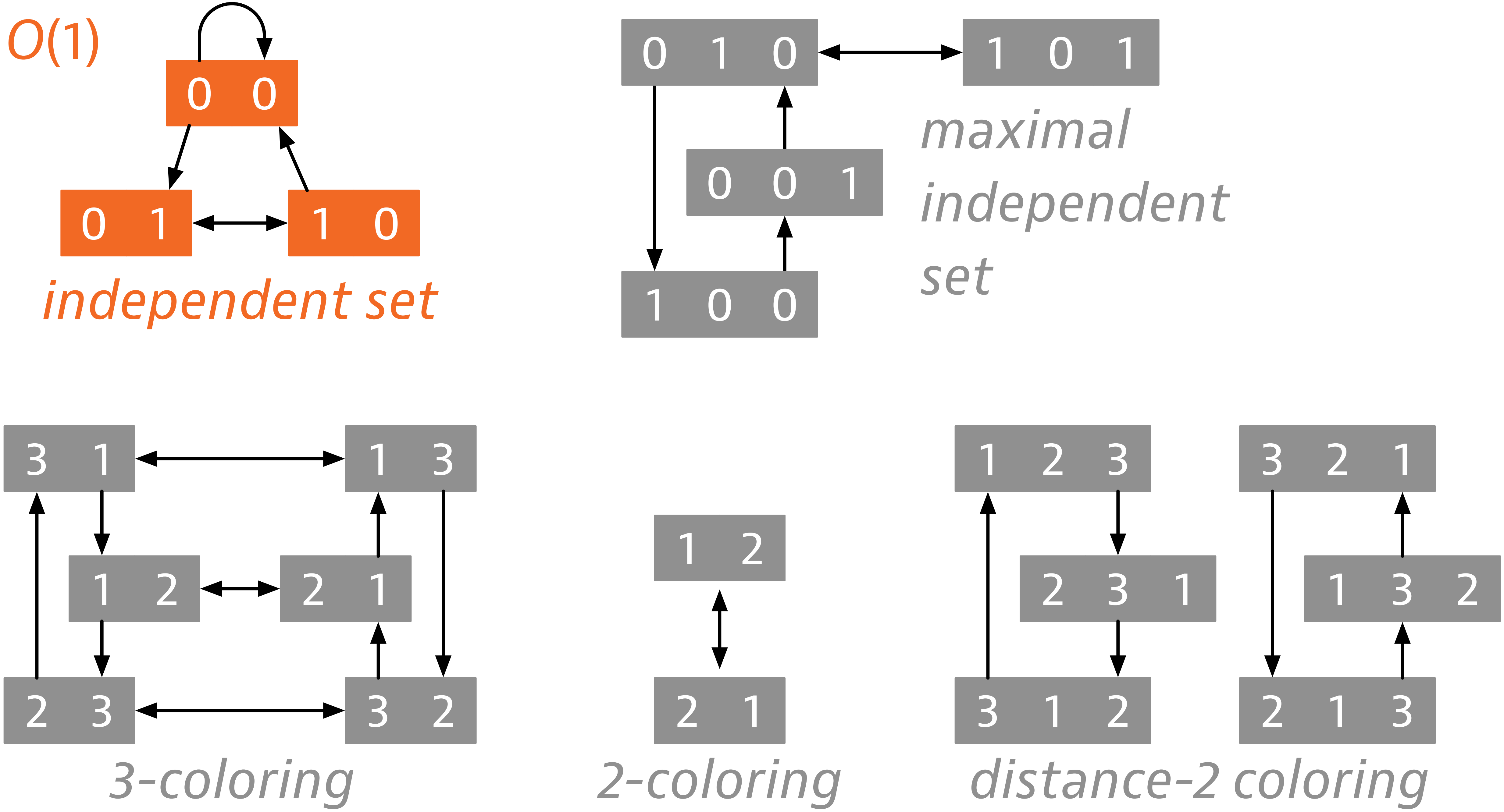
maximal independent set

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

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 ***o*(*n*)** rounds



0 0
0 1
1 0
independent set
0 1 0
1 0 1
0 0 1
1 0 0
maximal independent set
3 1
1 3
1 2
2 1
2 3
3 2
3-coloring
1 2
2 1
2-coloring
1 2 3
3 2 1
2 3 1
1 3 2
3 1 2
2 1 3
distance-2 coloring


O(1)
0 0
0 1
1 0
independent set
0 1 0
1 0 1
0 0 1
1 0 0
maximal independent set
3 1
1 3
1 2
2 1
2 3
3 2
3-coloring
1 2
2 1
2-coloring
1 2 3
3 2 1
2 3 1
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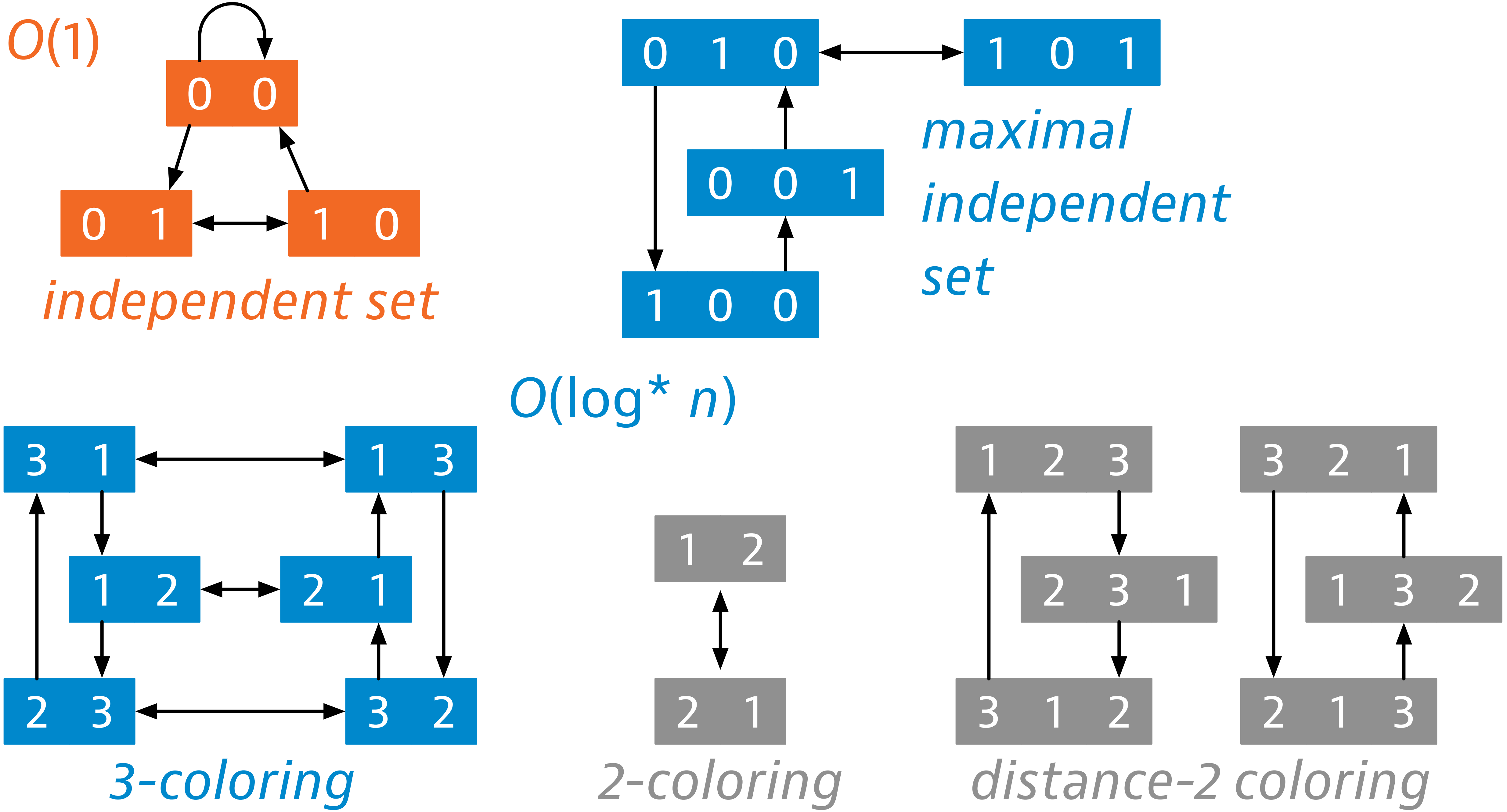
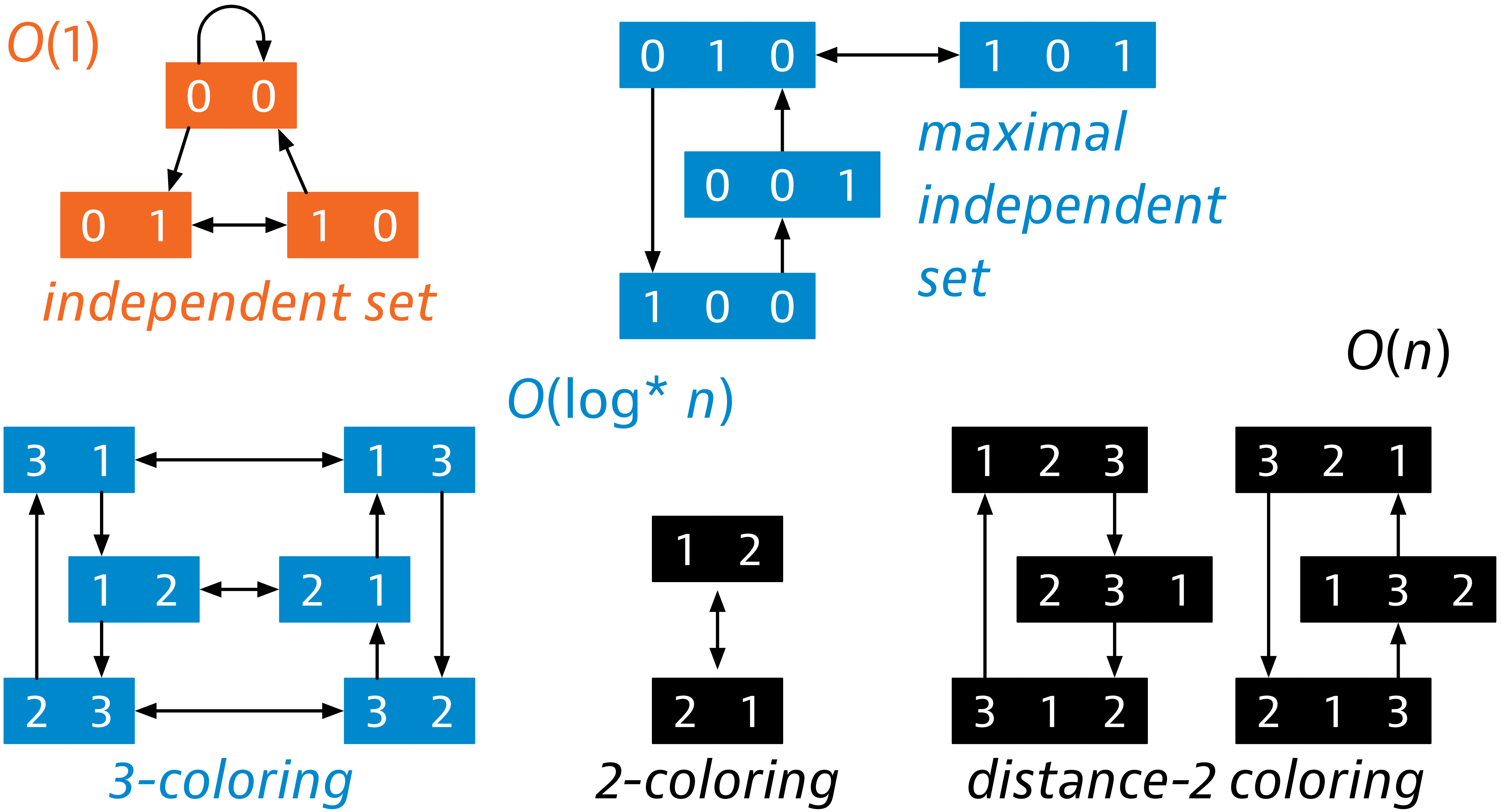

O(1)
0 0
0 1
1 0
independent set
0 1 0
1 0 1
0 0 1
1 0 0
maximal independent set
O(log* n)
3 1
1 3
1 2
2 1
2 3
3 2
3-coloring
1 2
2 1
2-coloring
1 2 3
3 2 1
2 3 1
1 3 2
3 1 2
2 1 3
distance-2 coloring



O(1)
0 0
0 1
1 0
independent set
0 1 0
1 0 1
0 0 1
1 0 0
maximal independent set
O(n)
O(log* n)
3 1
1 3
1 2
2 1
2 3
3 2
3-coloring
1 2
2 1
2-coloring
1 2 3
3 2 1
2 3 1
1 3 2
3 1 2
2 1 3
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

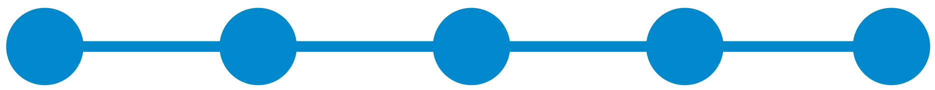
X = { 001, 010, 100, 101 }

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

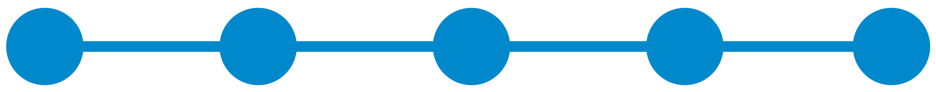
"Oh but doing it for ***this*** *case is of course trivial…"*

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

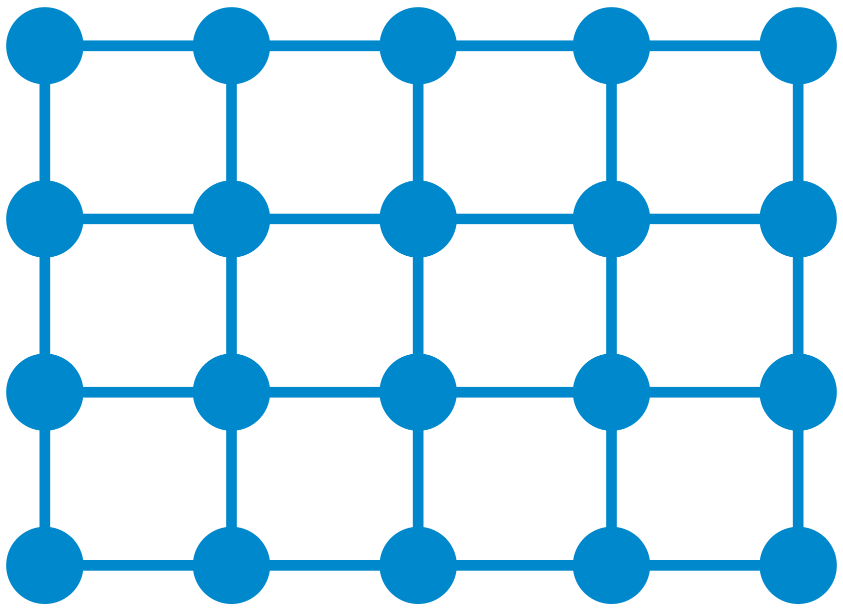
Cycles, paths



Cycles, paths



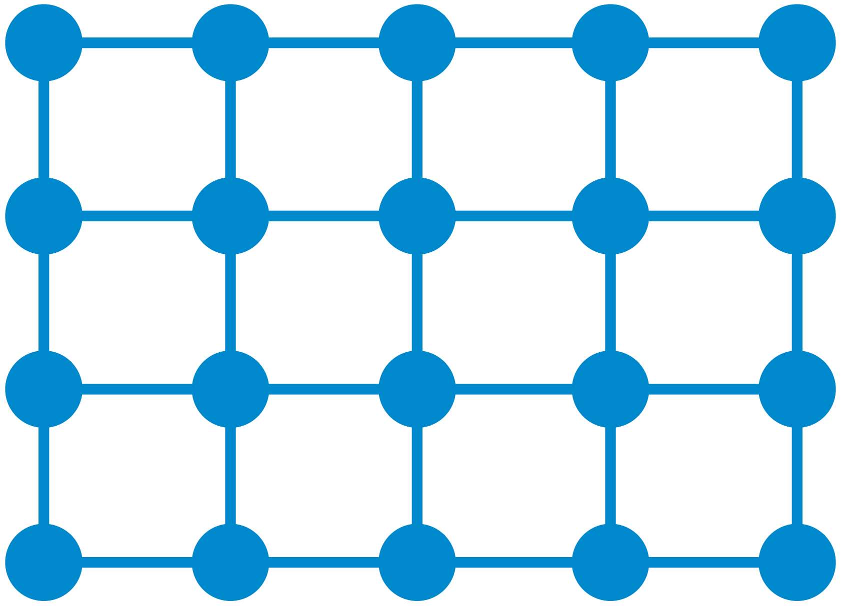
Grids



Cycles, paths

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

Grids



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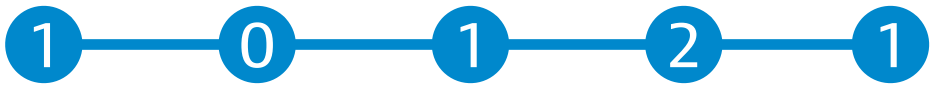
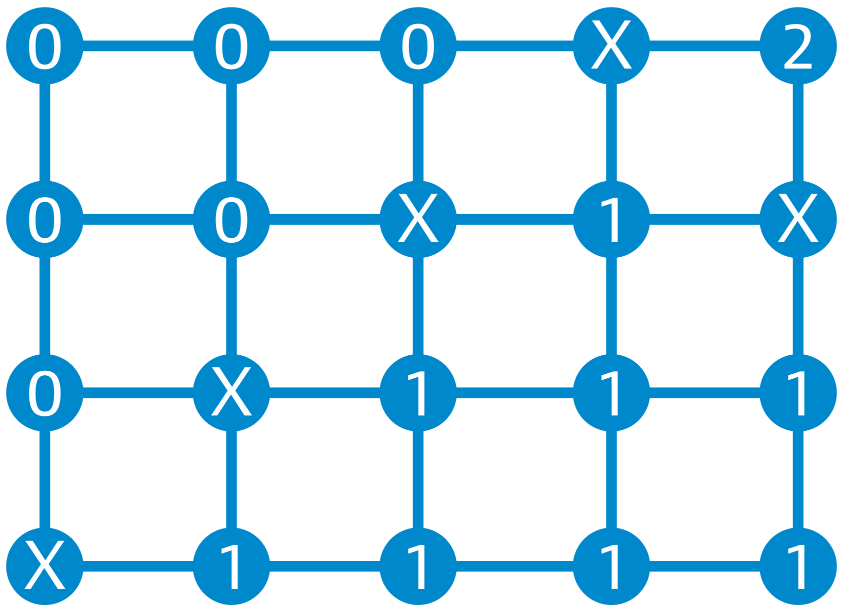


Grids

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



Cycles, paths

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Many questions
(efficiently)
decidable

Grids

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Cycles, paths

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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.

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For each k = 1, 2, 3, ...:

- check all possible candidate functions B
- if any of them is good → fast algorithm found!

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Normal forms

Any algorithm ***A*** that solves a locally checkable problem X fast can be written as ***A*** = ***B*** ∘ C_k

- C_k =
- ***B*** = ... explored neighbourhoods

For each *k* = 2, 3, ...:

- check all possible candidate functions ***B***
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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

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  neighborhoods

Computational complexity:
typically doubly-exponential in k

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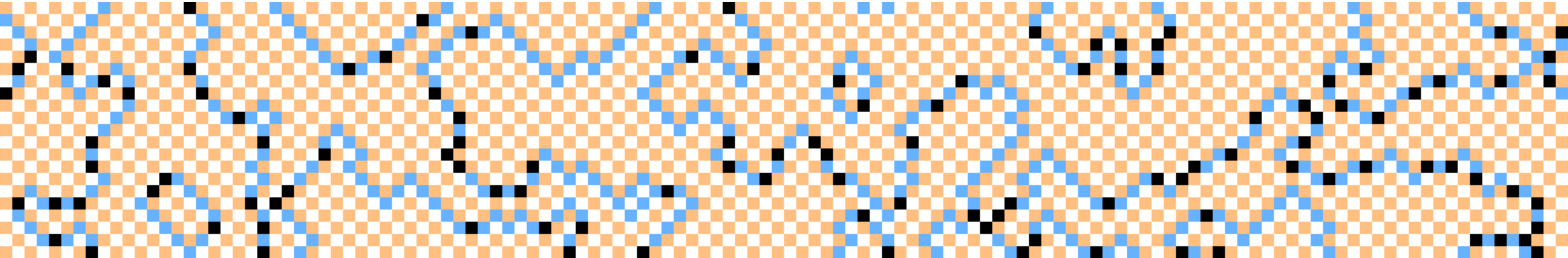
- We can make it more feasible in practice:
    - more ***“compact” normal forms***,
      e.g. distance-*k* coloring → ruling set
    - represent *“candidate B is good for this value of k”*
      as a Boolean formula and use modern ***SAT solvers***
      to find such a *B*

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]



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solution ≈
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Many questions
(efficiently)
decidable

Grids

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

Cycles, paths

solution ≈
execution history of
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Grids + beyond

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

Bad news apply to
any graph family that
contains large grids

Cycles, paths

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Grids + beyond

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What is here between paths and grids?

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Grids + beyond

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Trees
Bounded treewidth
High girth

Cycles, paths

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Grids + beyond

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lots of open questions,
no known obstacles!

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

Cycles, paths

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execution history of
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Grids + beyond

solution ≈
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a **Turing machine**

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

- **Classification:** *"Any problem in this family belongs to one of these classes"*

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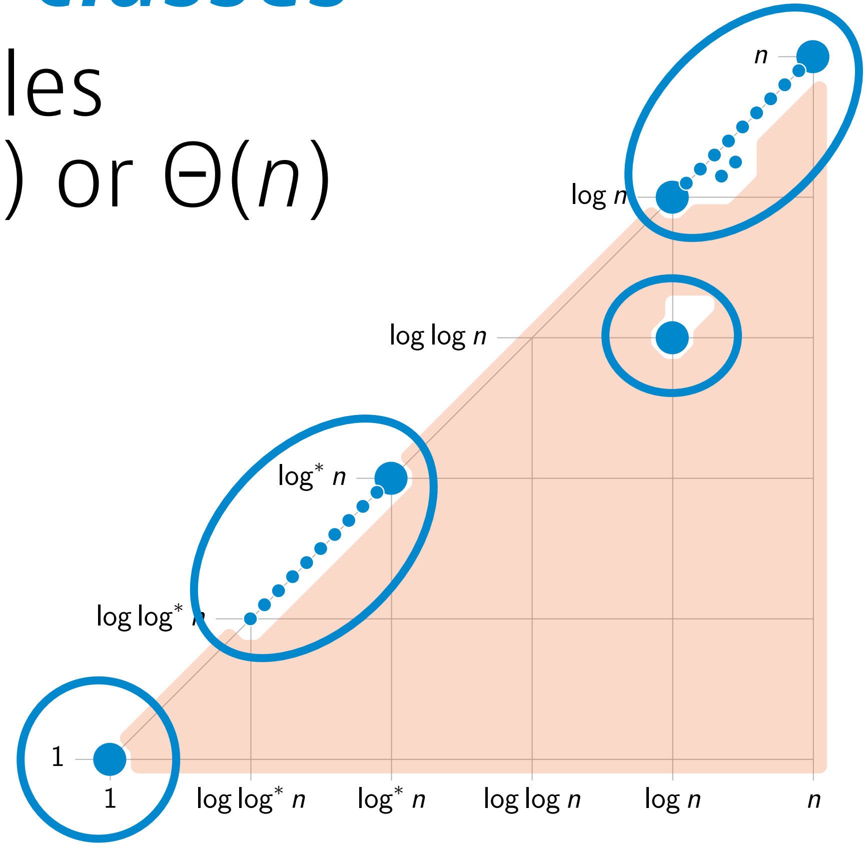
  - locally checkable problems in general graphs belong to one of four broad classes



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- Identify interesting nontrivial problems
  - e.g. where computers fail
- Detect patterns, generalize

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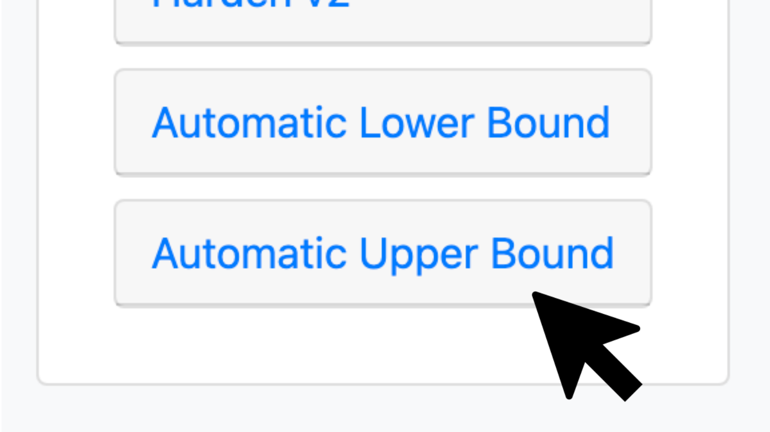
- Identify inter… nontrivial problems
  - e.g. where cor… fail
- Detect p…

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

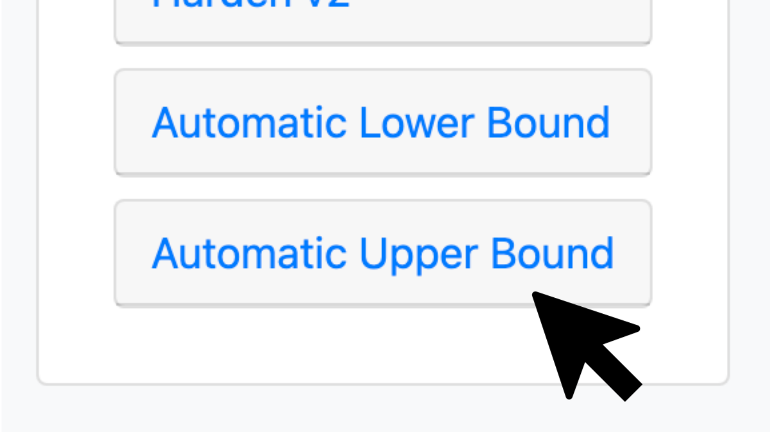
General techniques



- 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

- *Can we automate our own work?*

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Take-home messages

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