How Limited Interaction Hinders Real Communication (and What it Means for Proof and Circuit Complexity)

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Proof Complexity

Setup

Prove CNF formula unsatisfiable.

Present proof on board.

- Write down axiom clauses
- Infer new clauses

$$\frac{C \lor x \qquad D \lor \overline{x}}{C \lor D}$$

- Erase clauses to save space

Goal: derive empty clause $\perp$

$$F = \{x \lor y,\ \overline{x} \lor y,\ \overline{y}\}$$

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$x \vee y$

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$x \lor y$

$\overline{x} \lor y$

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$x \vee y$
$\overline{x} \vee y$
y

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~~$x \lor y$~~

$\overline{x} \lor y$

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~~$\overline{x} \lor y$~~

y

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y

$\overline{y}$

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$$y$$
$$\overline{y}$$
$$\perp$$

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$$F = \{x \vee y,\ \overline{x} \vee y,\ \overline{y}\}$$

y

$\overline{y}$

$\perp$

Questions

- How much time will this take? (Length)
- How large is the blackboard? (Space)

Proof Systems

Resolution

- Logic reasoning
- Most current SAT solvers
- Very well understood
  - Strong length lower bounds
  - Strong space lower bounds
  - Wide range of trade-offs

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  - Wide range of trade-offs

Cutting planes

- Pseudoboolean reasoning
- Experimental solvers
- Not well understood
  - Strong length lower bound
  - Weak space lower bounds
  - Some trade-offs

Cutting Planes

Work with inequalities

$x \vee \overline{y} \quad \rightarrow \quad x + (1 - y) \geq 1 \quad \rightarrow \quad x - y \geq 0$

Cutting Planes

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$$x \vee \overline{y} \quad \rightarrow \quad x + (1 - y) \geq 1 \quad \rightarrow \quad x - y \geq 0$$

Rules

Variable axioms

$$\frac{}{x \geq 0} \qquad \frac{}{-x \geq -1}$$

Addition

$$\frac{\sum a_i x_i \geq a \qquad \sum b_i x_i \geq b}{\sum (a_i + b_i) x_i \geq a + b}$$

Division

$$\frac{\sum a_i x_i \geq a}{\sum (a_i / k) x_i \geq \lceil a/k \rceil}$$

Cutting Planes

Work with inequalities

$$x \vee \overline{y} \quad \rightarrow \quad x + (1 - y) \geq 1 \quad \rightarrow \quad x - y \geq 0$$

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Division

$$\frac{\sum a_i x_i \geq a}{\sum (a_i / k) x_i \geq \lceil a/k \rceil}$$

Goal: derive $0 \geq 1$

Complexity Measures

Length

$y + x \geq 1$	$y + x \geq 1$ $y - x \geq 0$	$y + x \geq 1$ $y - x \geq 0$ $2y \geq 1$	$y + x \geq 1$ $y - x \geq 0$ $2y \geq 1$ $y \geq 1$	~~$y + x \geq 1$~~ ~~$y - x \geq 0$~~ ~~$2y \geq 1$~~ $y \geq 1$	$y \geq 1$ $-y \geq 0$	$y \geq 1$ $-y \geq 0$ $0 \geq 1$
1	2	3	4		5	6

Length of a proof: # Lines

Length of refuting a formula: $\min$ over all proofs

Worst case $\exp(\Omega(N^{\epsilon}))$. [Pudlák '97]

Complexity Measures

Size

$y + x \geq 1$	$y + x \geq 1$ $y - x \geq 0$	$y + x \geq 1$ $y - x \geq 0$ $2y \geq 1$	$y + x \geq 1$ $y - x \geq 0$ $2y \geq 1$ $y \geq 1$	~~$y + x \geq 1$~~ ~~$y - x \geq 0$~~ ~~$2y \geq 1$~~ $y \geq 1$	$y \geq 1$ $-y \geq 0$	$y \geq 1$ $-y \geq 0$ $0 \geq 1$
5	10	13	16		19	20

Size of a proof: # Bits

Size of refuting a formula: $\min$ over all proofs

Size $\exp(\mathrm{O}(N))$ always possible.

Complexity Measures

Line Space

[Esteban, Torán '99] [Alekhnovich, Ben Sasson, Razborov, Wigderson '00]

$y + x \geq 1$	$y + x \geq 1$	$y + x \geq 1$	$y + x \geq 1$	~~$y + x \geq 1$~~	$y \geq 1$	$y \geq 1$
	$y - x \geq 0$	$y - x \geq 0$	$y - x \geq 0$	~~$y - x \geq 0$~~	$-y \geq 0$	$-y \geq 0$
		$2y \geq 1$	$2y \geq 1$	~~$2y \geq 1$~~		$0 \geq 1$
			$y \geq 1$	$y \geq 1$		
1	2	3	4	1	2	3

Line Space of a proof: $\max$ lines in configuration (whiteboard)

Line Space of refuting a formula: $\min$ over all proofs

Line Space 5 always possible. [Galesi, Pudlák, Thapen '15]

Complexity Measures

Total Space

[Esteban, Torán '99] [Alekhnovich, Ben Sasson, Razborov, Wigderson '00]

$y+x\geq 1$	$y+x\geq 1$ $y-x\geq 0$	$y+x\geq 1$ $y-x\geq 0$ $2y\geq 1$	$y+x\geq 1$ $y-x\geq 0$ $2y\geq 1$ $y\geq 1$	~~$y+x\geq 1$~~ ~~$y-x\geq 0$~~ ~~$2y\geq 1$~~ $y\geq 1$	$y\geq 1$ $-y\geq 0$	$y\geq 1$ $-y\geq 0$ $0\geq 1$
5	10	13	16	3	6	7

Total Space of a proof: $\max$ bits in configuration (whiteboard)
Total Space of refuting a formula: $\min$ over all proofs
Total Space $\mathrm{O}(N^2)$ always possible; worst case $\Omega(N)$.

Trade-offs

Question

Assume F has a proof in length L and another proof in space s.
Is there a proof in length $\mathrm{O}(L)$ and space $\mathrm{O}(s)$?

Trade-offs

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Assume F has a proof in length L and another proof in space s.
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Trade-offs

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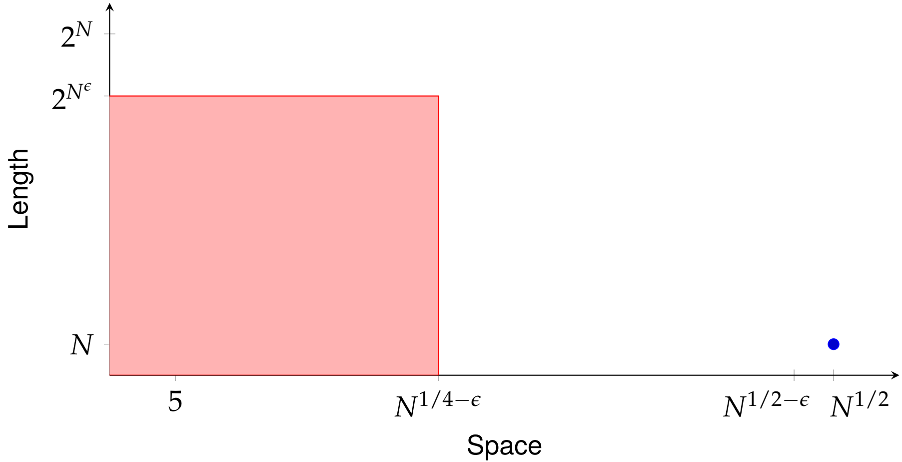
Is there a proof in length $\mathrm{O}(L)$ and space $\mathrm{O}(s)$?

No

Previously studied for resolution and polynomial calculus

[Ben Sasson, Nordström '11] [Beame, Beck, Impagliazzo '12] [Beck, Nordström, Tang '13]

Trade-offs

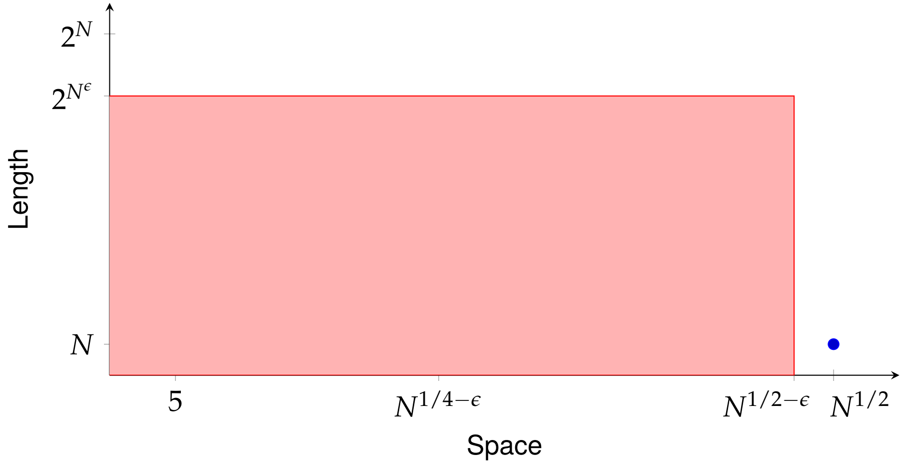


[Huynh, Nordström '12]

Can do length $\mathrm{O}(N)$, space $N^{1/2}$.

But space $N^{1/4-\epsilon}$ requires size $\exp(N^{\epsilon-\mathrm{o}(1)})$.

Trade-offs

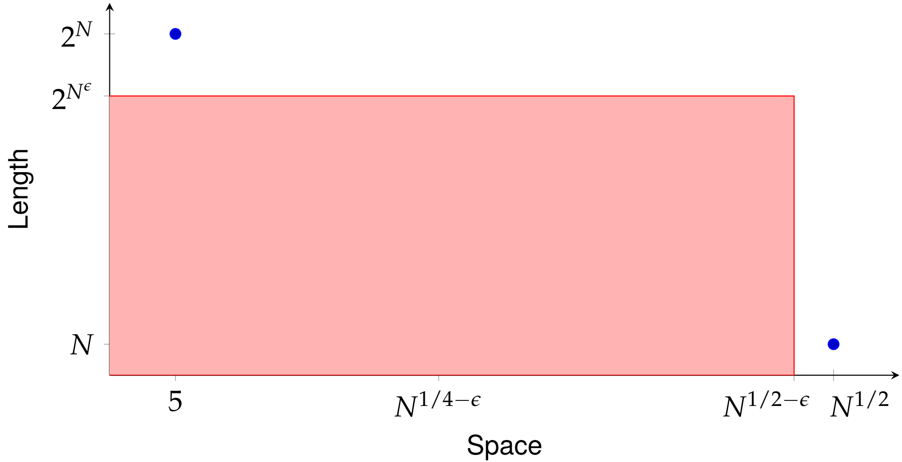


[Göös, Pitassi '14]

Can do length $N^{1+o(1)}$, space $N^{1/2+o(1)}$.

But space $N^{1/2-\epsilon}$ requires size $\exp(N^{\epsilon-o(1)})$.

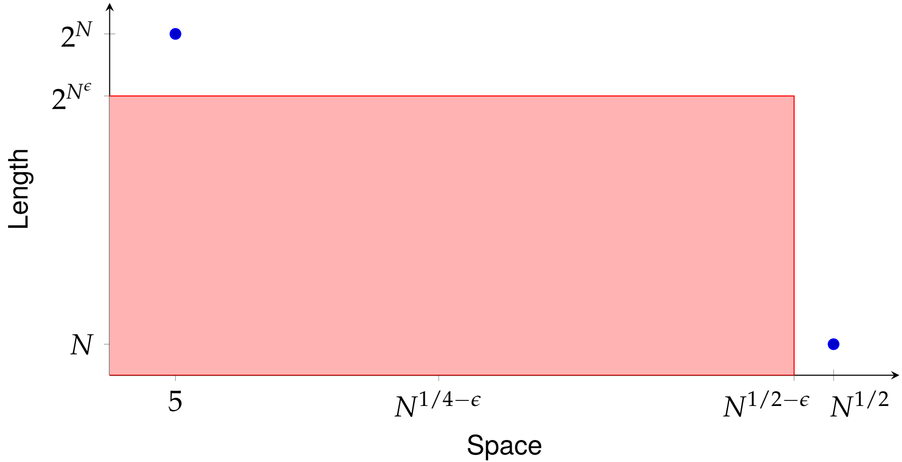
Trade-offs



[Galesi, Pudlák, Thapen '15]

Can do length $\exp(N)$, space 5.

Trade-offs



[Galesi, Pudlák, Thapen ’15]

Can do length $\exp(N)$, space 5.

But exponential coefficients and quadratic total space.

Trade-offs

Question

Assume F has a proof in small total space with polynomial coefficients. Are there still trade-offs?

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Cannot answer with previous techniques (provably)

Trade-offs

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Assume F has a proof in small total space with polynomial coefficients.
Are there still trade-offs?

Cannot answer with previous techniques (provably)

This talk:

Yes

Main Result

Theorem

There is a family of 6-CNF formulas with

- *short proofs: size $\mathrm{O}(N)$, total space $\mathrm{O}(N^{2/5})$;*

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There is a family of 6-CNF formulas with

- *short proofs: size* $\mathrm{O}(N)$, *total space* $\mathrm{O}(N^{2/5})$;
- *small space proofs: total space* $\mathrm{O}(N^{1/40})$, *size* $\exp(\mathrm{O}(N^{1/40}))$;

Main Result

Theorem

There is a family of 6-CNF formulas with

- *short proofs: size* $O(N)$, *total space* $O(N^{2/5})$;
- *small space proofs: total space* $O(N^{1/40})$, *size* $\exp(O(N^{1/40}))$;
- *but line space* $N^{1/20-\epsilon}$ *requires length* $\exp(\Omega(N^{1/40}))$.

Main Result

Theorem

There is a family of 6-CNF formulas with

- *short proofs: size $O(N)$, total space $O(N^{2/5})$;*
- *small space proofs: total space $O(N^{1/40})$, size $\exp(O(N^{1/40}))$;*
- *but line space $N^{1/20-\epsilon}$ requires length $\exp(\Omega(N^{1/40}))$.*

- Upper bounds with constant coefficients, counting all bits.
- Lower bound with unbounded coefficients, only counting lines.
- Lower bound for semantic cutting planes.

Main Result

Theorem

There is a family of 6-CNF formulas with

- *short proofs: size $O(N)$, total space $O(N^{2/5})$;*
- *small space proofs: total space $O(N^{1/40})$, size $\exp(O(N^{1/40}))$;*
- *but line space $N^{1/20-\epsilon}$ requires length $\exp(\Omega(N^{1/40}))$.*

- Upper bounds with constant coefficients, counting all bits.
- Lower bound with unbounded coefficients, only counting lines.
- Lower bound for semantic cutting planes.

- Holds for resolution and polynomial calculus proof systems.

Spin-off

Exponential separation of the monotone-AC hierarchy

Theorem

There is a monotone Boolean function with

- *small monotone circuits: size* $\mathrm{O}(n)$*, depth* $\log^i(n)$*, fan-in* $n^{4/5}$
- *but monotone circuits of depth* $\mathrm{O}(\log^{i-1} n)$ *require size* $\exp(\Omega(n^\epsilon))$*.*

Superpolynomial separation known [Raz, McKenzie '97]

Devious Plan

Assume refutation in length L and space s

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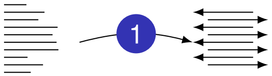
Assume refutation in length L and space s

$\downarrow$

1. Communication protocol for falsified clause search problem



Devious Plan

Assume refutation in length L and space s

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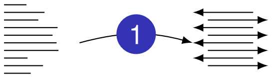
1. Communication protocol for Search(F)



Devious Plan

Assume refutation in length L and space s

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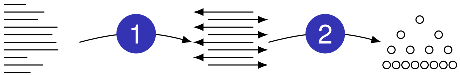
1. Communication protocol for Search(F)

$\downarrow$

2. Parallel decision tree for Search(F)



Devious Plan

Assume refutation in length L and space s

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1. Communication protocol for Search(F)

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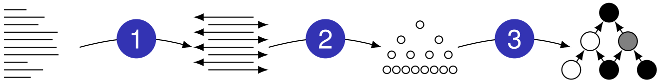
3. Strategy for Dymond–Tompa pebble game



Devious Plan

Assume refutation in length L and space s

↓

1. Communication protocol for Search(F)

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2. Parallel decision tree for Search(F)

↓

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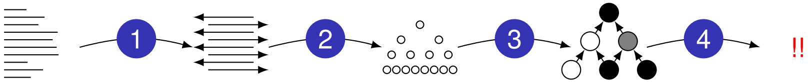
↓

4. Construct graph with trade-offs



Devious Plan 1: Proof $\rightarrow$ Protocol

Refutation in length L, space $s \rightarrow$
Protocol for Search(F) in $\log L$ rounds, communication $s \log L$

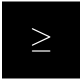
- Inspired by [Beame, Pitassi, Segerlind '05] [Beame, Huynh, Pitassi '10], explicit in [Huynh, Nordström '12].
- Key twists:
  - Real communication model
  - Measure number of rounds

Real Communication

Introduced in [Krajíček '98] to study cutting planes

- Compare real numbers at cost 1

Alice



Referee

Bob

Real Communication

Introduced in [Krajíček '98] to study cutting planes

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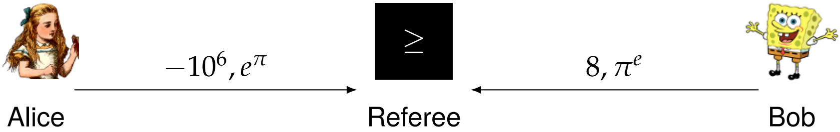

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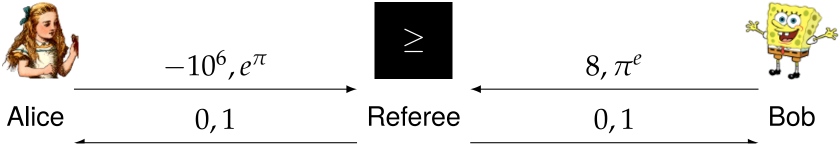

Real Communication

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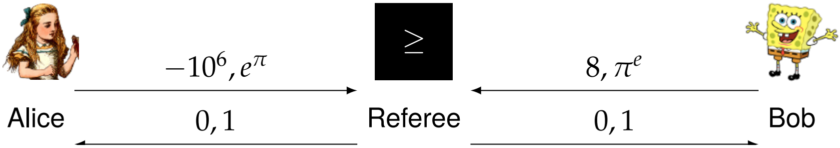

- Simulates deterministic communication (Alice sends m, Bob sends $1/2$)
- Stronger than deterministic communication (EQ)

Devious Plan 1: Proof $\to$ Protocol

Falsified clause search on CNF $F(x, y)$

- Alice $\leftarrow$ assignment to x variables
- Bob $\leftarrow$ assignment to y variables
- Task: Find falsified clause

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$\emptyset$																$\perp$

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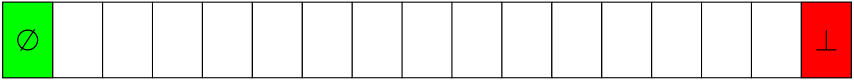

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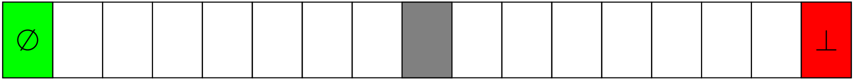

- Alice evaluates $\sum a_i x_i - a$ in s inequalities
- Bob evaluates $-\sum a_i y_i$ in s inequalities
- $\alpha(\mathbb{C}) = 1$ iff Referee answers $111\ldots1$

Devious Plan ❶: Proof $\to$ Protocol

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- Bob $\leftarrow$ assignment to y variables
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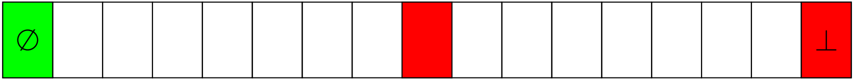

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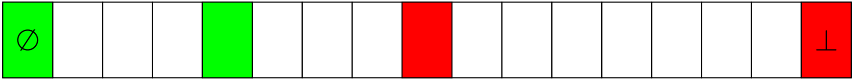

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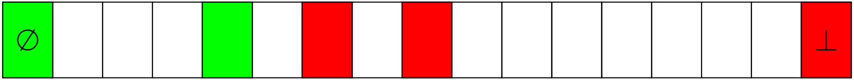

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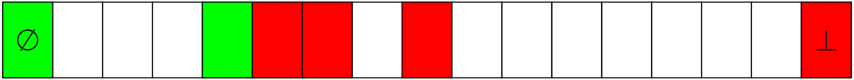

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Falsified clause search on CNF $F(x, y)$

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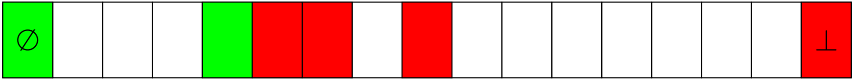
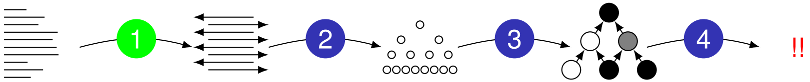


- $\alpha(\mathbb{C}) = 1 \quad \alpha(\mathbb{C} \cup \{A\}) = 0 \quad \Rightarrow \quad \alpha(A) = 0$
- $\log L$ rounds, communication $s \log L$

Devious Plan

Assume refutation in length L and space s

1. Communication protocol for Search(F) in $\log L$ rounds and communication $s \log L$
2. Parallel decision tree for Search(F)
3. Strategy for Dymond–Tompa pebble game
4. Construct graph with trade-offs



Devious Plan 2: Protocol $\to$ Decision Tree

Protocol for Lift(S) in r rounds, communication c $\to$
Parallel decision tree for S of depth r, c queries

Lifted Problem

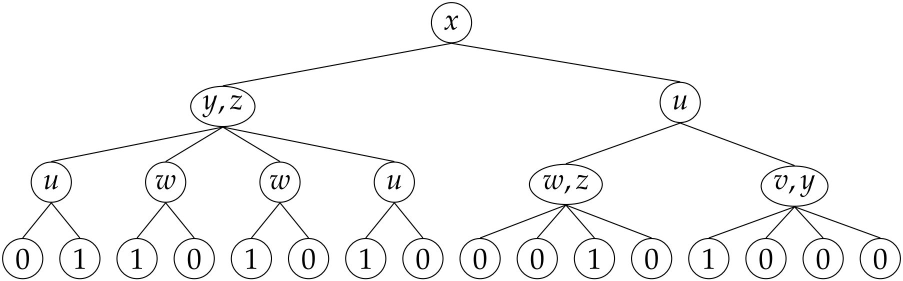
- Function $f(z_1, \ldots, z_n)$
- Alice $\leftarrow n$ indices $x_1, \ldots, x_n$
- Bob $\leftarrow n$ arrays $y_1, \ldots, y_n$

$z_1 = y_1[5] = 1$	5	0	0	1	0	0	1	1	1
$z_2 = y_2[1] = 0$	1	1	0	0	1	0	1	1	1

- Lifted function $\mathrm{Lift}(f)(x, y) = f(y_1[x_1], \ldots, y_n[x_n])$

Parallel Decision Trees

Decision tree with many queries per node [Valiant ’75]



Depth Longest branch

Queries # queries in a branch

Devious Plan ❷: Protocol $\rightarrow$ Decision Tree

Protocol for Lift(S) in r rounds, communication c $\rightarrow$
Parallel decision tree for S of depth r, c queries

Devious Plan 2: Protocol $\leftarrow$ Decision Tree

Protocol for Lift(S) in r rounds, communication c $\leftarrow$
Parallel decision tree for S of depth r, c queries

Communication

Decision tree

Query $\{z_3, z_{28}\}$

Devious Plan ②: Protocol $\leftarrow$ Decision Tree

Protocol for Lift(S) in r rounds, communication c $\leftarrow$
Parallel decision tree for S of depth r, c queries

Communication

Alice sends x_3, x_{28}
Bob sends $y_3[x_3], y_{28}[x_{28}]$

Decision tree

Query $\{z_3, z_{28}\}$

Devious Plan 2: Protocol $\to$ Decision Tree

Protocol for Lift(S) in r rounds, communication c $\to$
Parallel decision tree for S of depth r, c queries

Communication

Alice sends $x_1 + x_2 + \cdots + x_n$

Decision tree

Devious Plan ❷: Protocol $\rightarrow$ Decision Tree

Protocol for Lift(S) in r rounds, communication c $\rightarrow$
Parallel decision tree for S of depth r, c queries

Communication	Decision tree
Alice sends $x_1 + x_2 + \cdots + x_n$	???

Devious Plan ②: Protocol $\to$ Decision Tree

Protocol for Lift(S) in r rounds, communication c $\to$
Parallel decision tree for S of depth r, c queries

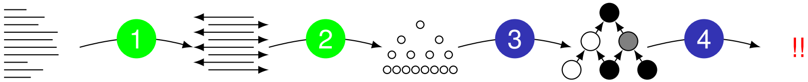
- Main technical result (Simulation Theorem)
  - Technique from [Raz, McKenzie '97]
  - Adapted to real communication in [Bonet, Esteban, Galesi, Johannsen '98]
  - Connection to decision trees made explicit in [Göös, Pitassi, Watson '15]
- Our contribution
  - Introduce rounds
  - Adapt to real communication preserving rounds

Devious Plan

Assume refutation of lifted formula in length L and space s

1. Communication protocol for Lift$(\text{Search}(F))$ in $\log L$ rounds and communication $s \log L$
2. Parallel decision tree for Search(F) of depth $\log L$ and $s \log L$ queries
3. Strategy for Dymond–Tompa pebble game

4. Construct graph with trade-offs



Devious Plan 3: Decision Tree $\rightarrow$ Dymond–Tompa

Parallel decision tree for Search(Peb_G) of depth r, c queries $\leftrightarrow$
Dymond–Tompa pebble game strategy for r rounds, c pebbles

Pebbling Formulas

- Sources are true

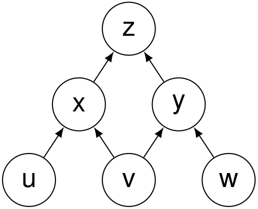
$$u$$
$$v$$
$$w$$

- Truth propagates

$$(u \wedge v) \rightarrow x$$
$$(v \wedge w) \rightarrow y$$
$$(x \wedge y) \rightarrow z$$

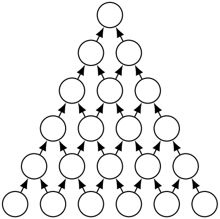
- Sink is false

$$\bar{z}$$



Dymond–Tompa Game

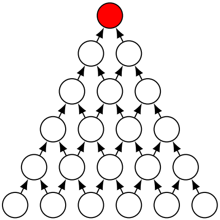
2-player pebble game on a DAG [Dymond, Dompa '85]



Dymond–Tompa Game

2-player pebble game on a DAG [Dymond, Dompa '85]

- Start with a challenged pebble on the sink



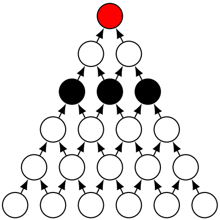
Rounds 0

Pebbles 1

Dymond–Tompa Game

2-player pebble game on a DAG [Dymond, Dompa '85]

- Start with a challenged pebble on the sink
- Each round:
  - Pebbler adds some pebbles



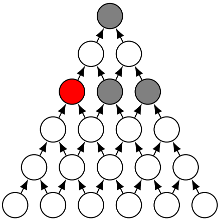
Rounds 1

Pebbles 4

Dymond–Tompa Game

2-player pebble game on a DAG [Dymond, Dompa '85]

- Start with a challenged pebble on the sink
- Each round:
  - Pebbler adds some pebbles
  - Challenger may challenge one new pebble



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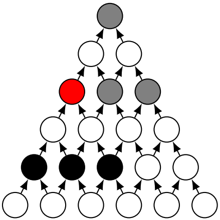

Rounds 2

Pebbles 7

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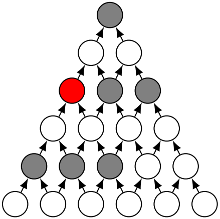

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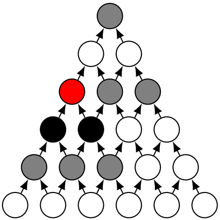

Rounds 3

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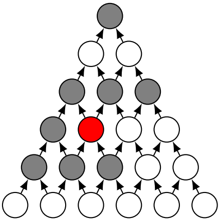
Dymond–Tompa Game

2-player pebble game on a DAG [Dymond, Dompa '85]

- Start with a challenged pebble on the sink
- Each round:
  - Pebbler adds some pebbles
  - Challenger may challenge one new pebble
- Ends when challenged pebble is surrounded



Rounds 3

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Devious Plan ❸: Decision Tree $\to$ Dymond–Tompa

Parallel decision tree for $\mathrm{Search}(\mathrm{Peb}_G)$ of depth r, c queries $\leftrightarrow$
Dymond–Tompa pebble game strategy for r rounds, c pebbles

- Done in [Chan '13]
- Tweak to preserve rounds

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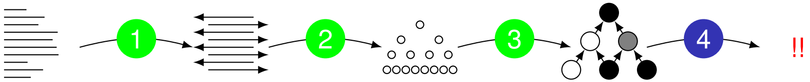
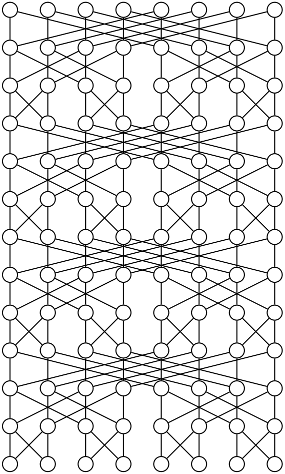


Devious Plan 4: Trade-off for Dymond–Tompa

Graph where r-round DT game needs $n/4$ pebbles

- Stack of $r+1$ butterfly graphs
- Can do $2r \log n$ pebbles in $r \log n$ rounds
- Or $n \log(r \log n)$ pebbles in $\log(r \log n)$ rounds



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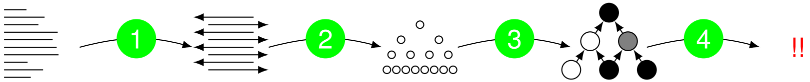
3. Strategy for Dymond–Tompa pebble game for $\log L$ rounds and $s \log L$ pebbles
4. Construct graph where such strategy does not exist



Take Home

Remarks

- Strong size-space trade-offs for cutting planes
- Hold for resolution, polynomial calculus, cutting planes
- Key to measure rounds

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- Smaller lift size
  - Progress in [Chattopadhyay, Koucký, Loff, Mukhopadhyay '17]
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Thanks!