Coverability in VASS Revisited: Improving Rackoff's Bound to Obtain Conditional Optimality

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About joint work with Marvin Künnemann, Filip Mazowiecki, Lia Schütze, and Karol Węgrzycki in ICALP'23.

Verification Seminar

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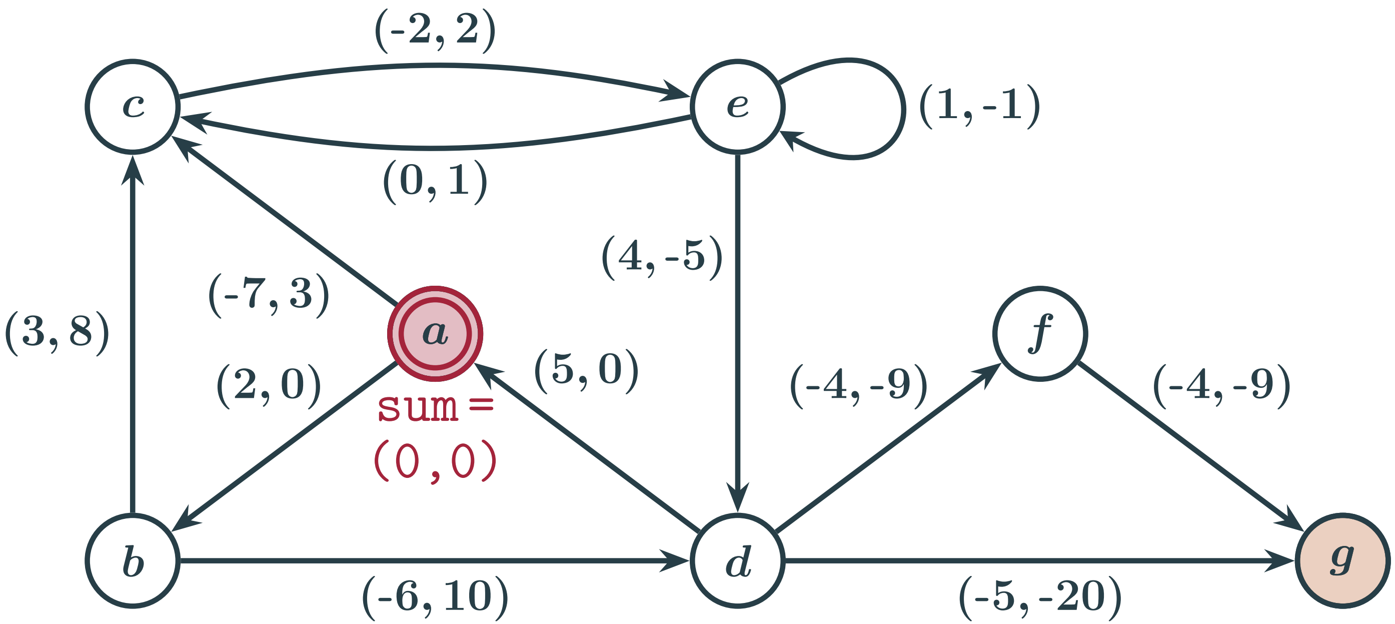
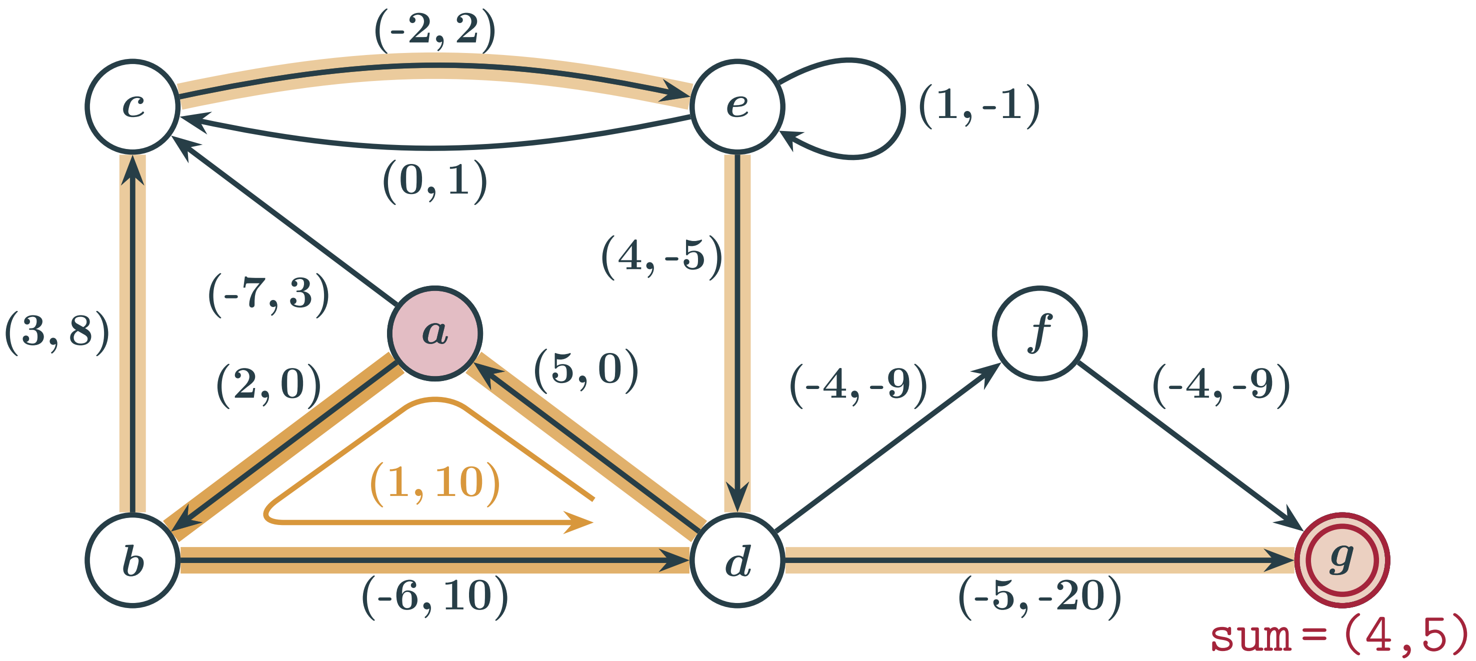
IRIF, Paris, France

Instance of Coverability in 2-Dimensional VASS



Question: from a can you reach g via a path that is *never negative on any component* ?

Instance of Coverability in 2-Dimensional VASS

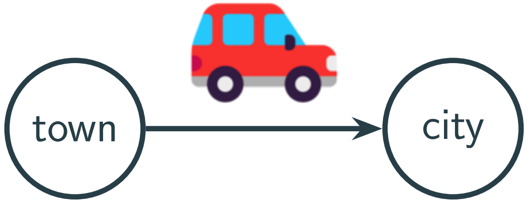


YES!

Question: from a can you reach g via a path that is *never negative on any component* ?

Motivation

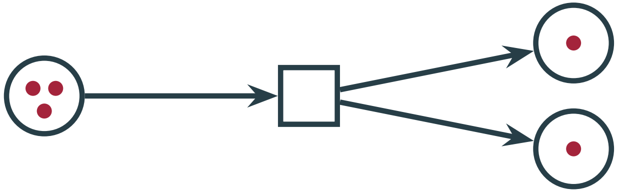
Resource Management



Road cost: $(-1\text{L fuel}, +2\text{kWh battery})$

Model of Concurrency

VASS are equivalent to Petri nets



Testing Safety

Positive instance of coverability

$\Downarrow$

Some action sequence reaches a 'bad' state

$\Downarrow$

System is unsafe!

Related Problems

Unboundedness

Reachability

Word problems for (commutative) semi-groups

Overview of this Presentation

1. The history and complexity of coverability.

2. Our improvement over Rackoff's upper bound.

   Main concepts: introducing 'thin configurations' and using Rackoff's bounding technique.

3. Obtaining an optimal space algorithm and a conditionally optimal time algorithm.

4. Our Exponential Time Hypothesis conditional lower bound.

   Main concepts: reducing clique detection to coverability and simulating bounded counter machines.

History and Complexity

$\boldsymbol{d}$ is the dimension: number of components.

$\boldsymbol{n}$ is the size: number of states plus the absolute values of all updates.
(unary encoding)

History and Complexity

Richard Lipton

Theorem: Coverability in VASS is EXPSPACE-hard. [Lipton '76]

Charles Rackoff

Theorem: Coverability in VASS is in EXPSPACE. [Rackoff '78]

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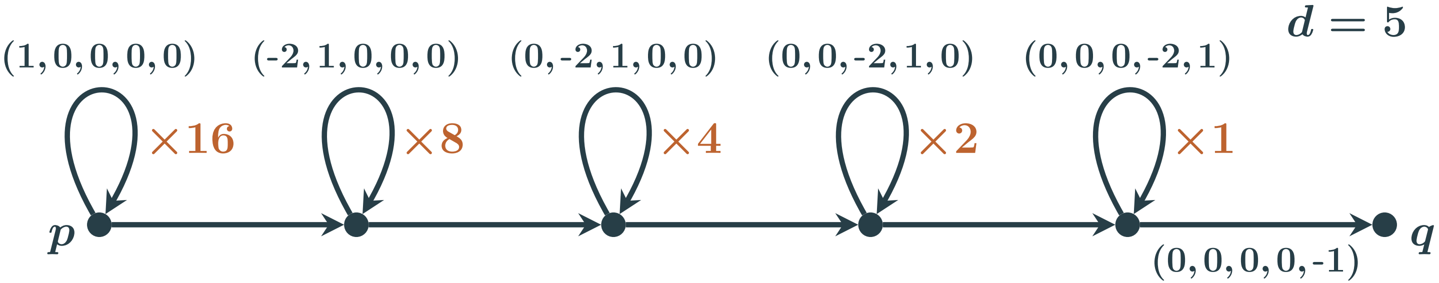
History and Complexity

Richard Lip

[Lipton '76]

Example of Long Coverability Runs



Any coverability run from p to q has length $2^{\Omega(d)}$.

d is the dimension: number of components.

n is the size: number of states plus the absolute values of all updates (unary encoding).

History and Complexity

Richard Lipton

Theorem: Coverability in VASS requires $2^{\Omega(d)} \cdot \log(n)$ space. [Lipton '76]

Idea: find instances only admitting $n^{2^{\Omega(d)}}$ length runs. *"Lipton's construction"*

Charles Rackoff

Theorem: Coverability in VASS can be decided in $2^{\mathcal{O}(d \log d)} \cdot \log(n)$ space. [Rackoff '78]

Idea: argue that there are always $n^{2^{\mathcal{O}(d \log d)}}$ length runs. *"Rackoff's bound"*

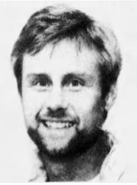
Ernst Mayr

Albert Meyer

Open Problem

Improve these bounds.

[Mayr and Meyer '82]


Louis Rosier

Hsu-Chun Yen

Refined via a multiparameter analysis.

[Rosier and Yen '85]

d is the dimension: number of components.
n is the size: number of states plus the absolute values of all updates (unary encoding).

Vector Addition Systems with(out) States

d-VASS	d-VAS
$(\boldsymbol{Q}, \boldsymbol{T})$	$(\boldsymbol{V})$
$\boldsymbol{Q}$ is a finite set of states. $\boldsymbol{T} \subseteq \boldsymbol{Q} \times \mathbb{Z}^{\boldsymbol{d}} \times \boldsymbol{Q}$ are the transitions.	$\boldsymbol{V} \subseteq \mathbb{Z}^{\boldsymbol{d}}$ is just a set of vectors.
Configurations are in $\boldsymbol{Q} \times \mathbb{N}^{\boldsymbol{d}}$.	Configurations are in $\mathbb{N}^{\boldsymbol{d}}$.

John Hopcroft

Jean-Jacques Pansiot

Lemma: A $\boldsymbol{d}$-VASS can be *simulated* by a $(\boldsymbol{d}+\boldsymbol{3})$-VAS. [Hopcroft and Pansiot '79]

Idea: maintain invariants containing information about the number of states and the current state on three dedicated additional counters.

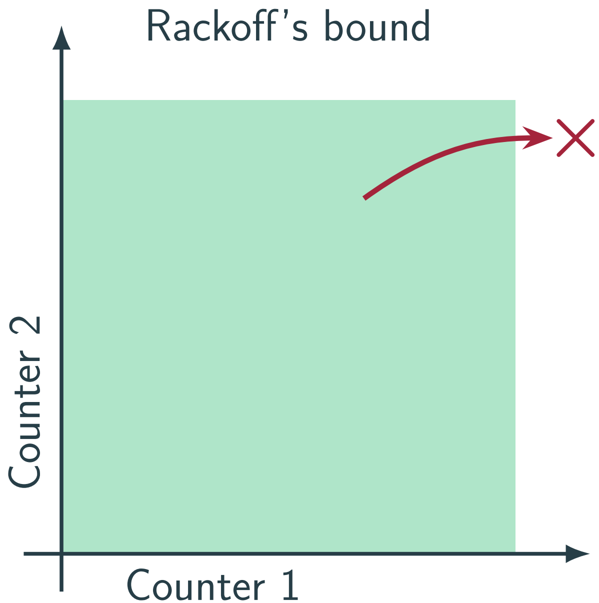
Takeaway: we will work with VAS because we do not fix the dimension.

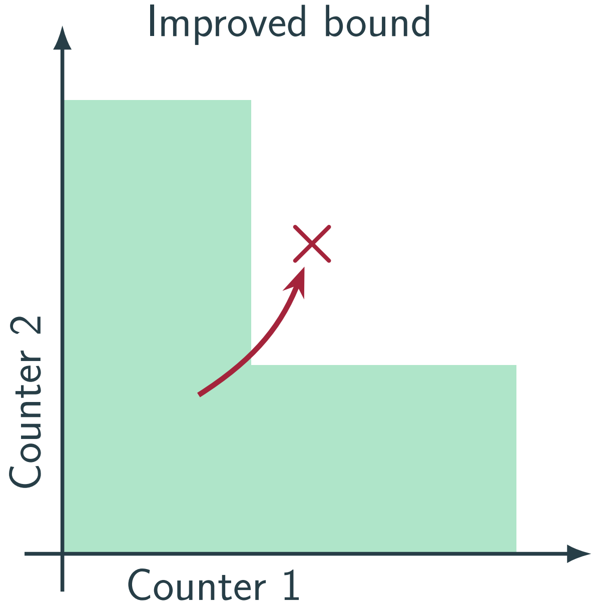
Improving Rackoff's Upper Bound

Theorem: Coverability in VASS is always witnessed by $n^{2^{\mathcal{O}(d)}}$ length runs.

[Künnemann, Mazowiecki, Schütze, S-B, and Węgrzycki '23]

Idea: Carefully use Rackoff's bounding technique with sharper counter value bounds.



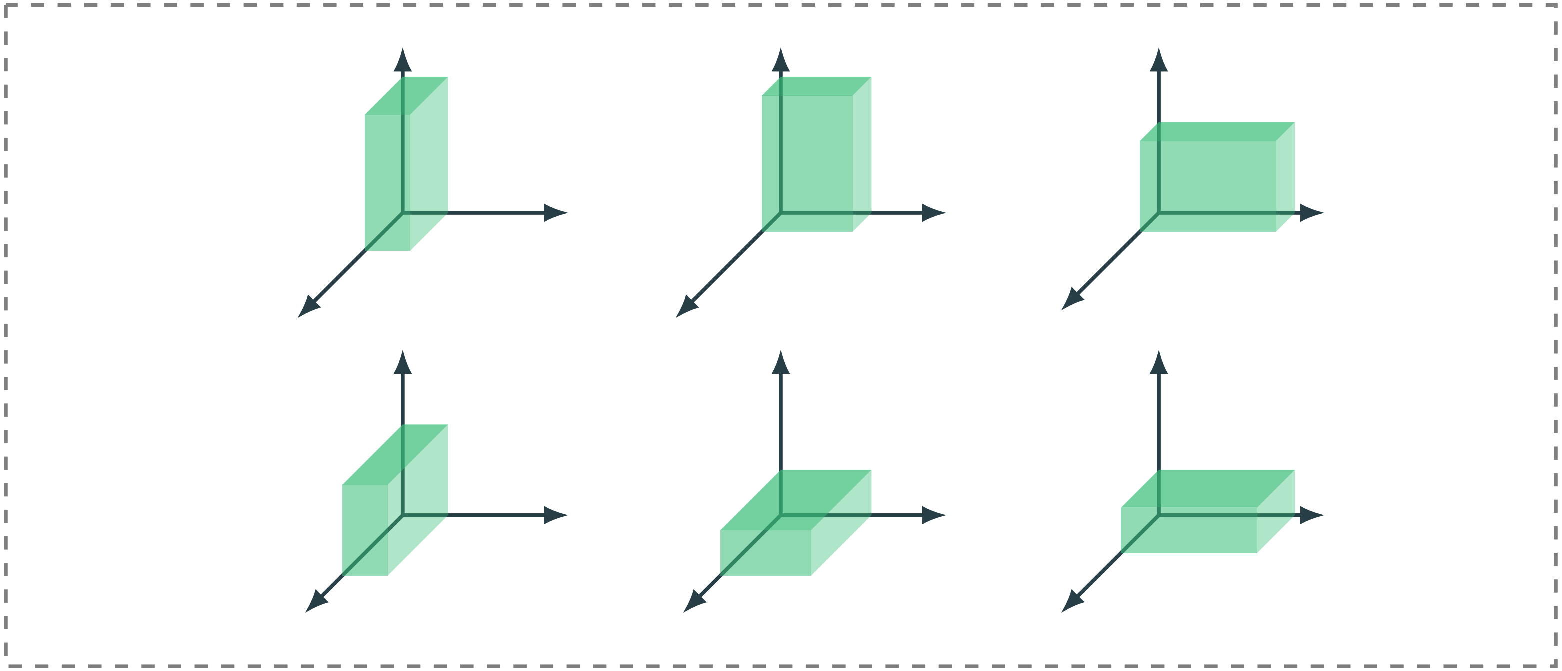


Improving Rackoff's Upper Bound

Theor

grzycki '23]

Idea: (

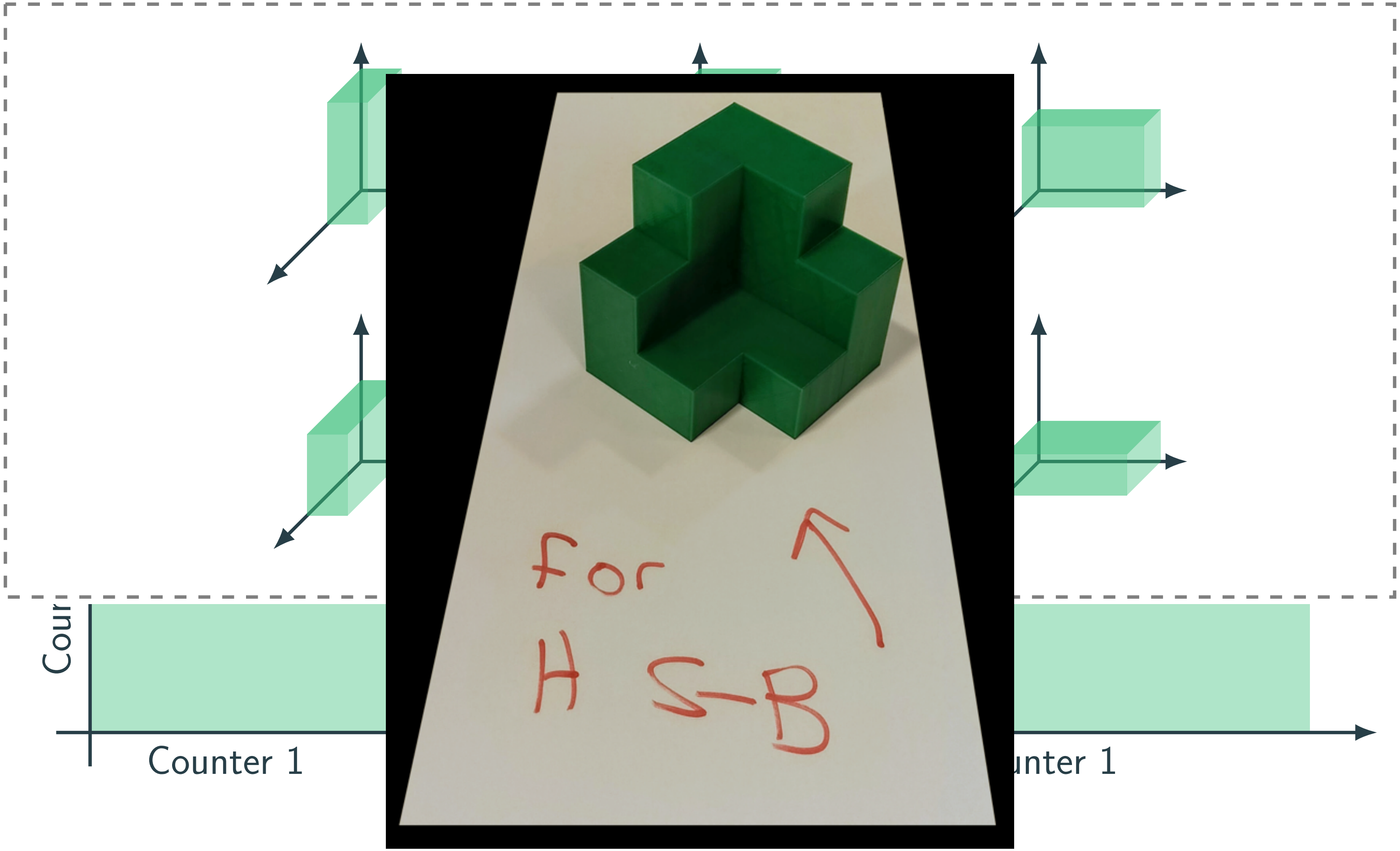


Improving Rackoff's Upper Bound

Theor

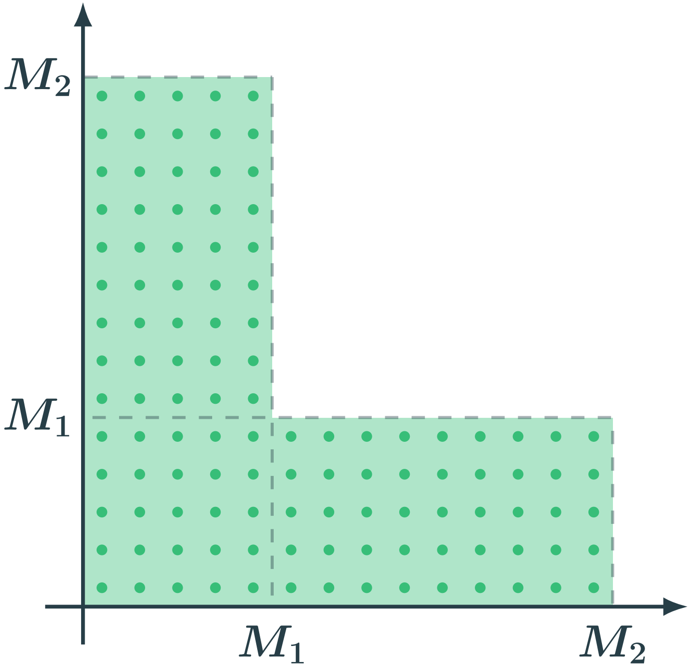
grzycki '23]

Idea:



Thin Configurations

Definition: A configuration $\vec{v} \in \mathbb{N}^d$ is *thin* if, after sorting the components, $\vec{v}[1] < M_1$, $\vec{v}[2] < M_2$, ..., $\vec{v}[d] < M_d$.



Importantly, to get an improvement over Rackoff's bound:

$M_1 << M_2 << \ldots << M_d$.

Precisely,

$M_1 = n \cdot n^{4^0}, M_2 = n \cdot n^{4^1}, \ldots, M_d = n \cdot n^{4^{d-1}}$.

How many thin configurations exist?

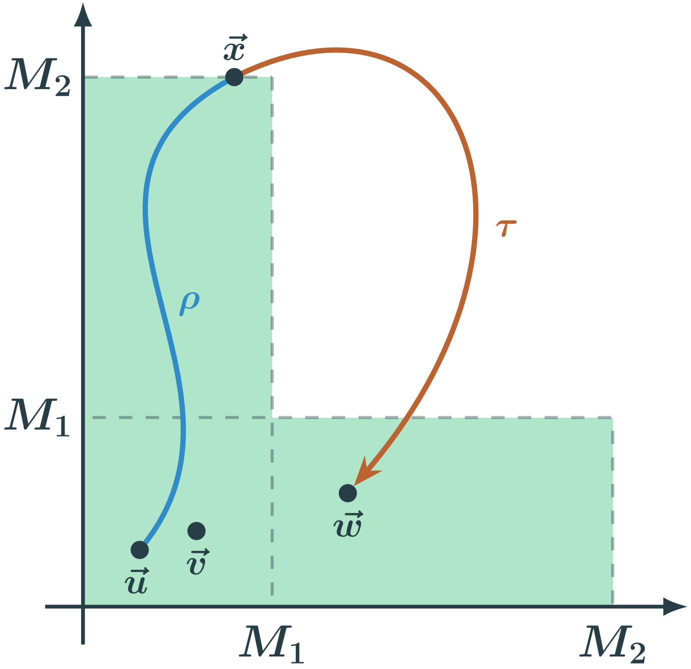
$$\leq d! \cdot M_1 \cdot M_2 \cdot \ldots \cdot M_d = d! \cdot (n \cdot n^{4^0}) \cdot (n \cdot n^{4^1}) \cdot \ldots \cdot (n \cdot n^{4^{d-1}}).$$

$$= d! \cdot n^d \cdot n^{\sum_{i=0}^{d-1} 4^i}.$$

Bounding the Length of Coverability Runs

Consider the shortest coverability run $\vec{u} \xrightarrow{\pi} \vec{w}$, where $\vec{w} \geq \vec{v}$.

Split π at first "non-thin" configuration: $\vec{u} \xrightarrow{\rho} \vec{x} \xrightarrow{\tau} \vec{w}$.



ρ is the *thin part* of the run, its length is bounded by the number of thin configurations.

Claim 1: $\mathit{len}(\rho) \leq d! \cdot n^d \cdot n^{\sum_{i=0}^{d-1} 4^i}$.

Proof idea: there cannot be any zero effect cycles in π.

τ is the *tail* of the run, at least one component had a large value at $\vec{x}$, so can then be 'ignored'.

Claim 2: $\mathit{len}(\tau) \leq n^{4^{d-1}}$.

Using Rackoff's Inductive Technique

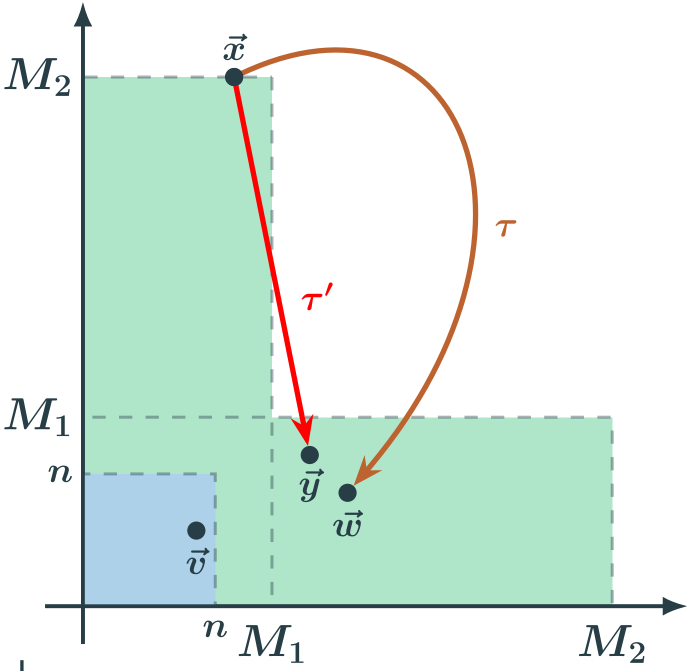
Claim 2: $\mathit{len}(\tau) \leq n^{4^{d-1}}$. **(Proof by induction on d)**

Sort the components $\vec{x}[1] \leq \vec{x}[2] \leq \ldots \leq \vec{x}[d]$.

There exists $i \in \{1, \ldots, d\}$ such that $M_i \leq \vec{x}[i]$.

Moreover, $M_i = n \cdot n^{4^{i-1}} \leq \vec{x}[i] \leq \ldots \leq \vec{x}[d]$.

Example: $\vec{x}[1] < M_1$ but $\vec{x}[2] \geq M_2$.



Use induction, focussing just on the first $i - 1$ components.

There is an alternative suffix τ' with $\mathit{len}(\tau') \leq n^{4^{i-1}}$ and

$$(x[1], \ldots, x[i-1]) \xrightarrow{\tau'} (\vec{y}[1], \ldots, \vec{y}[i-1]) \geq (\vec{v}[1], \ldots, \vec{v}[i-1]).$$

We know that τ' has at least $-n \cdot (\mathit{len}(\tau') - 1)$ effect on each of the remaining components. Fortunately, $(n \cdot n^{4^{i-1}}, \ldots, n \cdot n^{4^{i-1}}) \leq (\vec{x}[i], \ldots, \vec{x}[d])$.

So, $(\vec{x}[i], \ldots, \vec{x}[d]) \xrightarrow{\tau'} (\vec{y}[i], \ldots, \vec{y}[d]) \geq (n, \ldots, n) \geq (\vec{v}[i], \ldots, \vec{v}[d])$.

Proof of Main Theorem

Theorem: Coverability in VASS is always witnessed by $n^{2^{\mathcal{O}(d)}}$ length runs.

[Künnemann, Mazowiecki, Schütze, S-B, and Węgrzycki '23]

Proof: Let π be the shortest run witnessing coverability.

$$\begin{aligned}
\mathit{len}(\pi) &= \mathit{len}(\rho) + \mathit{len}(\tau) \\
&\leq d! \cdot n^d \cdot n^{\Sigma_{i=0}^{d-1} 4^i} + n^{4^{d-1}} && \text{(By **Claim 1** and **Claim 2**)} \\
&\leq 2 \cdot d! \cdot n^d \cdot n^{\Sigma_{i=0}^{d-1} 4^i} \\
&\leq n^{2^d} \cdot n^{\Sigma_{i=0}^{d-1} 4^i} && \text{(when } n \geq 2, \quad 2 \cdot d! \cdot n^d \leq n^{2^d} \text{)} \\
&\leq n^{4^d} && \text{(when } d \geq 1, \quad 2^d + \Sigma_{i=0}^{d-1} 4^i \leq 4^d \text{)} \\
&= n^{2^{2d}} = n^{2^{\mathcal{O}(d)}}.
\end{aligned}$$

□

Algorithms for Coverability

Theorem: Coverability in VASS is always witnessed by $n^{2^{\mathcal{O}(d)}}$ length runs.

[Künnemann, Mazowiecki, Schütze, S-B, and Węgrzycki '23]

Corollary 1: Coverability in VASS can be decided in $2^{\mathcal{O}(d)} \cdot \log(n)$ space. **OPTIMAL!**

Proof idea: Nondeterministically search through the configuration space, each configuration can be expressed with $2^{\mathcal{O}(d)} \cdot \log(n)$ bits.

Corollary 2: Coverability in VASS can be decided in $n^{2^{\mathcal{O}(d)}}$ time. **CONDITIONALLY OPTIMAL!**

Proof idea: Deterministically search through the configuration space.

Conditionally Optimal Time Bound

Corollary 2: Coverability in VASS can be decided in $n^{2^{\mathcal{O}(d)}}$ time.

Theorem: Assuming the Exponential Time Hypothesis, coverability in VASS requires $n^{2^{\Omega(d)}}$ time.

[Künnemann, Mazowiecki, Schütze, S-B, and Węgrzycki '23]

Idea: Reduce detecting a 2^d-clique in a 2^d-partite n-vertex directed graph to coverability.

Conjecture (Exponential Time Hypothesis): 3-SAT with k-variables requires $2^{\Omega(k)}$ time.

$$\Downarrow$$

Detecting whether there is a k-clique in a k-partite n-vertex graph requires $n^{\Omega(k)}$ time.

[Chen, Chor, Fellows, Huang, Juedes, Kanj, and Xia '05]

[Chen, Huang, Kanj, and Xia '06]

[Cygan, Fomin, Kowalik, Lokshtanov, Marx, Ma. Pilipczuk, and Mi. Pilipczuk '15]

Bounded Two-Counter Machines

Idea: Reduce detecting a 2^d-clique in a 2^d-partite n-vertex directed graph to coverability.

First, reduce to coverability in a $n^{2^{\mathcal{O}(d)}}$-bounded two-counter machine.

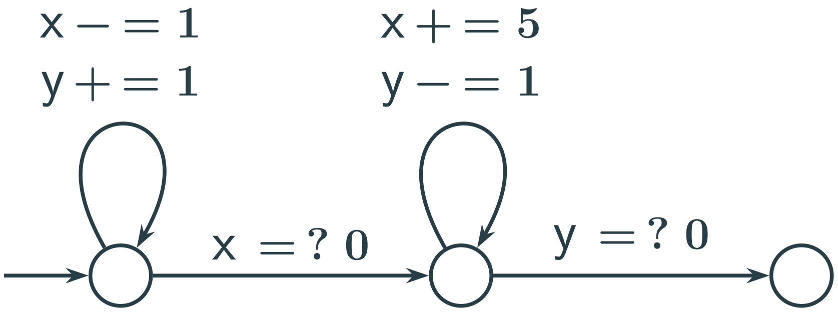
Then, simulate a $n^{2^{\mathcal{O}(d)}}$-bounded two-counter machine using an $\mathcal{O}(n)$-state $\mathcal{O}(d)$-VASS.

An **$n^{2^{\mathcal{O}(d)}}$-bounded two-counter machine** has two counters $\mathsf{x}, \mathsf{y} \in \{0, 1, \ldots, n^{2^{\mathcal{O}(d)}}\}$ that can be added to ($\mathsf{x} \mathrel{+}= 2$), subtracted from ($\mathsf{y} \mathrel{-}= 3$), and zero-tested ($\mathsf{x} =? \, 0$).

Pre: $\mathsf{x} = x, \ \mathsf{y} = 0$

```
1. LOOP ($\mathsf{x} \mathrel{-}= 1, \mathsf{y} \mathrel{+}= 1$)
2. $\mathsf{x} =? \, 0$
3. LOOP ($\mathsf{x} \mathrel{+}= 5, \mathsf{y} \mathrel{-}= 1$)
4. $\mathsf{y} =? \, 0$
```

Post: $\mathsf{x} = x \cdot 5, \ \mathsf{y} = 0$



MULTIPLY(x, 5)

Bounded Two-Counter Machines

Idea: Reduce detecting a 2^d-clique in a 2^d-partite n-vertex directed graph to coverability.

First, reduce to coverability in a $\boxed{n^{2^{\mathcal{O}(d)}}\text{-bounded two-counter machine.}}$

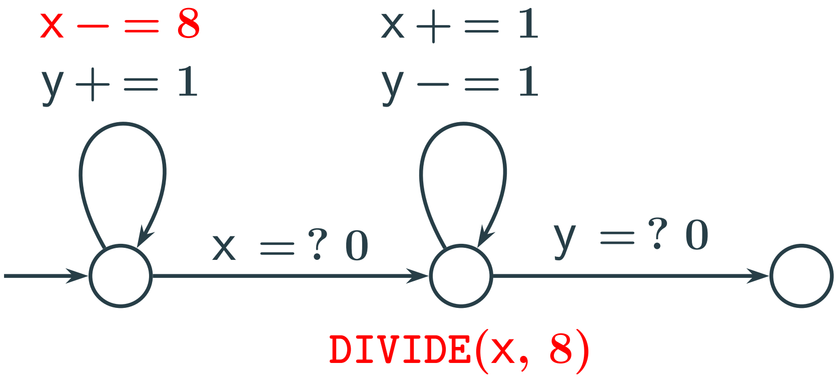
Then, simulate a $\boxed{n^{2^{\mathcal{O}(d)}}\text{-bounded two-counter machine}}$ using an $\mathcal{O}(n)$-state $\mathcal{O}(d)$-VASS.

An **$n^{2^{\mathcal{O}(d)}}$-bounded two-counter machine** has two counters $\mathsf{x}, \mathsf{y} \in \{0, 1, \ldots, n^{2^{\mathcal{O}(d)}}\}$ that can be added to ($\mathsf{x} \mathrel{+}= 2$), subtracted from ($\mathsf{y} \mathrel{-}= 3$), and zero-tested ($\mathsf{x} =? 0$).

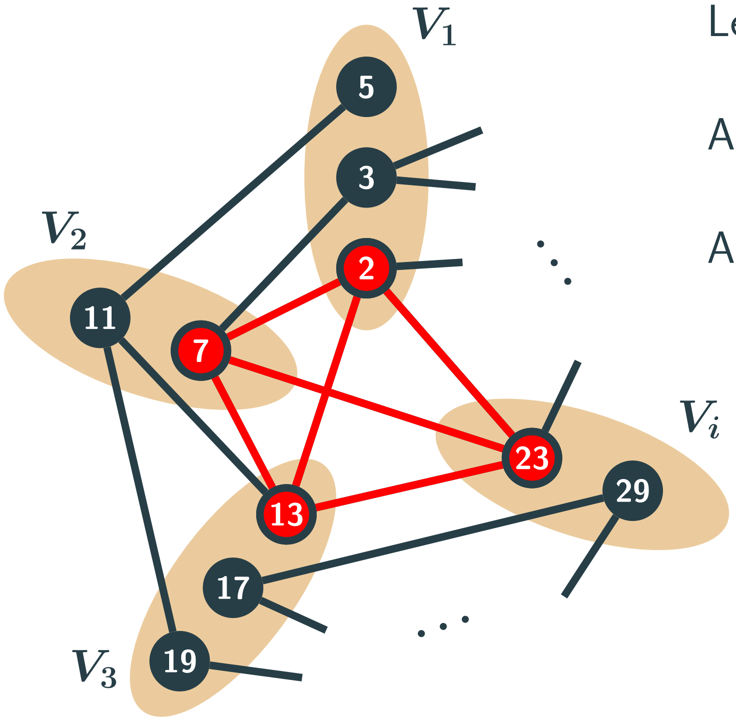
Pre: $\mathsf{x} = x,\ \mathsf{y} = 0$

```
1. LOOP ($\mathsf{x} \mathrel{-}= 8, \mathsf{y} \mathrel{+}= 1$)
2. $\mathsf{x} =? 0$
3. LOOP ($\mathsf{x} \mathrel{+}= 1, \mathsf{y} \mathrel{-}= 1$)
4. $\mathsf{y} =? 0$
```

Post: $\mathsf{x} = x \div 8, \mathsf{y} = 0$



Detecting Cliques using Divisibility Tests



Let $(V_1 \cup V_2 \cup \cdots \cup V_k, E)$ be a k-partite n-vertex graph.

Associate the first n primes with the verticies.

A candidate k-clique is represented by a product of k primes.

Example: $c = 2 \cdot 7 \cdot 13 \cdot \ldots \cdot 23$.

To check if v represents a clique, use divisibility tests to verify all nodes are adjacent.

Example: $(2 \cdot 7)|c\,?$ $(2 \cdot 13)|c\,?$ $(7 \cdot 13)|c\,?$ $\ldots$
$(2 \cdot 23)|c\,?$ $(7 \cdot 23)|c\,?$ $(13 \cdot 23)|c\,?$

There exist $p_1 \in \text{Primes}(V_1), \ldots, p_k \in \text{Primes}(V_k)$ such that for every pair $1 \leq i < j \leq k$, there is an edge $\{p, q\} \in (V_i \times V_j) \cap E$ such that $(p \cdot q) \mid p_1 \cdot \ldots \cdot p_k \iff$ there exists a k-clique.

Bounded Two-Counter Machine Implementation

There e $\boldsymbol{k}$, there

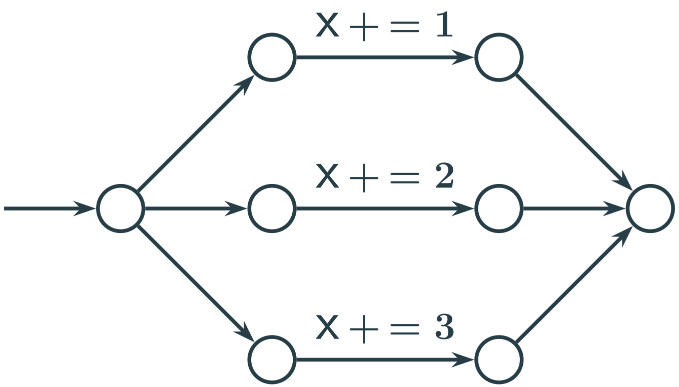
is an ec $\boldsymbol{k}$-clique.

Guessing with Nondeterministic Branching

Pre: $\mathsf{x} = x$

```
1. GUESS: $c \in \{1, 2, 3\}$
2. $\mathsf{x} += c$
```

Post: $\mathsf{x} = x + 1$, or
$\mathsf{x} = x + 2$, or
$\mathsf{x} = x + 3$.



Bounded Two-Counter Machine Implementation

There exist $p_1 \in \text{Primes}(V_1), \ldots, p_k \in \text{Primes}(V_k)$ such that for every pair $1 \leq i < j \leq k$, there is an edge $\{p, q\} \in (V_i \times V_j) \cap E$ such that $(p \cdot q) \mid p_1 \cdot \ldots \cdot p_k \iff$ there exists a k-clique.

Part one: Guess a candidate clique.

Pre: $\mathtt{x} = 1,\ \mathtt{y} = 0$.

```
    1.  GUESS: $p_1 \in \text{Primes}(V_1)$
    2.  MULTIPLY(x, $p_1$)
        ⋮
 2k-1.  GUESS: $p_k \in \text{Primes}(V_k)$
   2k.  MULTIPLY(x, $p_k$)
```

Post: $\mathtt{x} = p_1 \cdot \ldots \cdot p_k,\ \mathtt{y} = 0$.

This two-counter program terminates

$\iff$ there exists a k-clique.

Part two: Check the candidate is a clique.

Pre: $\mathtt{x} = p_1 \cdot \ldots \cdot p_k,\ \mathtt{y} = 0$.

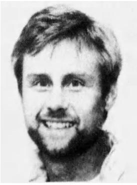
```
       1.  GUESS: $\{p_1, p_2\} \in (V_1 \times V_2) \cap E$
       2.  DIVIDE(x, $p_1 \cdot p_2$)
       3.  MULTIPLY(x, $p_1 \cdot p_2$)
           ⋮
 <3k$^2$.  GUESS: $\{p_{k-1}, p_k\} \in (V_{k-1} \times V_k) \cap E$
 <3k$^2$.  DIVIDE(x, $p_{k-1} \cdot p_k$)
 <3k$^2$.  MULTIPLY(x, $p_{k-1} \cdot p_k$)
```

Post: $\mathtt{x} = p_1 \cdot \ldots \cdot p_k,\ \mathtt{y} = 0$.

VASS can Simulate Bounded Two-Counter Machines

Counter bound of k-clique detecting two-counter machine: $\mathcal{O}(p_{\mathsf{max}}^k) \leq \mathcal{O}(n^k \log(n)^k) \leq \mathcal{O}(n^{2k})$.

Size of k-clique detecting two-counter machine: $\mathcal{O}(n^{11}) \leq \mathit{poly}(n)$.


Louis Rosier

Hsu-Chun Yen

Lemma: In *poly*(n) time, one can construct a $\mathcal{O}(\log(k))$-VASS that can *simulate* an $\mathcal{O}(n^k)$-bounded $\mathcal{O}(1)$-counter machine of *poly*(n) size.

[Rosier and Yen '85]

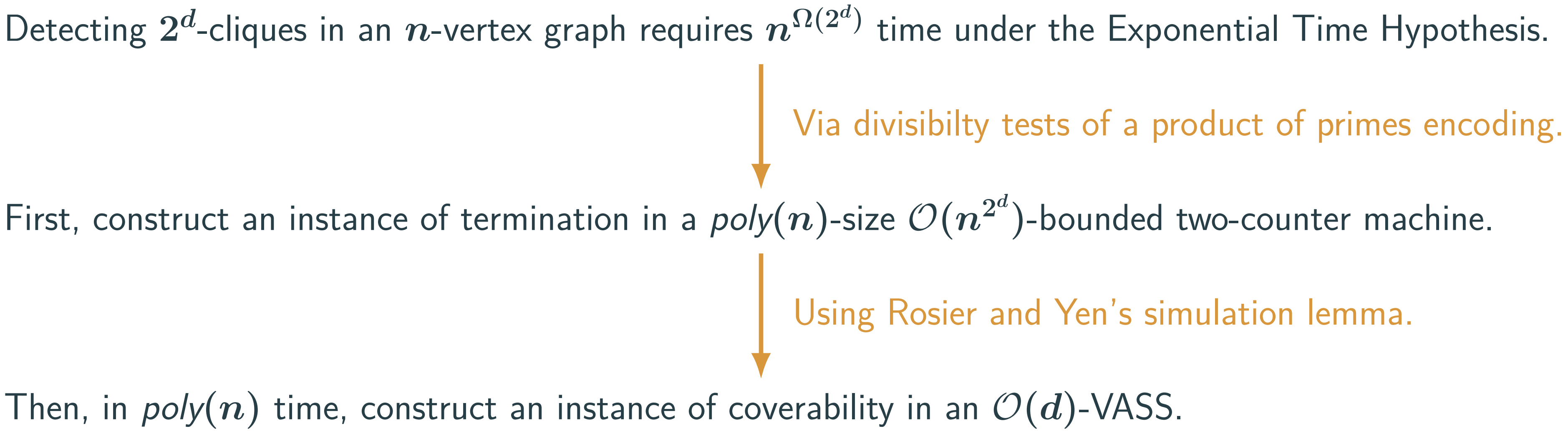
If we set $k = 2^d$, the *poly*(n)-size two-counter machine for detecting 2^d-cliques is $\mathcal{O}(n^{2^d})$-bounded.

$\implies$ In *poly*(n) time, one can construct an $\mathcal{O}(d)$-VASS for detecting 2^d-cliques.

Remark: Here, termination is coverability.

"Can I get to the end of the program with any (at least zero) value on each of the counters?"

Reducing to Coverability in VASS



Detecting 2^d-cliques in an n-vertex graph requires $n^{\Omega(2^d)}$ time under the Exponential Time Hypothesis.

Via divisibilty tests of a product of primes encoding.

First, construct an instance of termination in a *poly*(n)-size $\mathcal{O}(n^{2^d})$-bounded two-counter machine.

Using Rosier and Yen's simulation lemma.

Then, in *poly*(n) time, construct an instance of coverability in an $\mathcal{O}(d)$-VASS.

Theorem: Assuming the Exponential Time Hypothesis, coverability in VASS requires $n^{2^{\Omega(d)}}$ time.

[Künnemann, Mazowiecki, Schütze, S-B, and Węgrzycki '23]

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Theorem: Coverability in VASS is always witnessed by $n^{2^{\mathcal{O}(d)}}$ length runs.

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Corollary 1: Coverability in VASS can be decided in $2^{\mathcal{O}(d)} \cdot \log(n)$ space. **OPTIMAL!**

Corollary 2: Coverability in VASS can be decided in $n^{2^{\mathcal{O}(d)}}$ time. **CONDITIONALLY OPTIMAL!**

Theorem: Assuming the Exponential Time Hypothesis, coverability in VASS requires $n^{2^{\Omega(d)}}$ time.

[Künnemann, Mazowiecki, Schütze, S-B, and Węgrzycki '23]

Thank You!

Presented by Henry Sinclair-Banks, University of Warwick, UK

Verification Seminar in IRIF, Paris, France

DIMAP

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Established by the European Commission

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