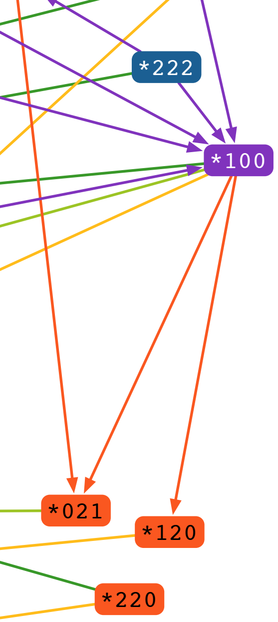
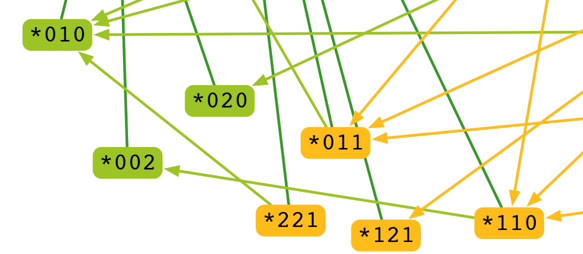




Synthesizing fault-tolerant distributed algorithms

Danny Dolev
Hebrew University of Jerusalem

Christoph Lenzen
MPI Saarbrücken

Keijo Heljanko
Joel Rybicki
Jukka Suomela
Siert Wieringa
Aalto University & HIIT

Janne H. Korhonen
Matti Järvisalo
University of Helsinki & HIIT

Ulrich Schmid
TU Wien

July 24, 2014
FRIDA 2014, Vienna, Austria

What is this talk about?

Developing fault-tolerant distributed algorithms for consensus-like problems using *computational techniques*.

Verification vs synthesis

Verification:

*"**Check** that given A satisfies the specification S."*

Synthesis:

*"**Construct** an A that satisfies a specification S."*

The model problem

The *synchronous counting problem*:

- Closely related to consensus
- Self-stabilization
- Byzantine fault tolerance
- Hard to come up with correct algorithms

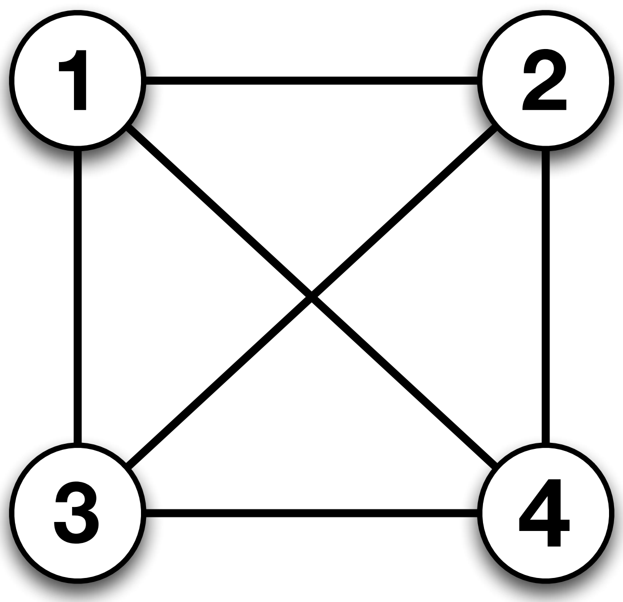
Our work

Prior work: Are there **efficient** and **compact** deterministic algorithms?
Dolev et al. (**SSS 2013**)

Recent work: Developing and evaluating different **synthesis techniques**

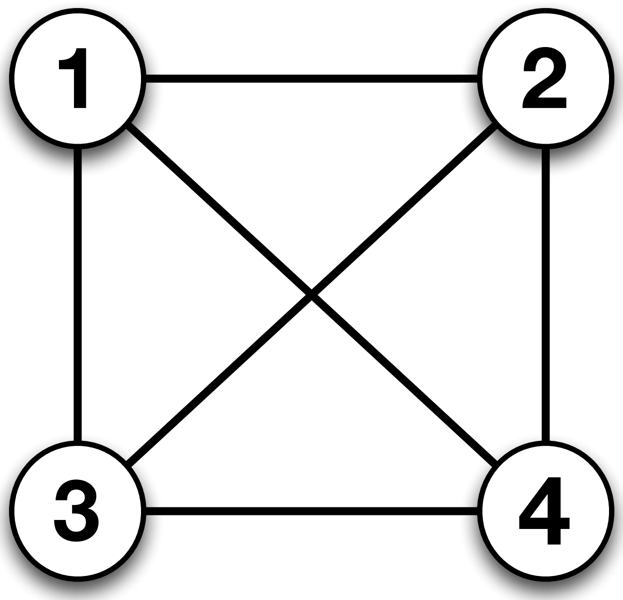
Synchronous counting

The model



- *n* processors
- *s* states per node
- arbitrary initial state

The model



- *n* processors
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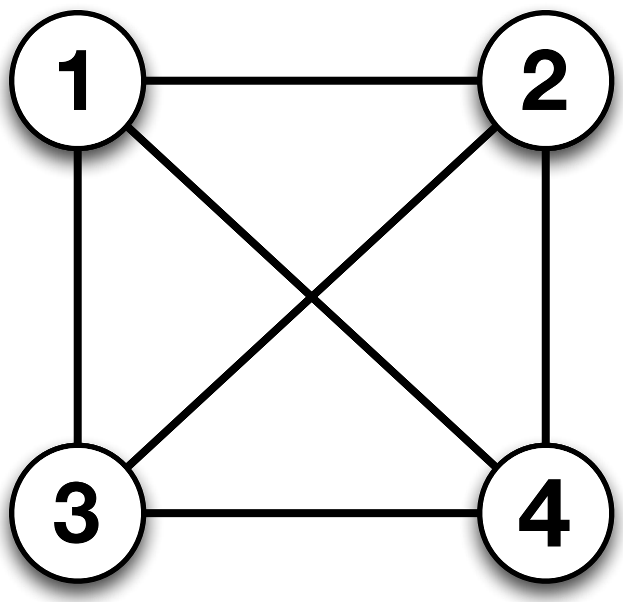
Synchronous step:

1. send state to all neighbours
2. update state

The model



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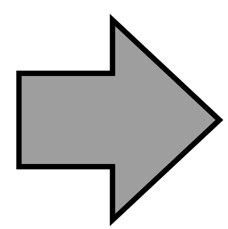
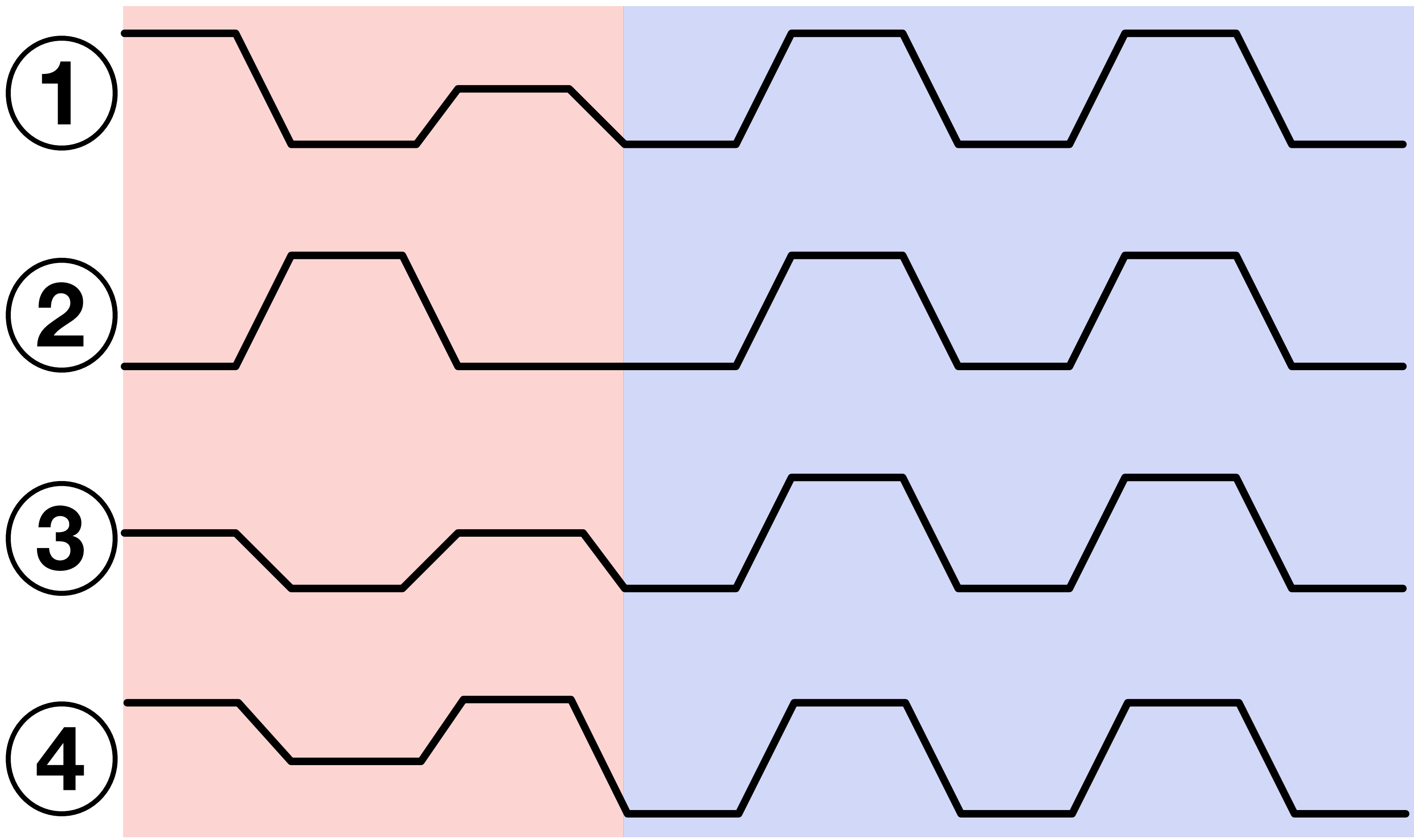


algorithm
=
transition function

Self-stabilizing counting



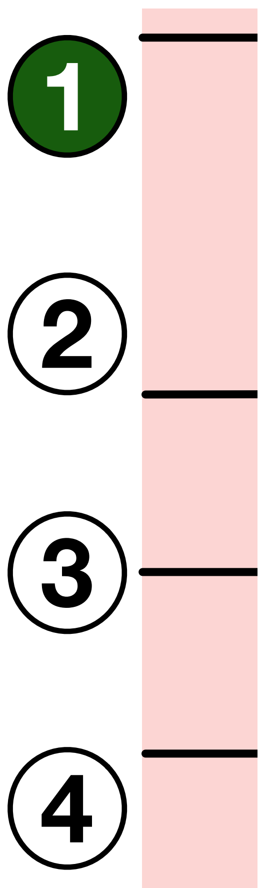
Stabilization **Counting**

Self-stabilizing counting

A simple algorithm solves the problem

Self-stabilizing counting

Solution: Follow the leader.



Self-stabilizing counting

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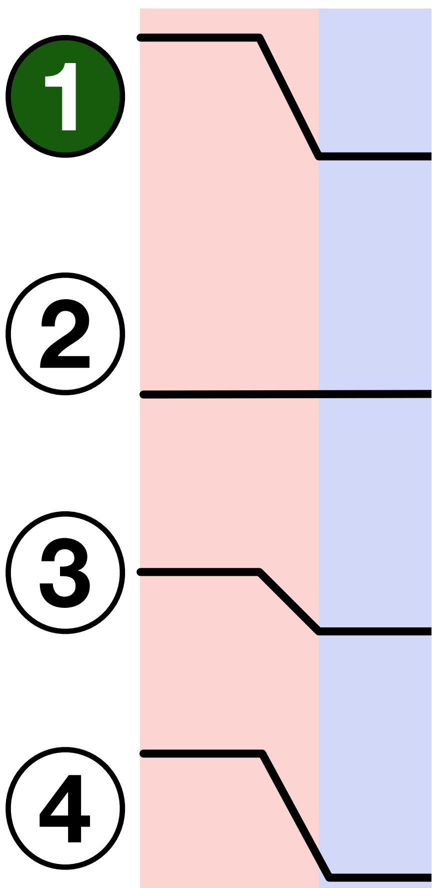
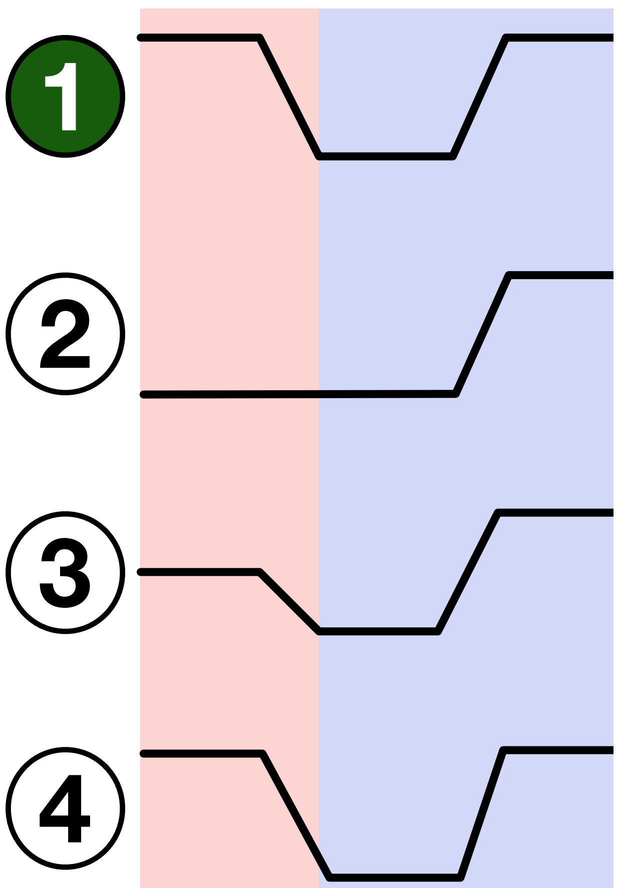


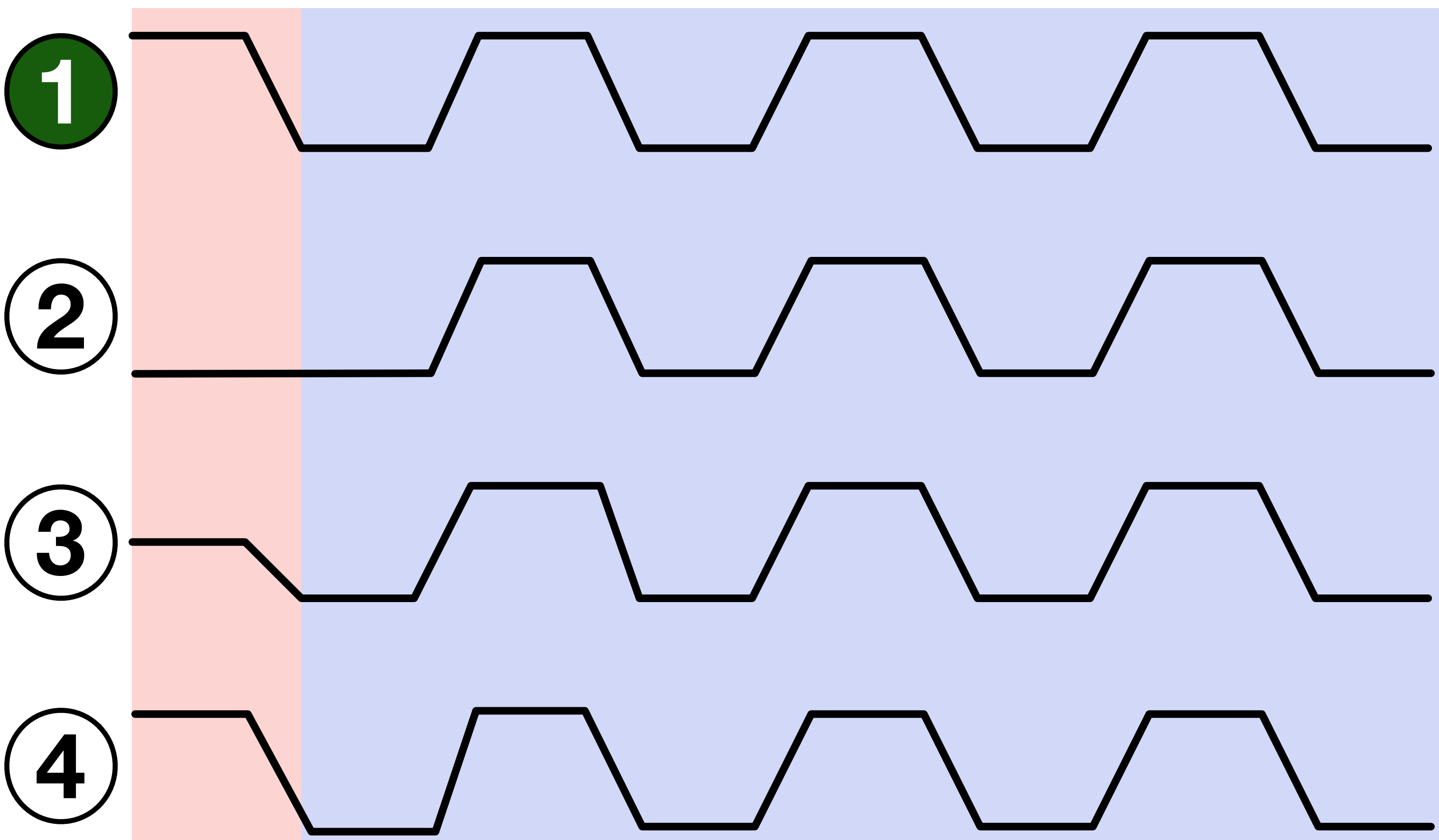
Self-stabilizing counting

Solution: Follow the leader.

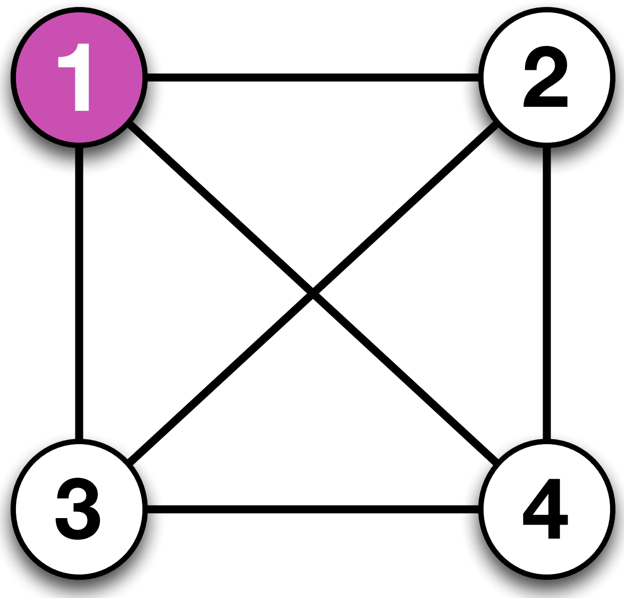


Self-stabilizing counting

Solution: Follow the leader.

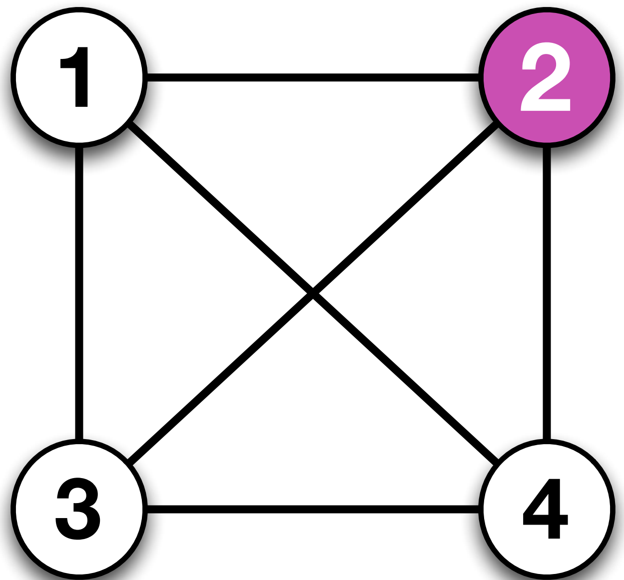


Tolerating Byzantine failures



Assume that at most *f* nodes may be **Byzantine**.

Tolerating Byzantine failures



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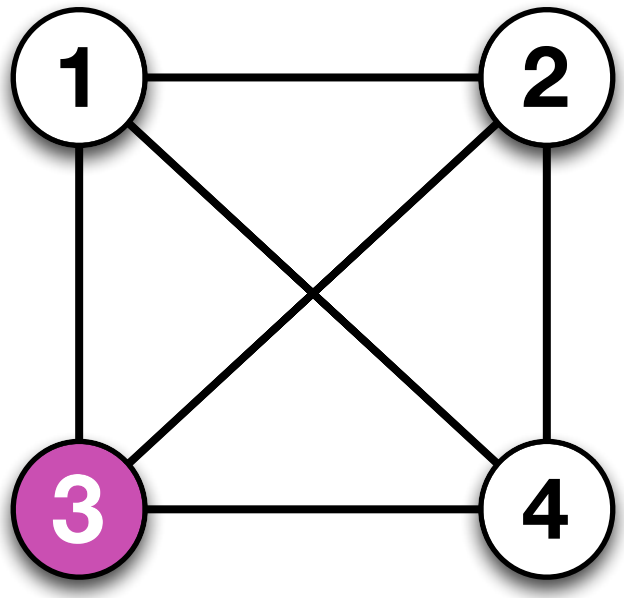
Tolerating Byzantine failures



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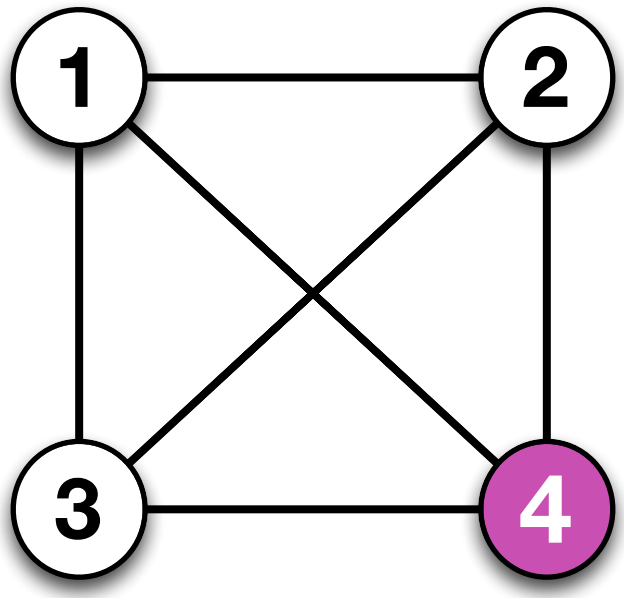
Tolerating Byzantine failures



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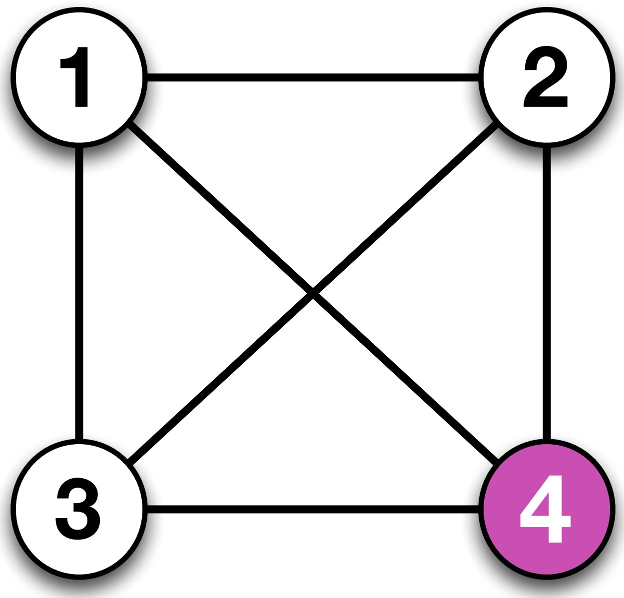
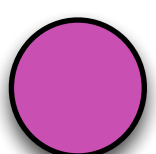
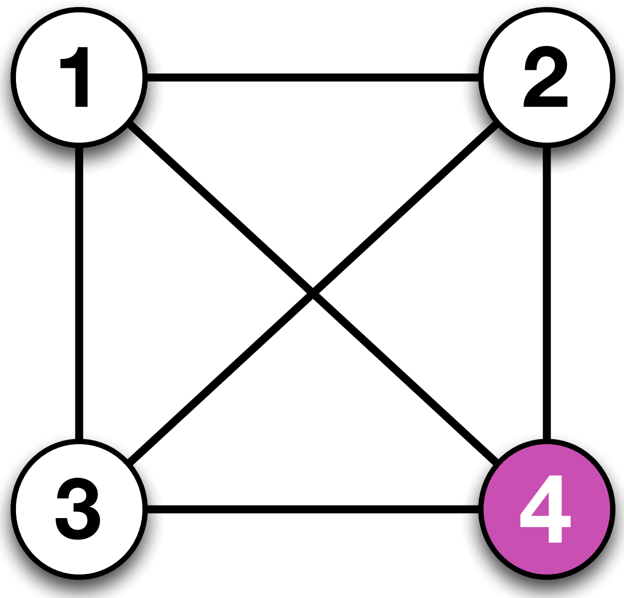
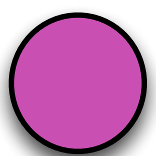
Tolerating Byzantine failures



 can send *different* messages to non-faulty nodes!

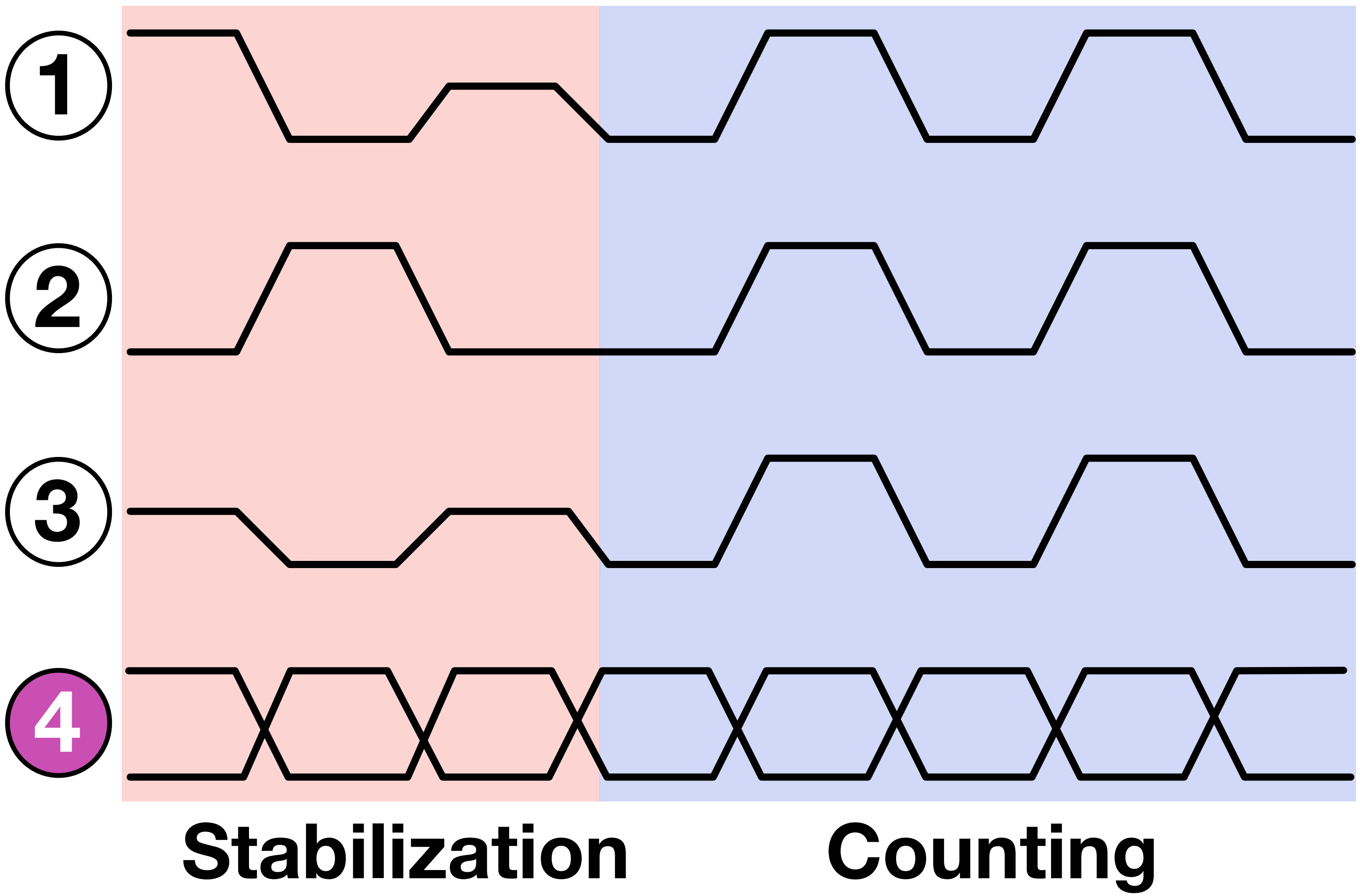
Tolerating Byzantine failures



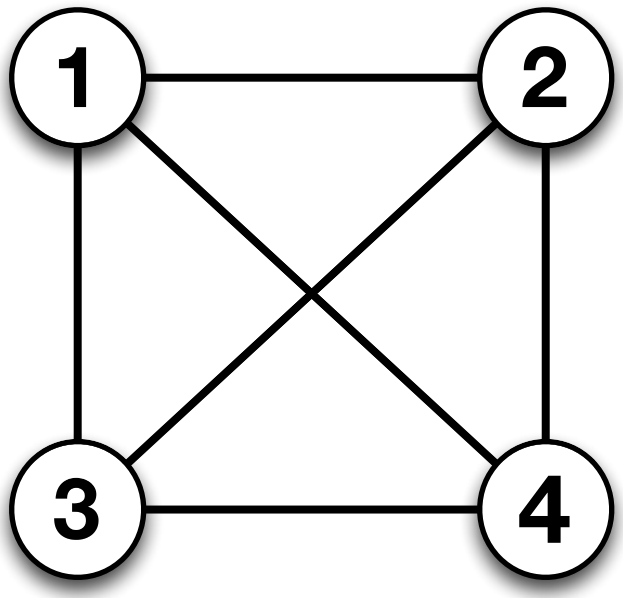
 can send *different* messages to non-faulty nodes!

Note: Easy if self-stabilization is not required!

Fault-tolerant counting



The model with failures



- *n* processors
- *s* states
- arbitrary initial state
- at most *f* Byzantine nodes

Some basic facts

- How many states (per node) do we need?
  - $s \geq 2$
- How many faults can we tolerate?
  - $f < n/3$
- How fast can we stabilize?
  - $t > f$

Pease et al., 1980
Fischer & Lynch, 1982

Solving synchronous counting

Deterministic solutions with large s known for similar problems (e.g. D. Dolev & Hoch, 2007)

Randomized solutions for counting with small s and large t in expectation (e.g. S. Dolev: Self-stabilization)

We have synthesized *deterministic* algorithms with small s and t for the case $f = 1$ (**SSS '13**)

Finding an algorithm

The size of the search space is s^b where $b = ns^n$.

parameters	search space
$n = 4$ $s = 2$	$2^{64} \approx 10^{19}$

Finding an algorithm

The size of the search space is s^b where $b = ns^n$.

parameters	search space
$n = 4$ $s = 2$	$2^{64} \approx 10^{19}$
$n = 4$ $s = 3$	$3^{324} \approx 10^{154}$

We need a clever way to do the search!

Main results, $f = 1$

If $4 \leq n \leq 5$:

- **lower bound:** no 2-state algorithm
- **upper bound:** 3 states suffice

If $n \geq 6$:

- 2 states always suffice

Synthesis techniques

Our initial approach

- Fix n, s and f
- The existence of an algorithm is a finite combinatorial decision problem
- Apply **SAT solvers** to a base case that implies a general solution

Generalizing from a base case

For any fixed *s*, *f* and *t*:

There is an algorithm **A** for *n* nodes

$$\Downarrow$$

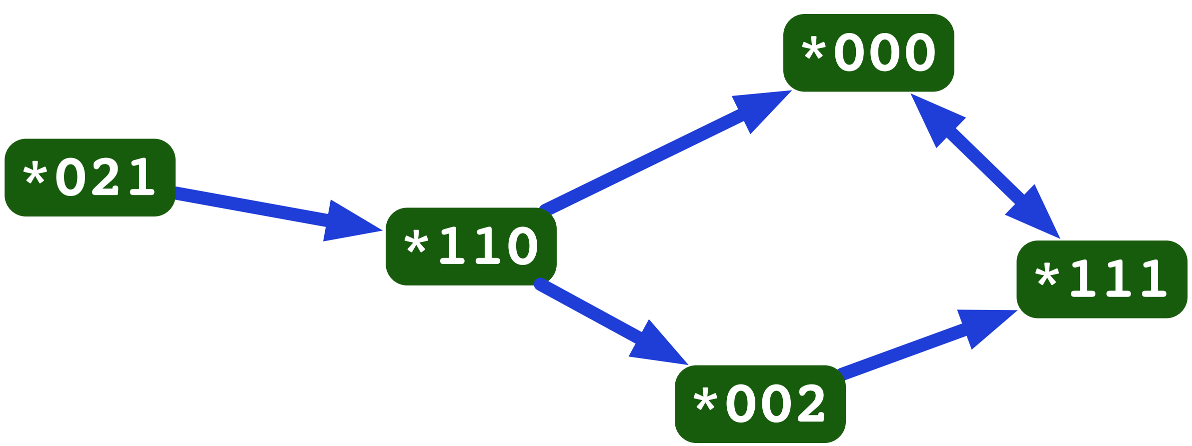
There is an algorithm **B** for *n*+1 nodes with same *s*, *f* and *t*

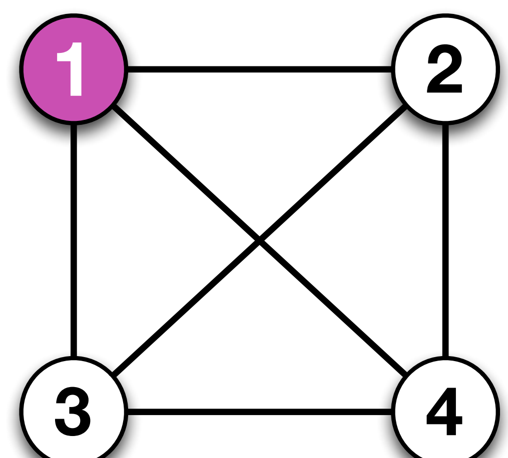
Verification is easy

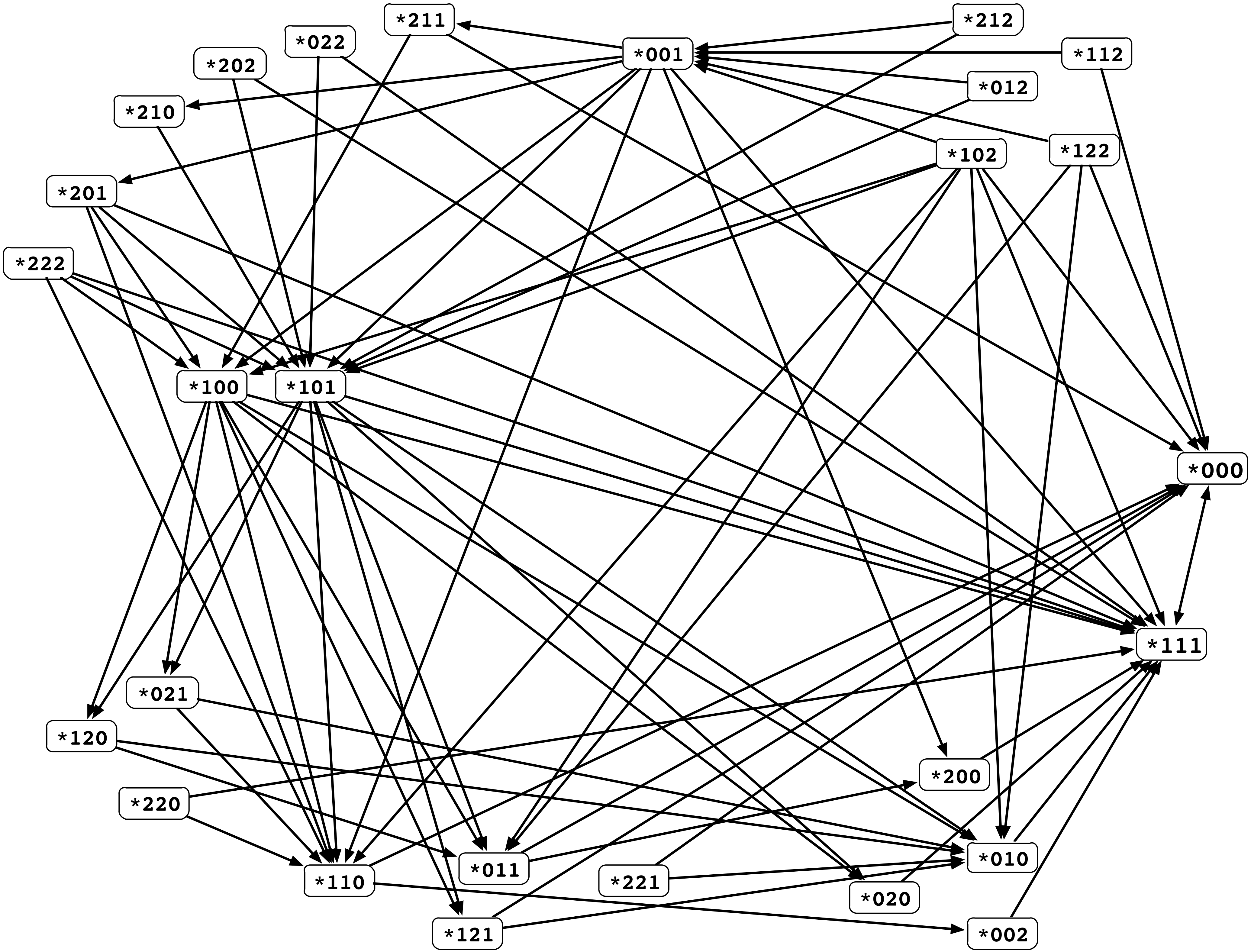
- Let *F* be a set of faulty nodes, |*F*| ≤ *f*
- Construct a *state graph* G_F from **A**:

  Nodes = actual states

  Edges = possible state transitions



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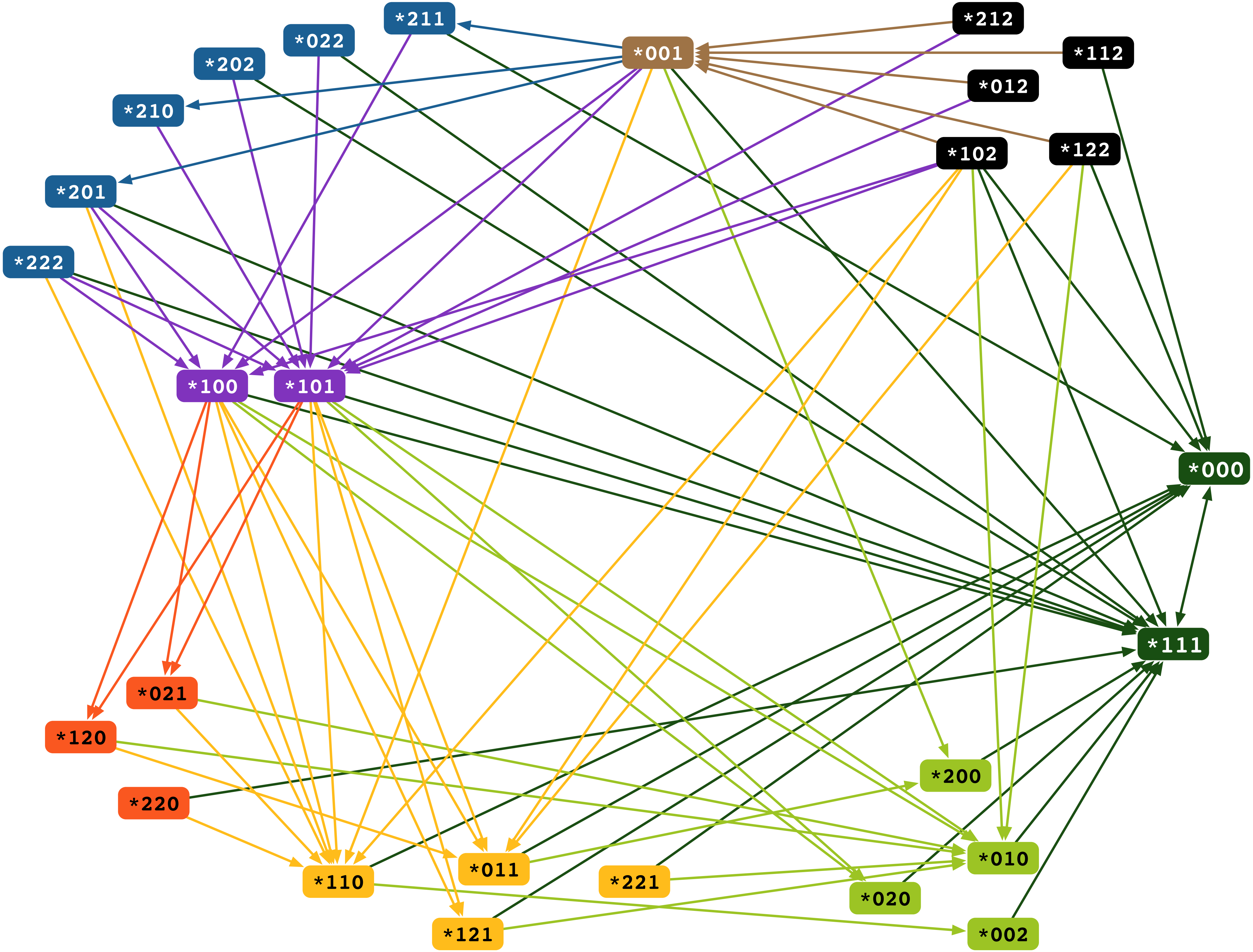
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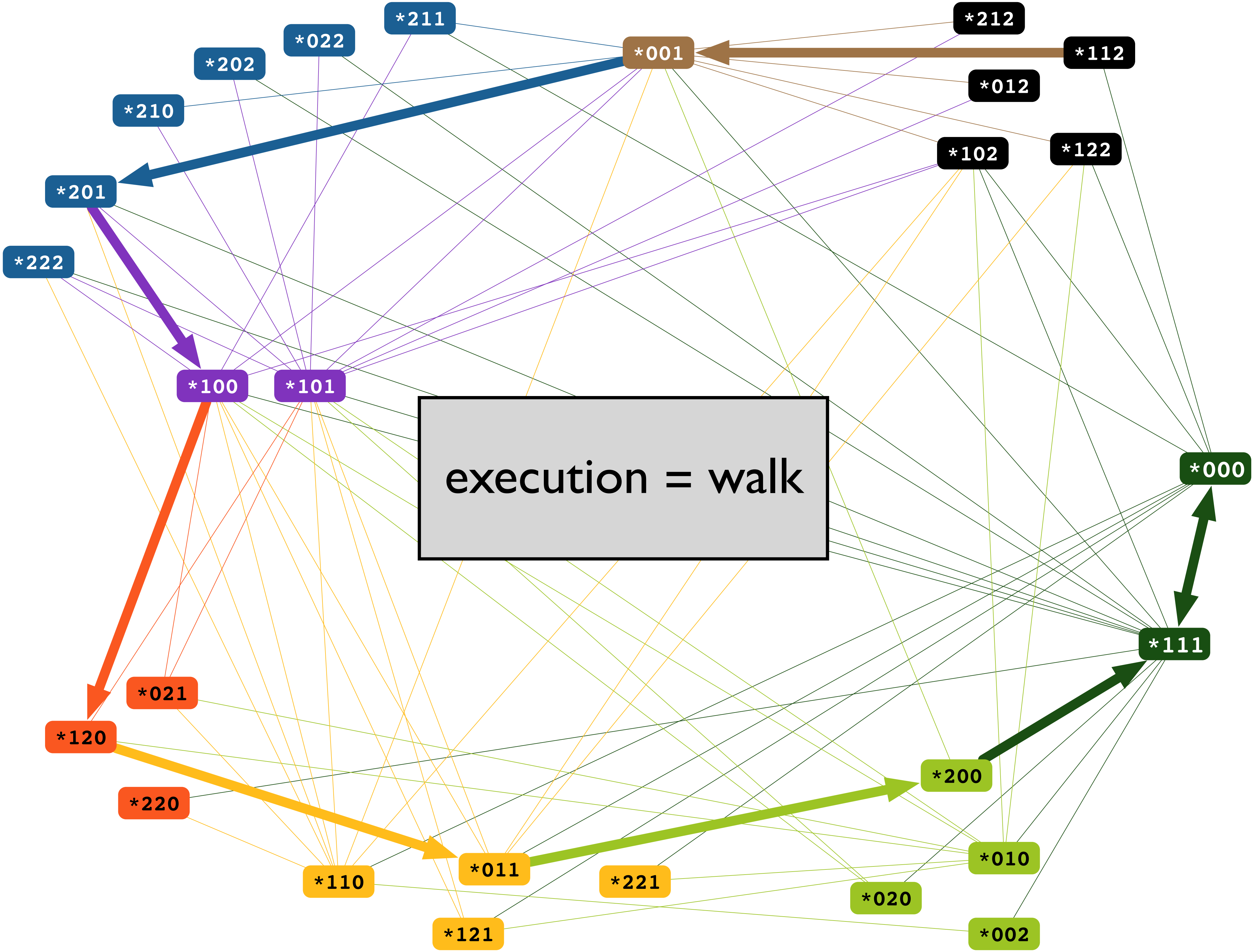
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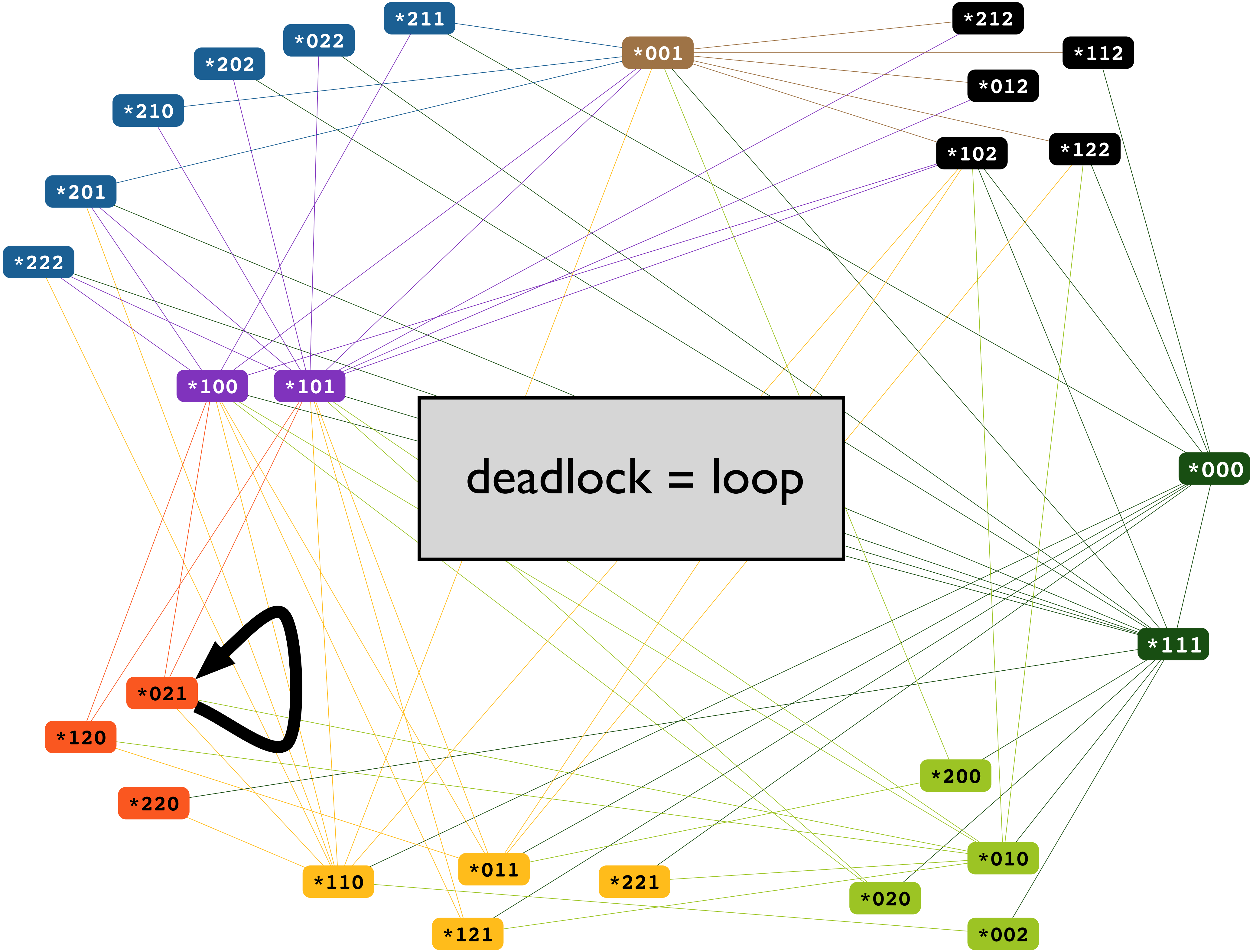

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deadlock = loop
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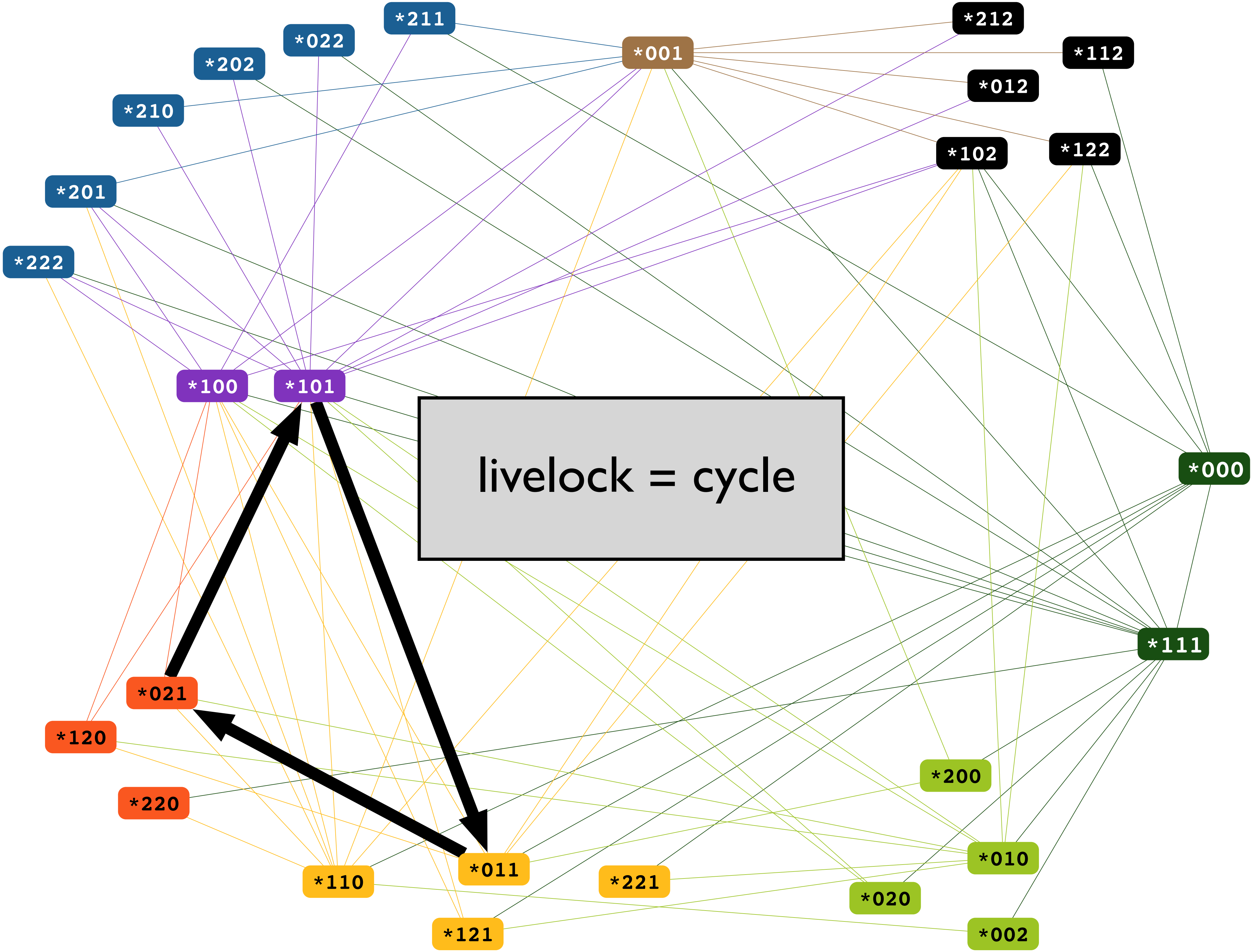
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livelock = cycle
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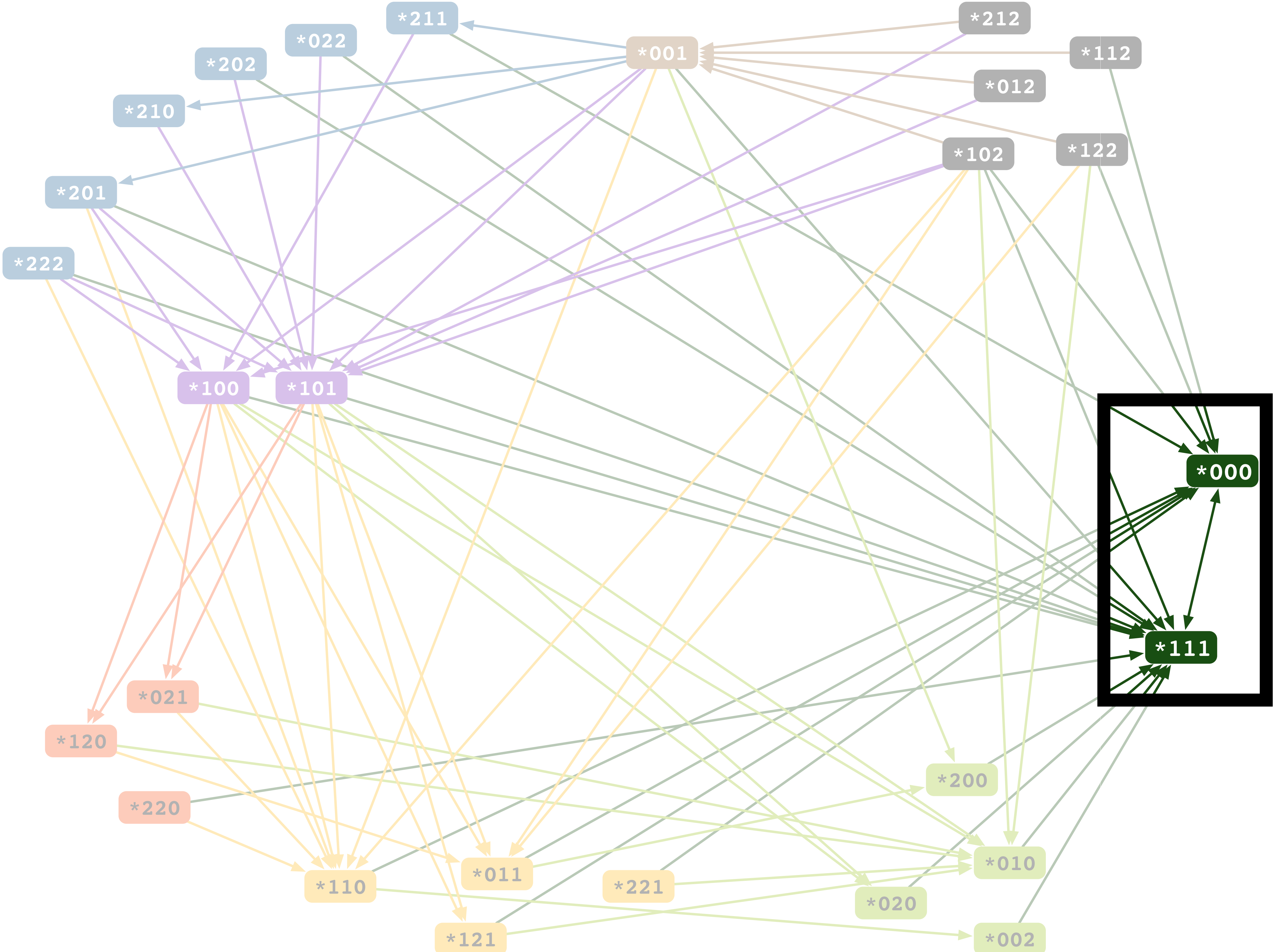
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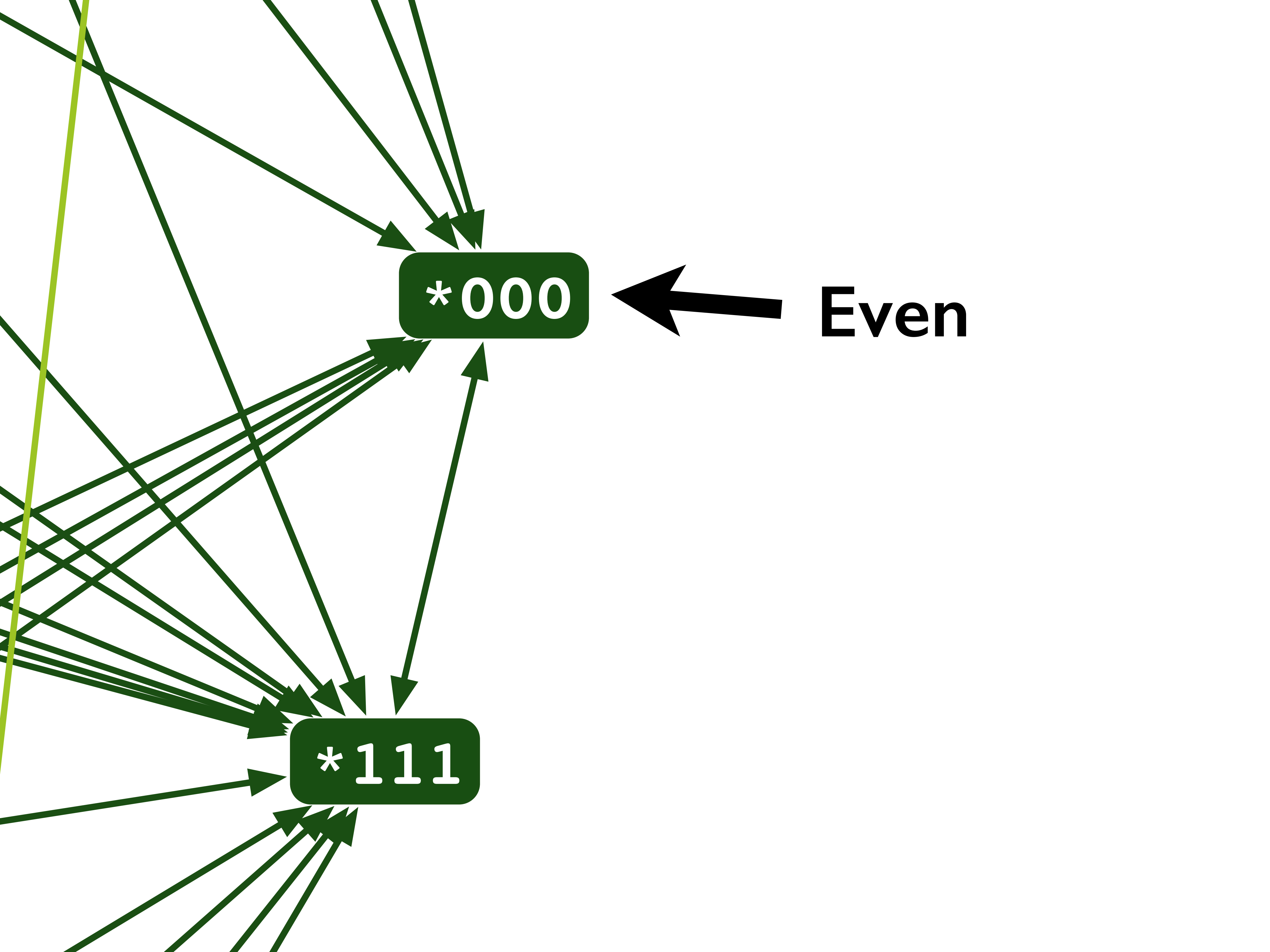
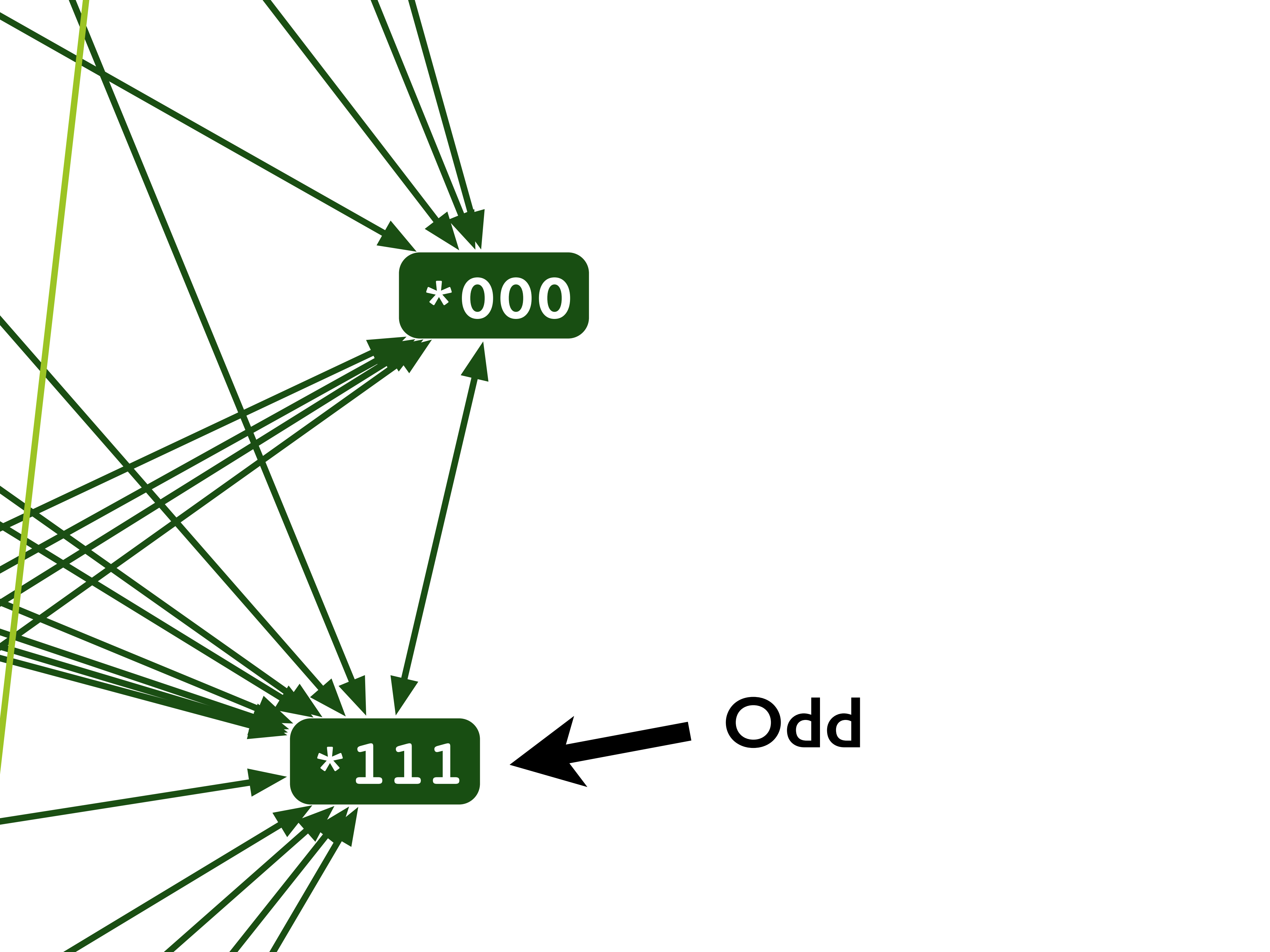

*000
*111
Even


*000
*111
Odd

Verification is easy

A is **correct**	$\Leftrightarrow$	Every G_F is **good**
no deadlocks	$\Leftrightarrow$	G_F is loopless
stabilization	$\Leftrightarrow$	All nodes have a path to **0**
counting	$\Leftrightarrow$	$\{\mathbf{0}, \mathbf{1}\}$ is the only cycle

From verification to synthesis

The encoding uses the following variables:

$$x_{i,u,s} \quad \Leftrightarrow \quad A_i(u) = s$$

$$e_{q,r} \quad \Leftrightarrow \quad \text{edge} \;\; (q, r) \;\; \text{exists}$$

$$p_{q,r} \quad \Leftrightarrow \quad \text{path} \;\; q \leadsto r \;\; \text{exists}$$

$$x_{i,u,s} \quad \Rightarrow \quad e_{q,r} \quad \Rightarrow \quad p_{q,r}$$

The SAT approach

- Solver is a black box: no domain-knowledge
- Relatively easy to setup
- Size of instances **blows up:**

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instance: n, s, t	**variables**	**clauses**
4 3 10	6k	31k
5 3 10	45k	36k
6 3 10	403k	4M

Counter-example guided search

- A problem-specific synthesis algorithm
- CEGAR-inspired search
- Uses SAT solver to find ***counter-examples***
- Learn constraints on-the-fly

A high-level overview

While algorithm candidates exist:

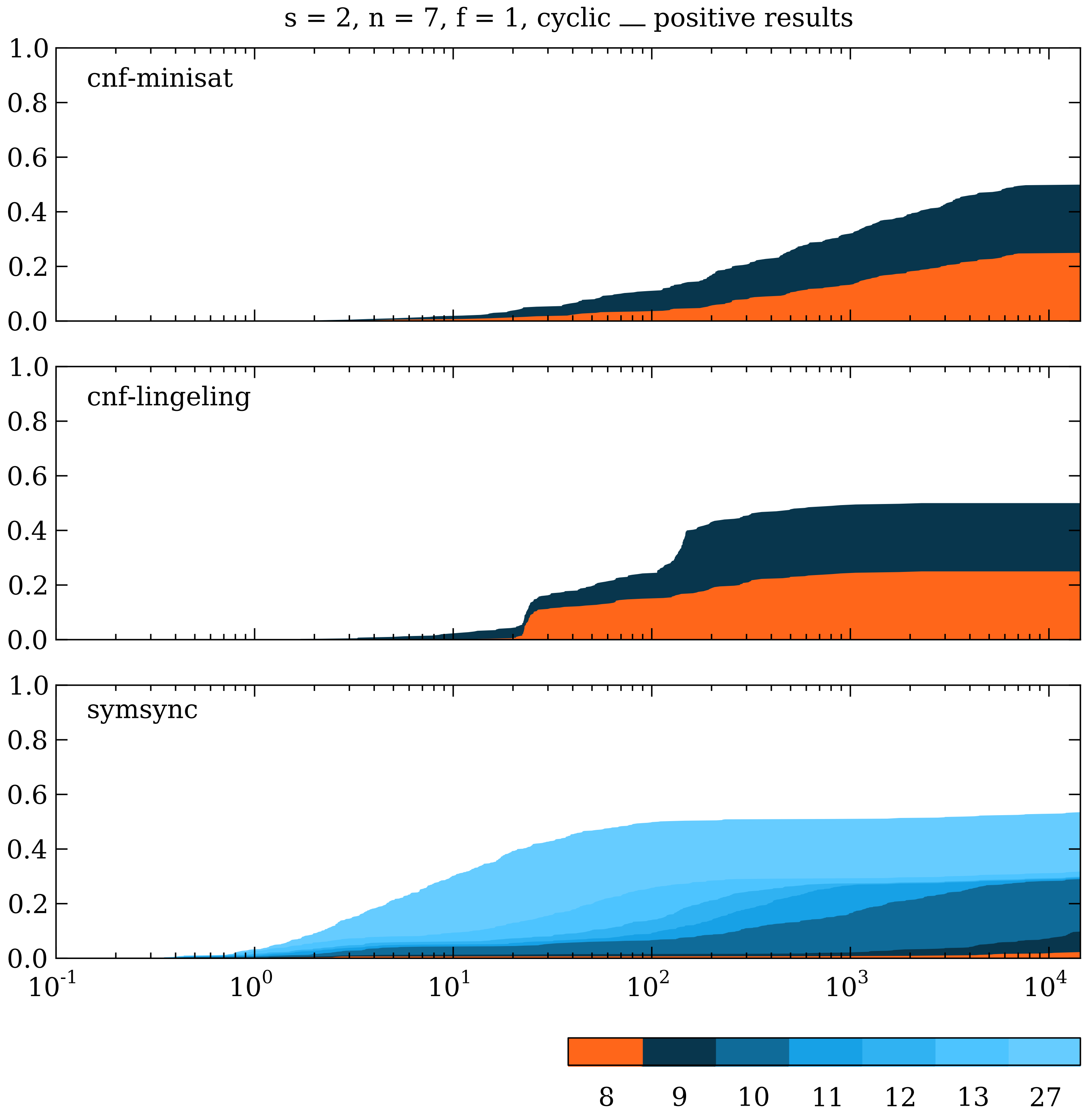
- Guess an algorithm **A**
- Use a SAT solver to check if **A** is correct
- If not, solver gives a counter-example. Learn new constraints that forbid bad algorithms

How to learn ***useful*** constraints from counter-examples?

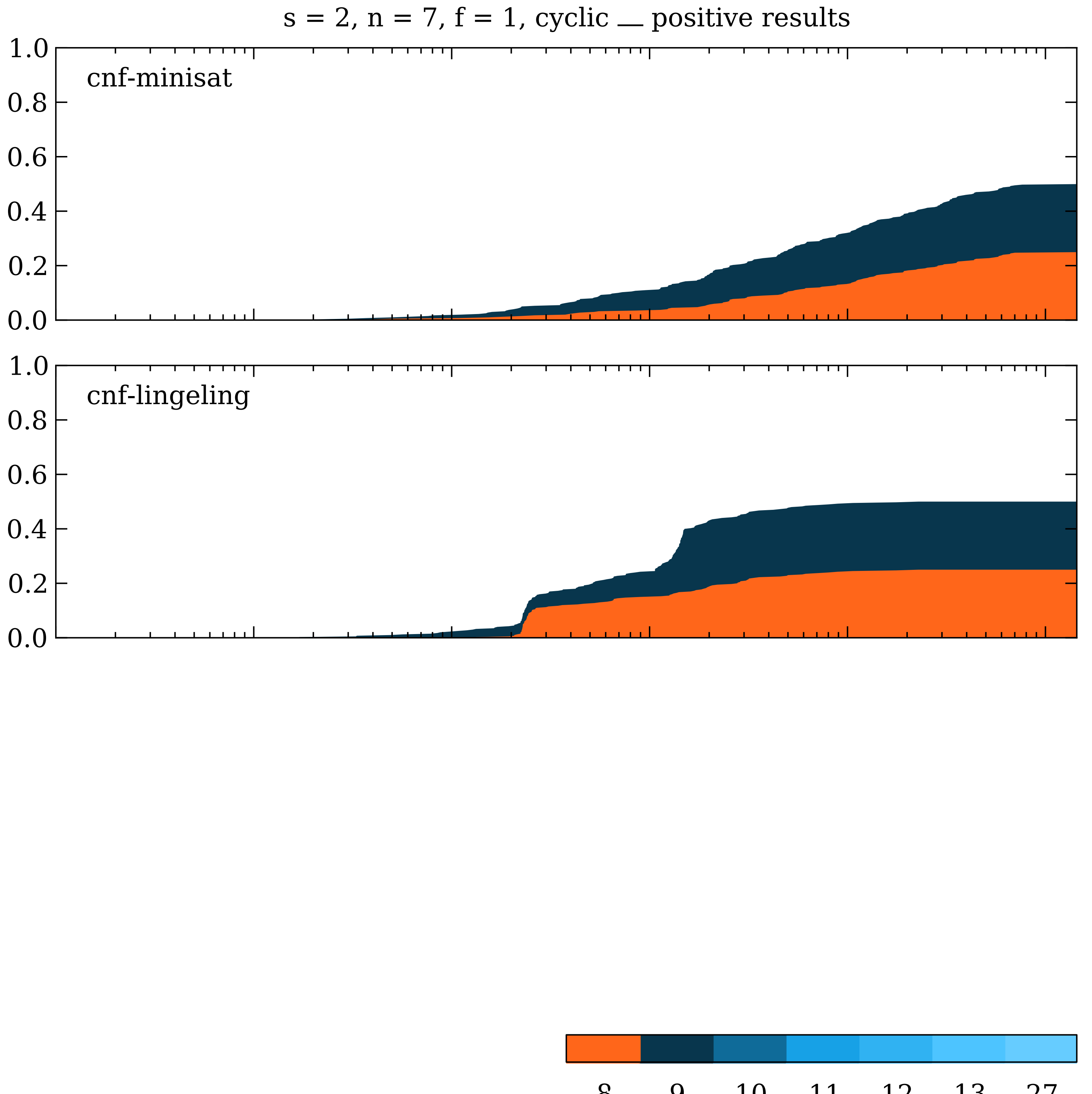
Some experiments

Experiment setup

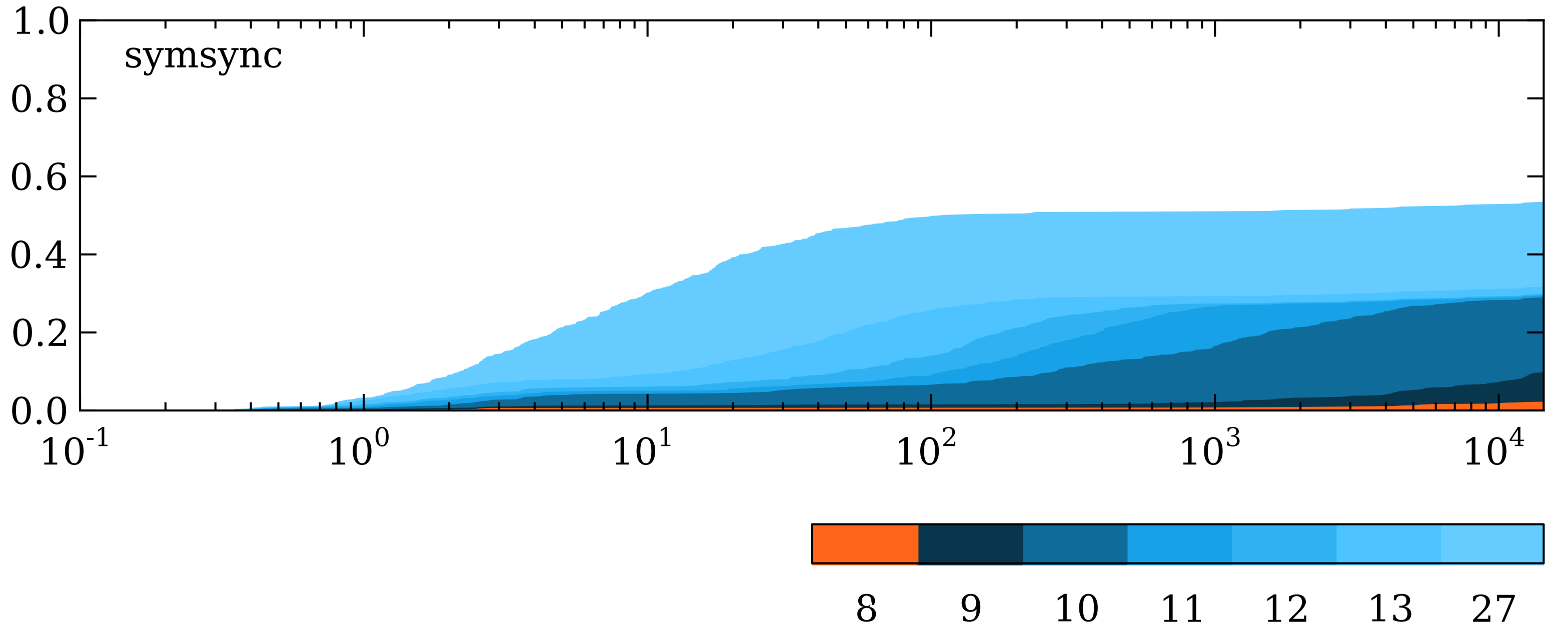
- SAT encoding: MiniSAT and lingeling solvers
- ‘symsync’: the guided search algorithm
- same instance on 100 processors in parallel, different random seeds

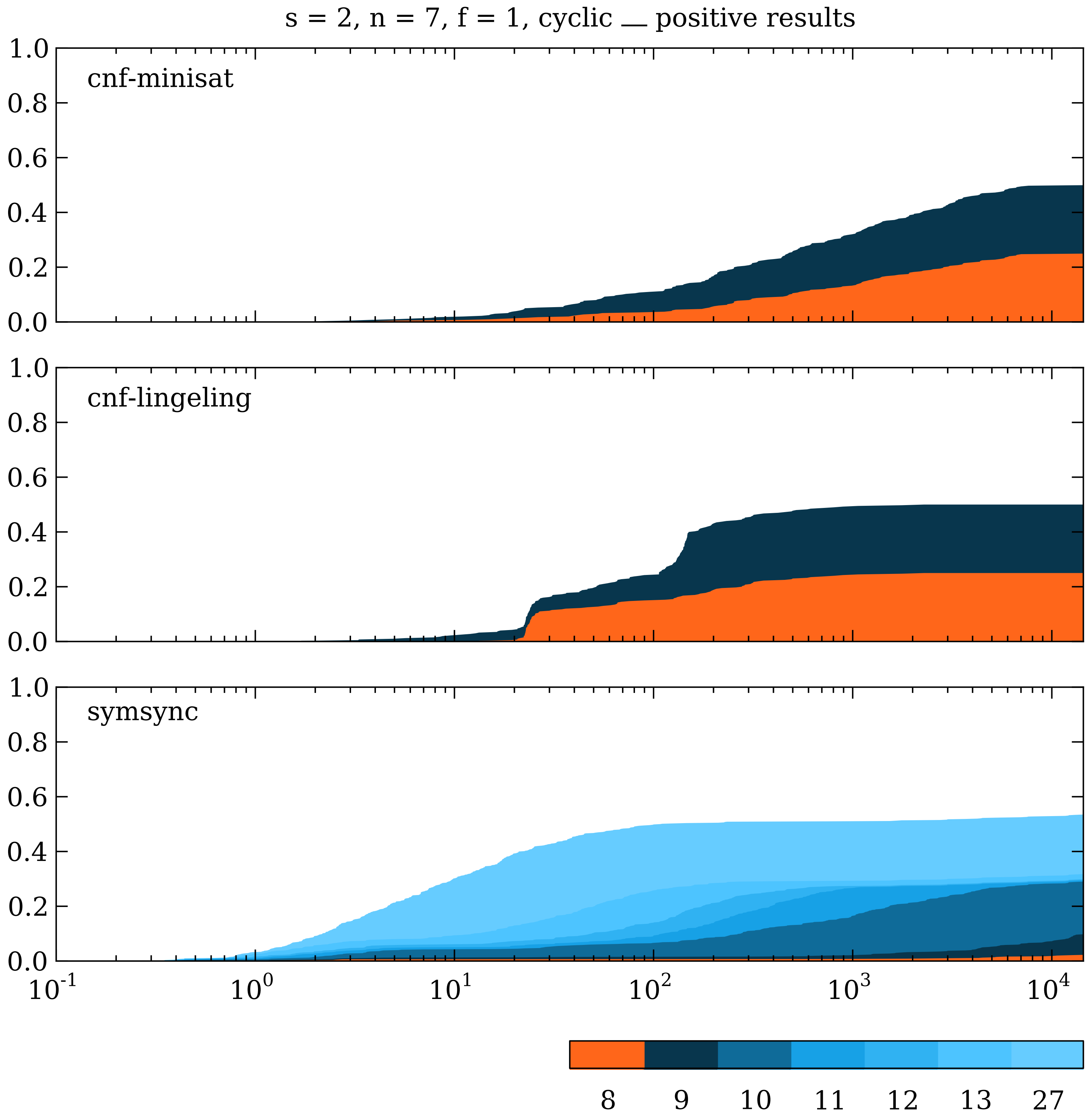

s = 2, n = 7, f = 1, cyclic — positive results
cnf-minisat
cnf-lingeling
symsync
1.0
0.8
0.6
0.4
0.2
0.0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
8
9
10
11
12
13
27

CNF encoding



guided search




s = 2, n = 7, f = 1, cyclic __ positive results
cnf-minisat
cnf-lingeling
symsync
1.0
0.8
0.6
0.4
0.2
0.0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
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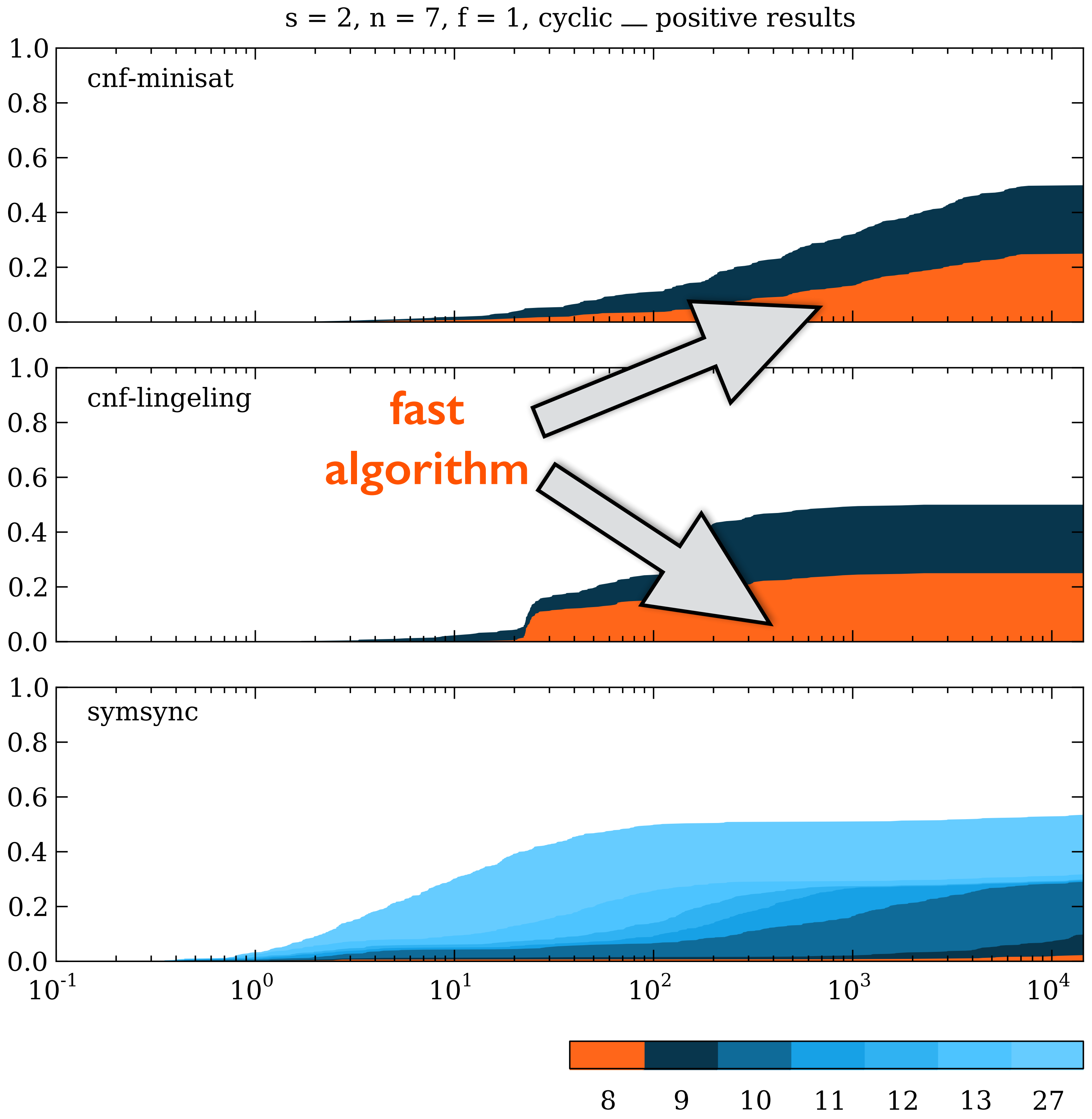
s = 2, n = 7, f = 1, cyclic — positive results
cnf-minisat
cnf-lingeling
symsync
fast
algorithm
1.0
0.8
0.6
0.4
0.2
0.0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
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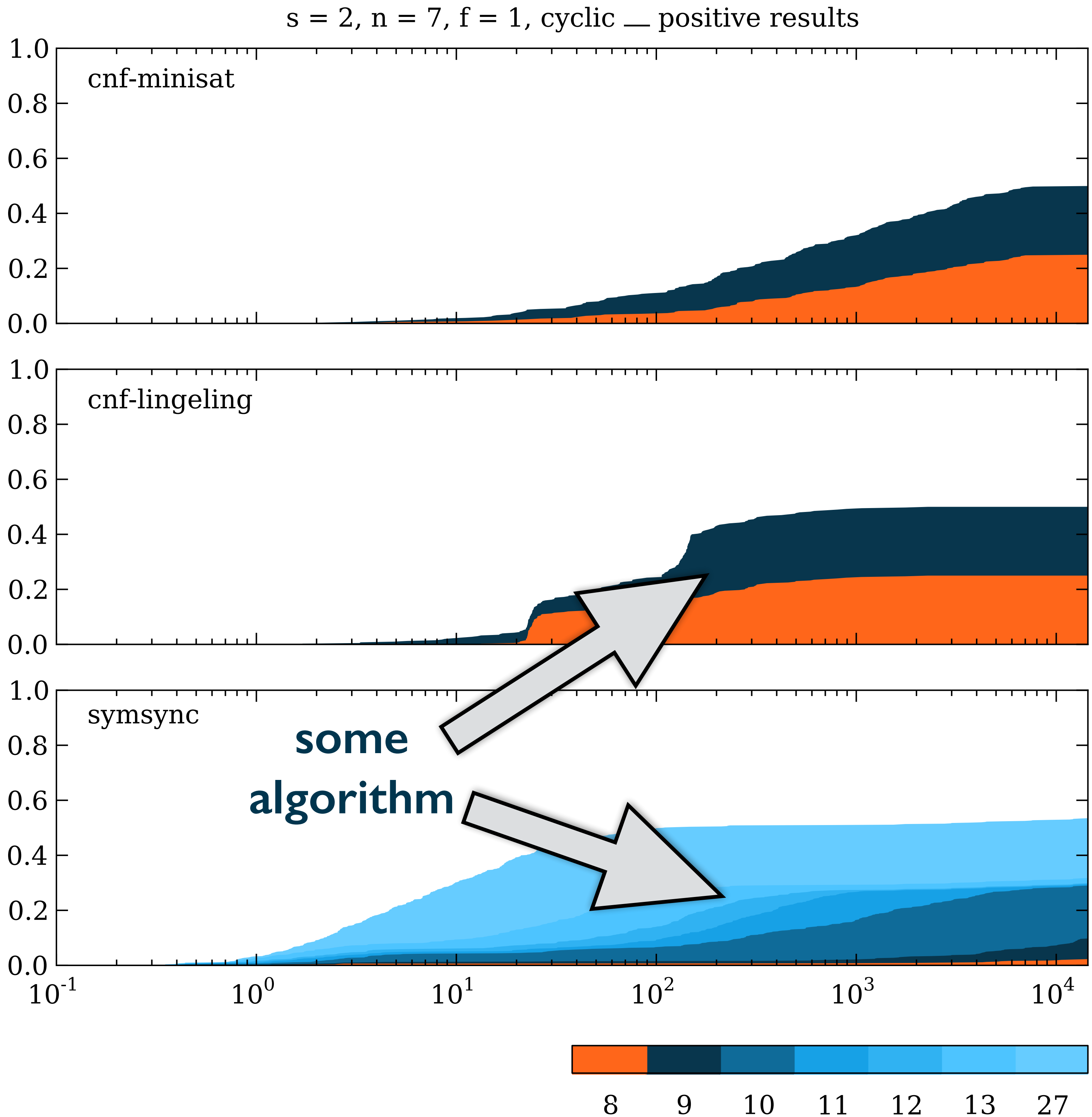
10
11
12
13
27


s = 2, n = 7, f = 1, cyclic — positive results
cnf-minisat
cnf-lingeling
symsync
some
algorithm
1.0
0.8
0.6
0.4
0.2
0.0
10-1
100
101
102
103
104
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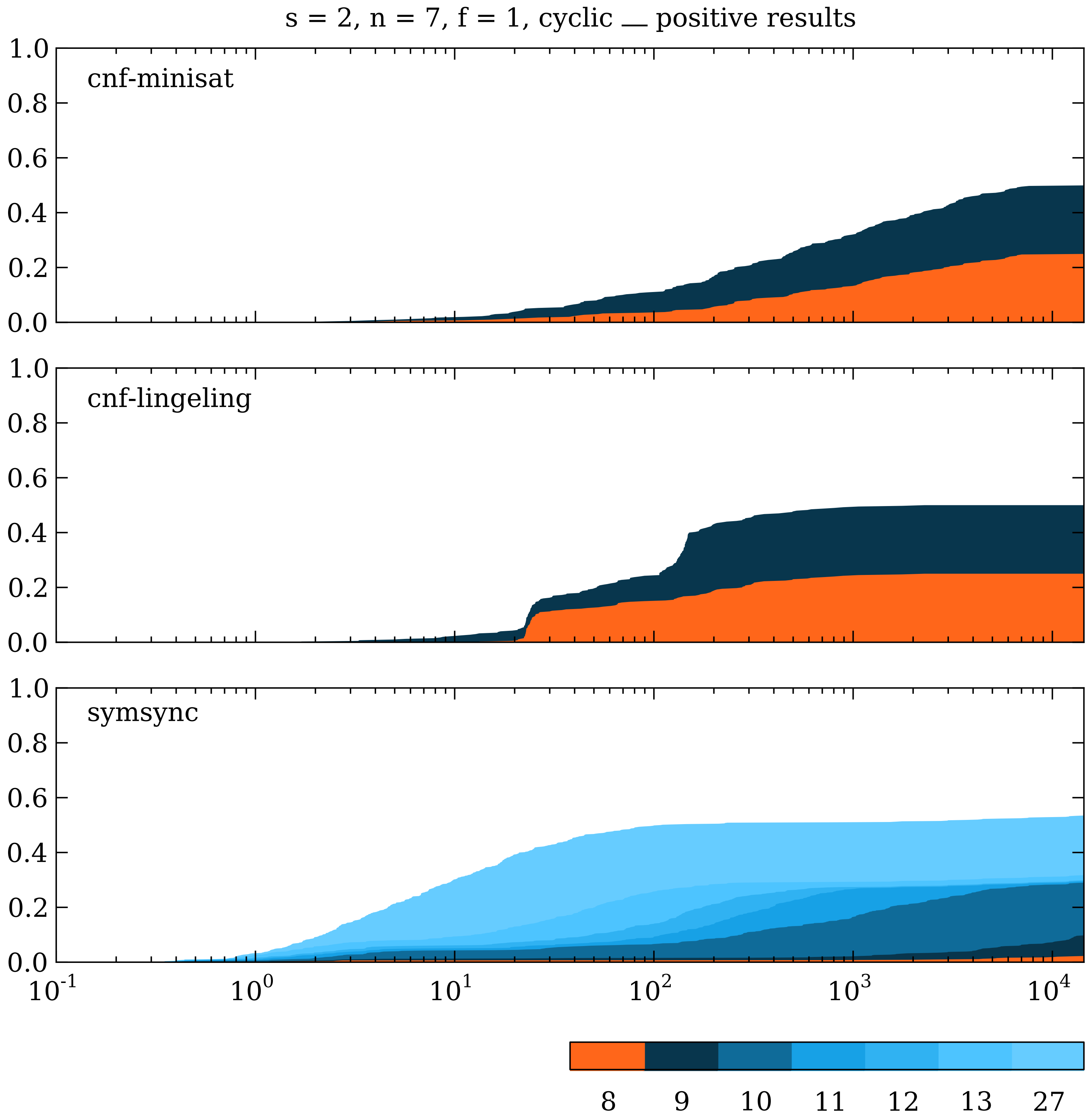
27

orange = fast algorithm

blue = some algorithm

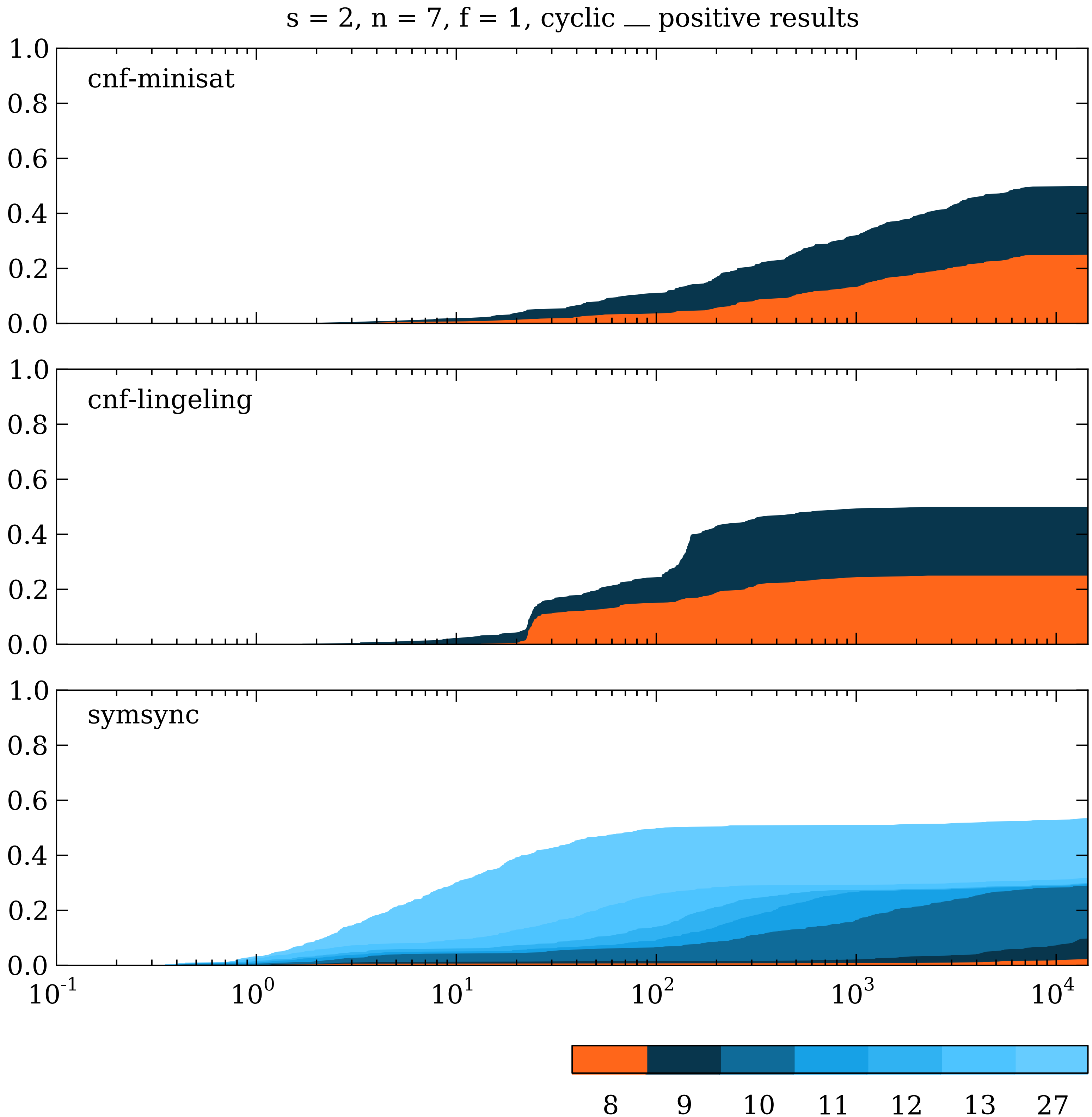


orange = fast algorithm

blue = some algorithm

SAT: finds best solutions faster

guided search: finds *some* solution faster



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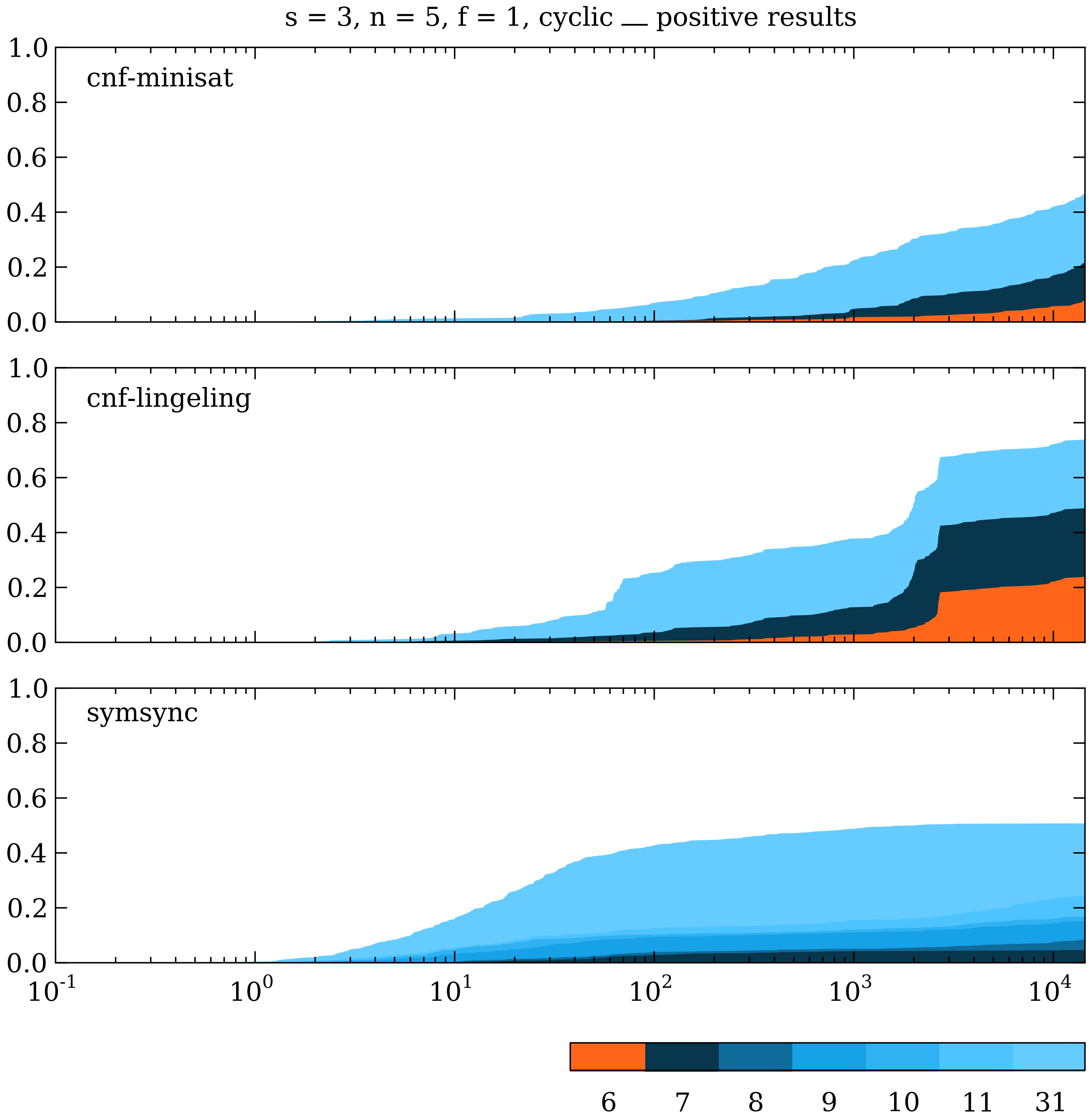

orange = fast algorithm

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SAT: finds best solutions faster

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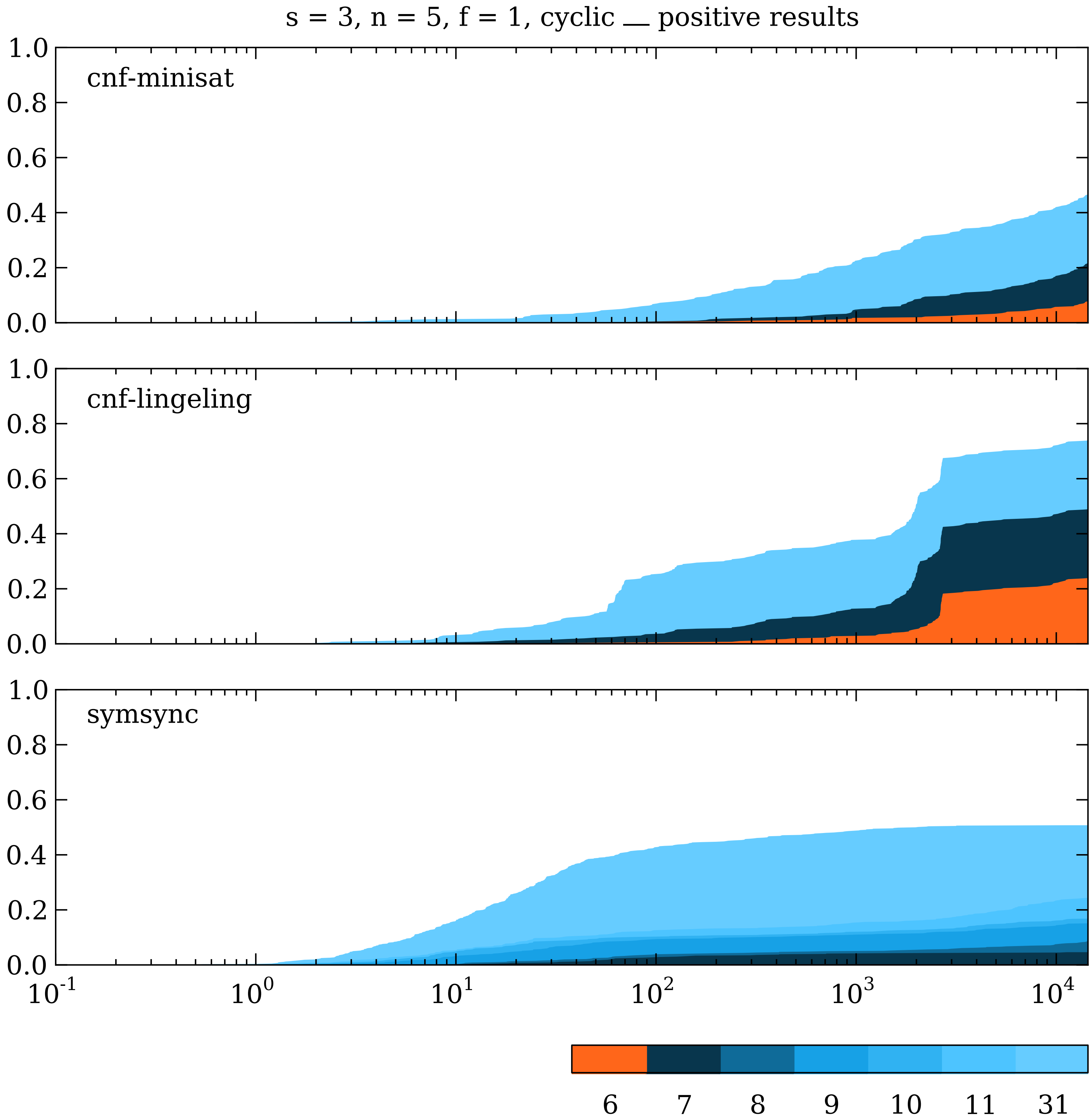
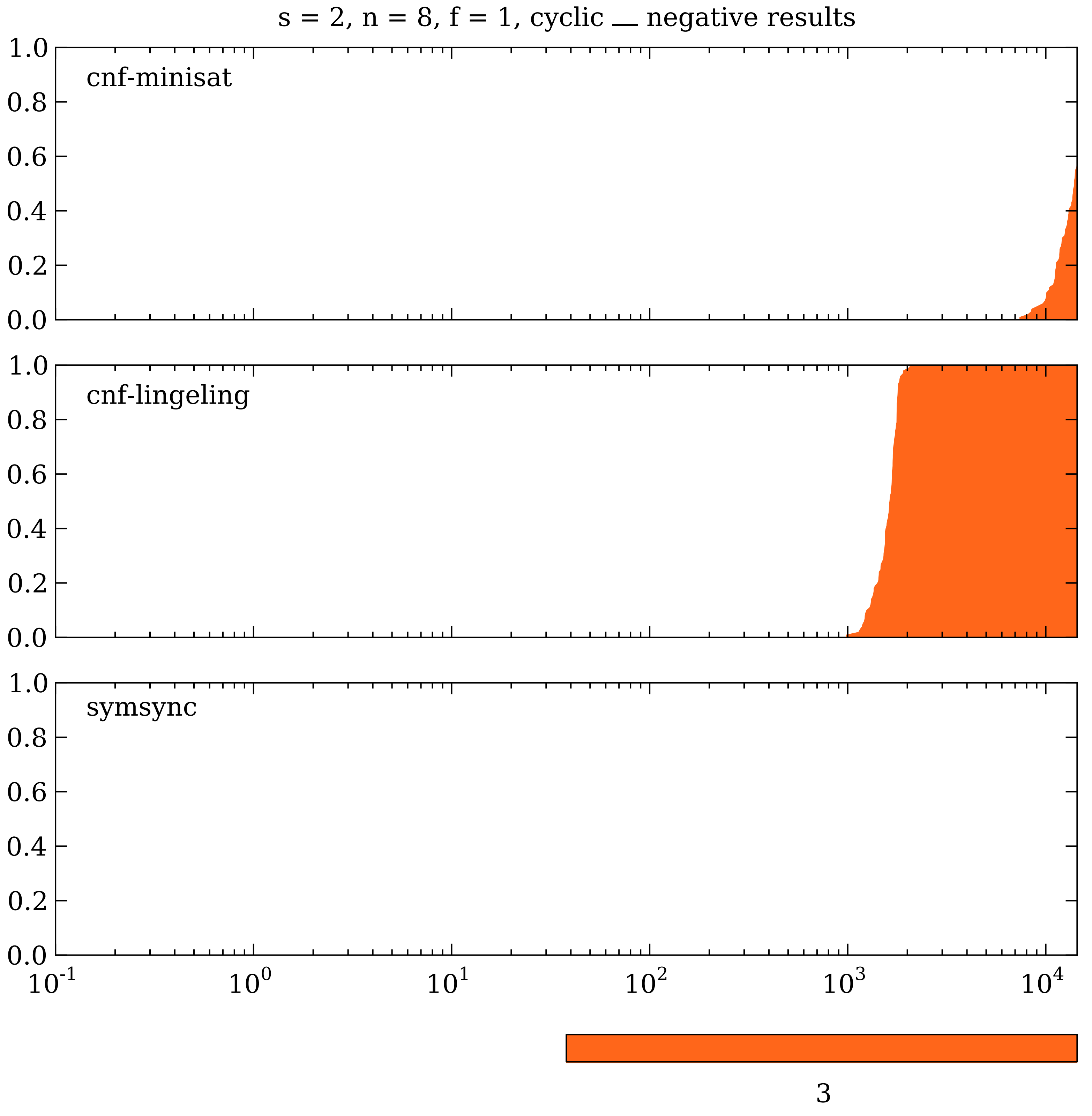


UNSAT instances



Summary

- Synthesis a tool for *theory of distributed computing*
- Results: optimal fault-tolerant algorithms
- Complementary approaches for fast synthesis

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Synthesis in our other work:

- local graph coloring
- finding large cuts **arXiv:1402.2543**

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Thanks!