

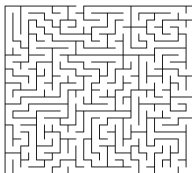
# A Curiously Effective Backtracking Strategy for Connection Tableaux

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# Section 1

## Introduction



- Proof search with the connection calculus frequently uses backtracking
- Restricted backtracking is incomplete, but frequently increases the number of proofs found in given time

## This Talk

- *Less restricted backtracking* is a new backtracking strategy
- It lies between restricted and unrestricted backtracking
- It is implemented in the new connection prover meanCoP
- On most evaluated datasets, it proves more problems than any other strategy

## Section 2

### Example

# Proof Search (Unrestricted Backtracking)

$$\left[ \begin{array}{l} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{l} \neg p(y) \\ r(y) \end{array} \right] [\neg p(z)] [\neg r(a)] [\neg r(b)] [\neg q(c)] \quad (1)$$

# Proof Search (Unrestricted Backtracking)

$$\left[ \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \right] \quad (1)$$

# Proof Search (Unrestricted Backtracking)

$$\left[ \begin{array}{c} [p(x)] \\ [q(x)] \end{array} \right] \begin{array}{c} \xrightarrow{1} \\ [ \neg p(y) ] \\ [ r(y) ] \end{array} \left[ \begin{array}{c} [ \neg p(z) ] \\ [ \neg r(a) ] \end{array} \right] [ \neg r(b) ] [ \neg q(c) ] \quad (1)$$

# Proof Search (Unrestricted Backtracking)

$$\left[ \begin{array}{c} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} \left[ \begin{array}{c} [\neg p(y)] \\ [r(y)] \end{array} \right] \xrightarrow{2} \left[ \begin{array}{c} [\neg p(z)] \\ [\neg r(a)] \end{array} \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \quad (1)$$

*⚡ 3*



# Proof Search (Unrestricted Backtracking)

$$\left[ \begin{array}{c} \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \begin{array}{c} \neg p(z) \\ \neg r(a) \end{array} \right] \left[ \begin{array}{c} \neg r(b) \\ \neg q(c) \end{array} \right] \end{array} \right] \quad (1)$$

*Diagram description: A sequence of six sub-problems in square brackets. A black arrow labeled '1' points from the top of the first sub-problem to the top of the second. A black arrow labeled '2' points from the bottom of the second sub-problem to the bottom of the third. A red 'X' is placed below the first sub-problem.*

$$\left[ \begin{array}{c} \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \begin{array}{c} \neg p(z) \\ \neg r(a) \end{array} \right] \left[ \begin{array}{c} \neg r(b) \\ \neg q(c) \end{array} \right] \end{array} \right] \quad (2)$$

*Diagram description: A sequence of six sub-problems in square brackets. A red arrow points from the top of the first sub-problem to the top of the second.*

# Proof Search (Unrestricted Backtracking)

$$\left[ \begin{array}{c} \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \begin{array}{c} \neg p(z) \\ \neg r(a) \end{array} \right] \left[ \begin{array}{c} \neg r(b) \\ \neg q(c) \end{array} \right] \end{array} \right] \quad (1)$$

*(Note: In the original image, a '3' with a slash is under  $q(x)$ , and arrows labeled '1' and '2' connect the first two columns.)*

$$\left[ \begin{array}{c} \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \begin{array}{c} \neg p(z) \\ \neg r(a) \end{array} \right] \left[ \begin{array}{c} \neg r(b) \\ \neg q(c) \end{array} \right] \end{array} \right] \quad (2)$$

*(Note: In the original image, a red arrow labeled '1' connects the second and fourth columns.)*

# Proof Search (Unrestricted Backtracking)

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \\ \not\! 3 \end{array} \right] \begin{array}{l} \xrightarrow{1} \\ \xrightarrow{2} \end{array} \left[ \begin{array}{l} [\neg p(y)] \\ [r(y)] \end{array} \right] \left[ \begin{array}{l} [\neg p(z)] \\ [\neg r(a)] \end{array} \right] [\neg r(b)] [\neg q(c)] \quad (1)$$

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \\ \not\! 2 \end{array} \right] \begin{array}{l} \xrightarrow{1} \\ \xrightarrow{1} \end{array} \left[ \begin{array}{l} [\neg p(y)] \\ [r(y)] \end{array} \right] \left[ \begin{array}{l} [\neg p(z)] \\ [\neg r(a)] \end{array} \right] [\neg r(b)] [\neg q(c)] \quad (2)$$

# Proof Search (Unrestricted Backtracking)

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} [\neg p(y)] \\ [r(y)] \end{array} \right] \xrightarrow{2} [\neg p(z)] \xrightarrow{1} [\neg r(a)] \quad [\neg r(b)] \quad [\neg q(c)] \quad (1)$$

*Diagram description: A sequence of logical formulas in square brackets. The first formula is a list containing  $p(x)$  and  $q(x)$ , with a crossed-out '3' below it. An arrow labeled '1' points to the second formula, which is a list containing  $\neg p(y)$  and  $r(y)$ . A second arrow labeled '2' points from the second formula to the third formula, which is  $\neg p(z)$ . A third arrow labeled '1' points from the third formula to the fourth formula, which is  $\neg r(a)$ . The remaining formulas are  $\neg r(b)$  and  $\neg q(c)$ .*

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} [\neg p(y)] \\ [r(y)] \end{array} \right] \xrightarrow{1} [\neg p(z)] \quad [\neg r(a)] \quad [\neg r(b)] \quad [\neg q(c)] \quad (2)$$

*Diagram description: Similar to (1), but the arrow from the second formula to the third formula is labeled '1' instead of '2'. The crossed-out '3' below the first formula is replaced by a crossed-out '2'.*

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \quad [\neg p(y)] \quad [r(y)] \quad [\neg p(z)] \quad [\neg r(a)] \quad [\neg r(b)] \quad [\neg q(c)] \quad (3)$$

*Diagram description: The formulas are now all separated into individual square brackets, with no arrows between them.*

# Proof Search (Unrestricted Backtracking)

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} [\neg p(y)] \\ [r(y)] \end{array} \right] \xrightarrow{2} [\neg p(z)] \xrightarrow{1} [\neg r(a)] \quad [\neg r(b)] \quad [\neg q(c)] \quad (1)$$

*Note: In the original image, a '3' with a slash is under the first column, and an arrow points from the first column to the second column.*

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} [\neg p(y)] \xrightarrow{1} [\neg p(z)] \xrightarrow{1} [\neg r(a)] \quad [\neg r(b)] \quad [\neg q(c)] \quad (2)$$

*Note: In the original image, a '2' with a slash is under the first column, and an arrow points from the first column to the second column.*

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} [\neg p(y)] \xrightarrow{1} [\neg p(z)] \quad [\neg r(a)] \quad [\neg r(b)] \quad [\neg q(c)] \quad (3)$$

# Proof Search (Unrestricted Backtracking)

$$\left[ \begin{array}{l} p(x) \\ q(x) \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} \neg p(y) \\ r(y) \end{array} \right] \xrightarrow{2} \left[ \begin{array}{l} \neg p(z) \\ \neg r(a) \end{array} \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \quad (1)$$

*Note: In the original image, a '3' with a slash is written below the first column.*

$$\left[ \begin{array}{l} p(x) \\ q(x) \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} \neg p(y) \\ r(y) \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} \neg p(z) \\ \neg r(a) \end{array} \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \quad (2)$$


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$$\left[ \begin{array}{l} p(x) \\ q(x) \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} \neg p(y) \\ r(y) \end{array} \right] \xrightarrow{2} \left[ \begin{array}{l} \neg p(z) \\ \neg r(a) \end{array} \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \quad (3)$$

# Proof Search (Restricted Backtracking)

$$\left[ \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \right] \quad (1)$$

# Proof Search (Restricted Backtracking)

$$\left[ \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \right] \quad (1)$$




# Proof Search (Restricted Backtracking)

$$\left[ \begin{array}{c} \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \end{array} \right] \quad (1)$$

# Proof Search (Restricted Backtracking)

$$\left[ \begin{array}{c} \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \begin{array}{c} \neg p(z) \\ \neg r(a) \end{array} \right] \left[ \begin{array}{c} \neg r(b) \\ \neg q(c) \end{array} \right] \end{array} \right] \quad (1)$$

The diagram shows a sequence of logical formulas in square brackets, arranged from left to right. The first formula is a vertical stack of  $p(x)$  and  $q(x)$ . A red lightning bolt symbol is positioned below the  $q(x)$  formula. An arrow labeled '1' starts from the top of the first formula and points to the top of the second formula. The second formula is a vertical stack of  $\neg p(y)$  and  $r(y)$ . An arrow labeled '2' starts from the bottom of the second formula and points to the bottom of the third formula. The third formula is a vertical stack of  $\neg p(z)$  and  $\neg r(a)$ . The fourth formula is a vertical stack of  $\neg r(b)$  and  $\neg q(c)$ .

# Proof Search (Restricted Backtracking)

$$\left[ \begin{array}{c} \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \end{array} \right] \quad (1)$$

The diagram shows a sequence of clause copies in square brackets. The first copy contains  $p(x)$  and  $q(x)$ , with a '3' and a checkmark below it. The second copy contains  $\neg p(y)$  and  $r(y)$ . The third copy contains  $\neg p(z)$ . The fourth copy contains  $\neg r(a)$ . The fifth copy contains  $\neg r(b)$ . The sixth copy contains  $\neg q(c)$ . An arrow labeled '1' points from  $p(x)$  to  $\neg p(y)$ . An arrow labeled '2' points from  $r(y)$  to  $\neg r(a)$ .

## Restricted backtracking

- A literal is *solved* if it is connected to a literal  $L$  of a fresh clause copy  $C$  and all other literals  $C \setminus L$  are solved
- Restricted backtracking does not consider alternative proofs for literals that have been solved
- Because  $p(x)$  is solved, we cannot backtrack to find an alternative proof for it, thus proof search fails


# Proof Search (Less Restricted Backtracking)

- Less restricted backtracking considers alternative proofs for literals that have been solved, but only if their root step is different

$$\left[ \begin{array}{c} [p(x)] \\ [q(x)] \end{array} \left[ \begin{array}{c} [\neg p(y)] \\ [r(y)] \end{array} \right] [\neg p(z)] [\neg r(a)] [\neg r(b)] [\neg q(c)] \right] \quad (1)$$

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$$\left[ \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \right] \quad (1)$$


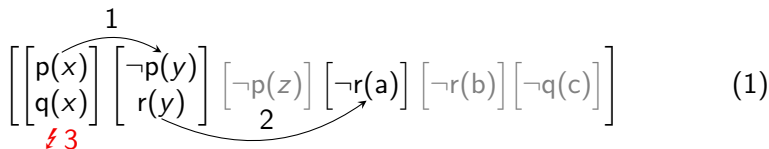
# Proof Search (Less Restricted Backtracking)

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$$\left[ \begin{array}{c} \overset{1}{\curvearrowright} \\ \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \end{array} \right] \quad (1)$$

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$$\left[ \begin{array}{c} \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \end{array} \right] \quad (1)$$

1

2

3

$$\left[ \begin{array}{c} \left[ \begin{array}{c} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{c} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \end{array} \right] \quad (3)$$



# Proof Search (Less Restricted Backtracking)

- Less restricted backtracking considers alternative proofs for literals that have been solved, but only if their root step is different

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} [\neg p(y)] \\ [r(y)] \end{array} \right] \xrightarrow{2} \left[ \begin{array}{l} [\neg p(z)] \\ [\neg r(a)] \end{array} \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \quad (1)$$

*(Note: In the original image, a '3' with a slash is under the first column, and a curved arrow labeled '2' connects the second column to the third column.)*

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} [\neg p(y)] \\ [r(y)] \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \quad (3)$$

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$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} \left[ \begin{array}{l} [\neg p(y)] \\ [r(y)] \end{array} \right] \xrightarrow{2} [\neg p(z)] \quad [\neg r(a)] \quad [\neg r(b)] \quad [\neg q(c)] \quad (1)$$

*(Note: In the original image, the first column is crossed out with a red 'X' and labeled '3'.)*

$$\left[ \begin{array}{l} [p(x)] \\ [q(x)] \end{array} \right] \xrightarrow{1} [\neg p(z)] \quad [\neg r(a)] \quad [\neg r(b)] \quad [\neg q(c)] \quad (3)$$

*(Note: In the original image, the second column is crossed out with a red 'X' and labeled '2'.)*

# Summary

$$\left[ \begin{array}{l} \left[ \begin{array}{l} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{l} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \\ \not\downarrow 3 \end{array} \right] \quad (1)$$

$$\left[ \begin{array}{l} \left[ \begin{array}{l} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{l} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \\ \not\downarrow 2 \end{array} \right] \quad (2)$$

$$\left[ \begin{array}{l} \left[ \begin{array}{l} p(x) \\ q(x) \end{array} \right] \left[ \begin{array}{l} \neg p(y) \\ r(y) \end{array} \right] \left[ \neg p(z) \right] \left[ \neg r(a) \right] \left[ \neg r(b) \right] \left[ \neg q(c) \right] \\ \not\downarrow 2 \end{array} \right] \quad (3)$$

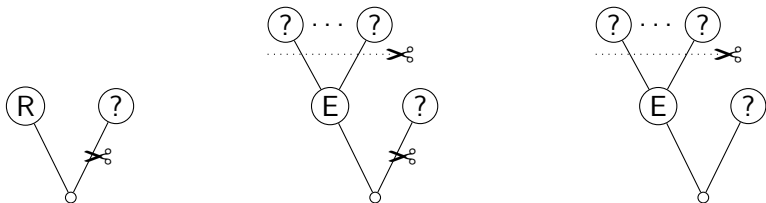
Strategy	UB	RB	LRB
Stages	(1), (2), (3)	(1)	(1), (3)
Proof steps	7	3 $\not\downarrow$	4

## Section 3

### A Zoo of Cuts

## Inclusive vs. Exclusive Cuts

- Inclusive cut discards all alternatives to solve a literal
- Exclusive cut discards all alternatives to solve a literal, *except for derivations starting with a different proof step*



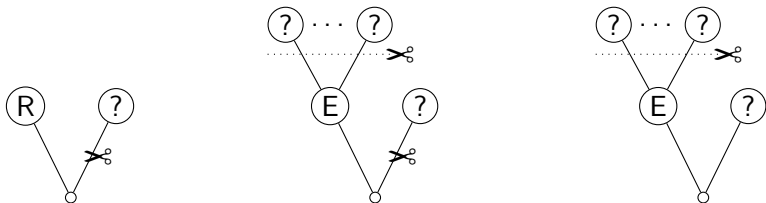
(a) Reduction (R).    (b) Extension, inclusive (EI).    (c) Extension, exclusive (EX).

Figure 1: Effect of different cuts on the tree of alternatives.

# A Zoo of Cuts

## Inclusive vs. Exclusive Cuts

- Inclusive cut discards all alternatives to solve a literal
- Exclusive cut discards all alternatives to solve a literal, *except for derivations starting with a different proof step*



(a) Reduction (R).    (b) Extension, inclusive (EI).    (c) Extension, exclusive (EX).

Figure 1: Effect of different cuts on the tree of alternatives.

It follows that cuts on reduction steps are always inclusive

# Backtracking Strategies

A backtracking strategy is a set of cuts:

Backtracking	Cuts
Unrestricted	$\emptyset$ (None)
Restricted	{R, EI} (REI)
Less restricted	{R, EX} (REX)
Others	{R}, {EI}, {EX}

leanCoP's cut option corresponds to restricted backtracking, i.e. REI

## Section 4

# Implementation





## meanCoP

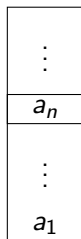
- connection prover for classical first-order logic with equality
- supports clausal and nonclausal proof search à la leanCoP/nanoCoP
- can perform precisely the same steps as leanCoP, for comparison
- includes a tiny proof checker and runs it before proof output
- written in Rust for high performance
- backed by the cop library, which provides building blocks for connection provers (formulas, terms, substitutions, backtracking ...)

Get it on: <https://github.com/01mf02/cop-rs>

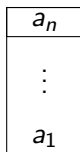
# Stack of Alternatives



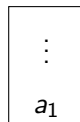
- meanCoP backtracks by using a stack of alternatives
- Whenever a literal is solved, the stack is shrunk



(a) No cut.



(b) Exclusive.



(c) Inclusive.

Figure 2: Effect of different cuts on the stack of alternatives.

## Section 5

# Evaluation

Dataset	TPTP	bushy	chainy	Miz40	FS-top
Problems	7492	2078	2078	32524	27111

- TPTP 6.3.0: nonclausal first-order problems (\*+?.p)
- bushy/chainy: from MPTP2078
- FS-top: translation to FOL of Flyspeck's HOL Light theorems

Timeout: 10 seconds/problem

Table 4: Number of solved problems.

Cut	TPTP	bushy	chainy	Miz40	FS-top
None	1731	546	208	9247	4038
R	1857	644	252	12965	4447
EI	1984	724	333	13853	4249
EX	2056	820	268	15507	4758
REI	1988	730	<b>341</b>	13562	4267
REX	<b>2126</b>	<b>850</b>	294	<b>16135</b>	<b>4994</b>

Table 5: Improvement of REX compared to REI.

Cut	TPTP	bushy	chainy	Miz40	FS-top
REX / REI	+6.9%	+16.4%	-13.8%	+19.0%	+17.0%

# Comparison of Inferences

Table 6: Percentage of problems solved by C1 that are identically solved by C2.

C1	C2	TPTP	bushy	chainy	Miz40	FS-top
None	REX	84.5	66.5	89.4	77.8	81.0
None	REI	68.3	46.7	57.7	54.2	67.4
REX	REI	63.3	40.8	59.2	50.1	66.6

Table 7: Ratio between inferences taken by C1 and inferences taken by C2, for problems identically solved by C1 and C2.

C1	C2	TPTP	bushy	chainy	Miz40	FS-top
None	REX	4.4	37.0	9.9	37.4	19.8
None	REI	4.2	55.4	32.0	54.6	28.8
REX	REI	3.3	4.0	<b>8.4</b>	2.4	2.2

# Comparison With Other Connection Provers

Table 8: Prover runtime in seconds for problems solved by leanCoP-REI.

Prover	TPTP	bushy	chainy	Miz40	FS-top
leanCoP-REI	1299.7	461.9	319.1	9308.7	2451.6
fleanCoP-REI	488.1	190.9	69.8	3845.6	657.2
meanCoP-REI	200.0	17.3	29.0	347.9	88.5

Table 9: Number of solved problems for different leanCoP implementations.

Prover	TPTP	bushy	chainy	Miz40	FS-top
leanCoP-REI	1673	606	182	11243	3664
fleanCoP-REI	1859	670	289	12204	3980
meanCoP-REI	1988	730	341	13562	4267

# Comparison With Other Provers

Table 10: Number of solved problems by different provers.

Prover	TPTP	bushy	chainy	Miz40	FS-top
Vampire	4404	1253	656	30341	6358
E	3664	1167	287	26003	7382
Metis	1376	500	75	18519	3537
meanCoP-REI	1988	730	<b>341</b>	13562	4267
meanCoP-REX	2126	850	294	16135	4994



# Comparison With Other Provers

Table 10: Number of solved problems by different provers.

Prover	TPTP	bushy	chainy	Miz40	FS-top
Vampire	4404	1253	656	30341	6358
E	3664	1167	287	26003	7382
Metis	1376	500	75	18519	3537
meanCoP-REI	1988	730	<b>341</b>	13562	4267
meanCoP-REX	2126	850	294	16135	4994



(Vampire 4.0 and E 2.0 were evaluated with strategy scheduling, giving them an advantage.)

## Section 6

### Conclusion

# Conclusion

- Less Restricted Backtracking is a new backtracking strategy
- On most evaluated datasets, it clearly improves performance compared to restricted backtracking
- meanCoP is a connection prover with state-of-the-art performance

## Open Question

Can we have less restricted backtracking in leanCoP?

- Less Restricted Backtracking is a new backtracking strategy
- On most evaluated datasets, it clearly improves performance compared to restricted backtracking
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## Open Question

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Thank you for your attention!