git clone https://github.com/data61/PSL

Towards Machine Learning Induction for Isabelle/HOL

This work was supported by the project AI&Reasoning (reg. no. CZ.02.1.01/0.0/0.0/15_003/0000466).

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Yutaka Ng
yutakang

Block or report user

CVUT, CTU, CIIRC

CZECH INSTITUTE OF INFORMATICS ROBOTICS AND CYBERNETICS CTU IN PRAGUE

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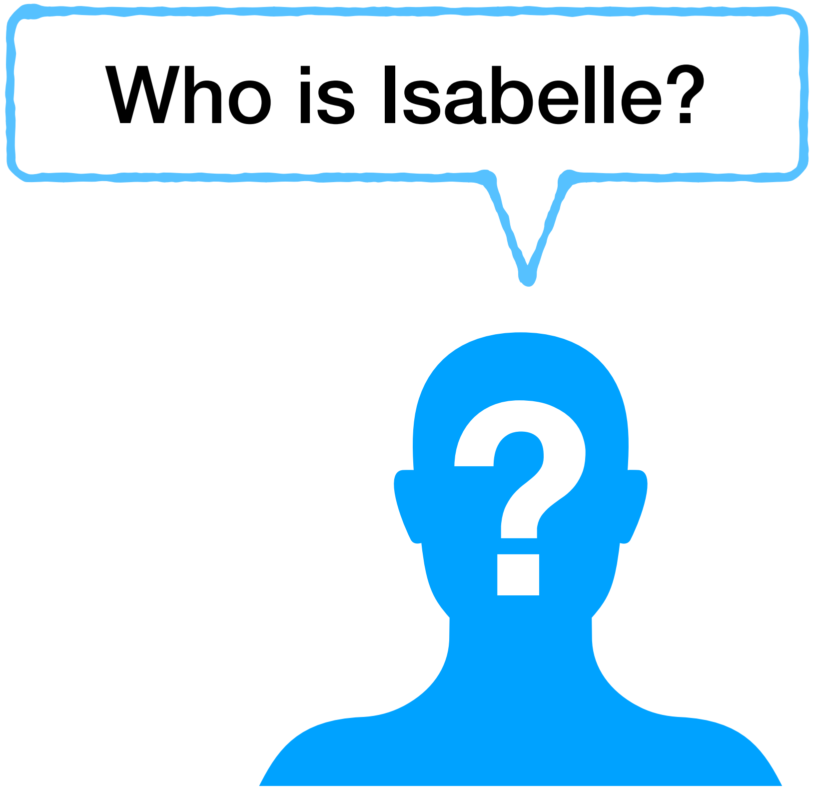

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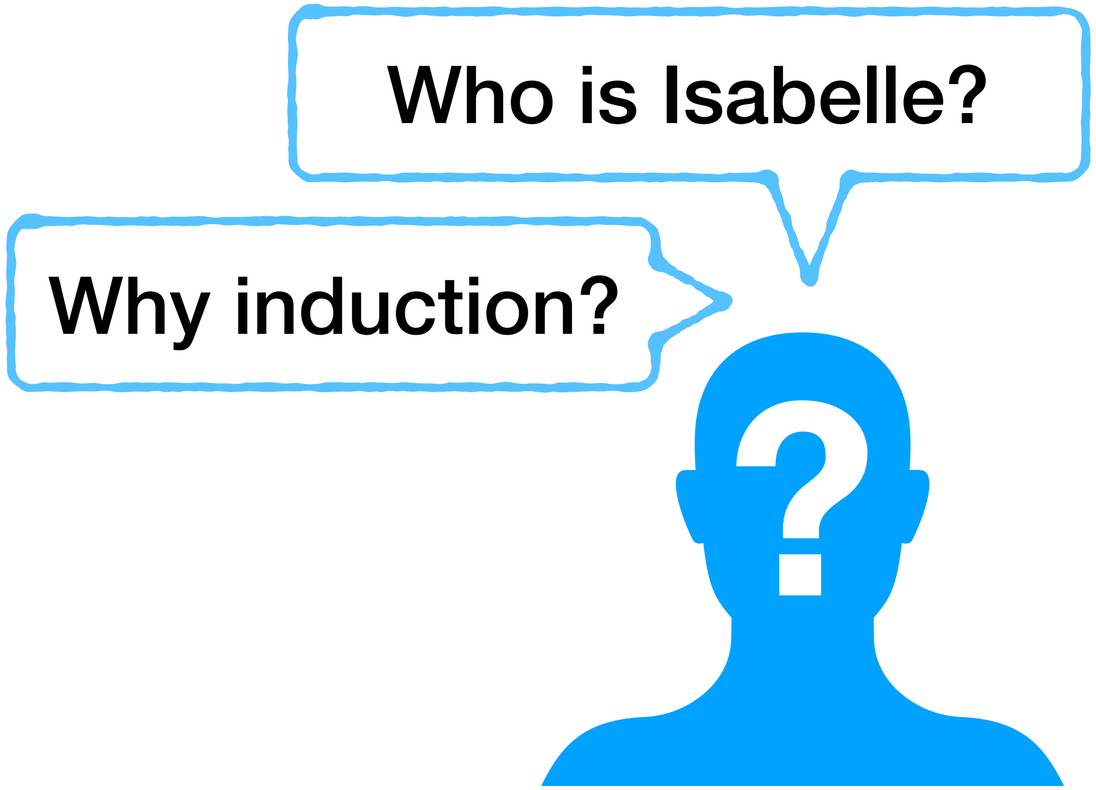

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Towards Machine Learning Induction for Isabelle/HOL

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ITP (Inductive Theorem Proving) problems are at the heart of many verification and reasoning tasks in

Prof. Bernhard Gramlich
https://www.logic.at/staff/gramlich/

Who is Isabelle?

Why induction?

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we are convinced that substantial progress in ITP will take time.

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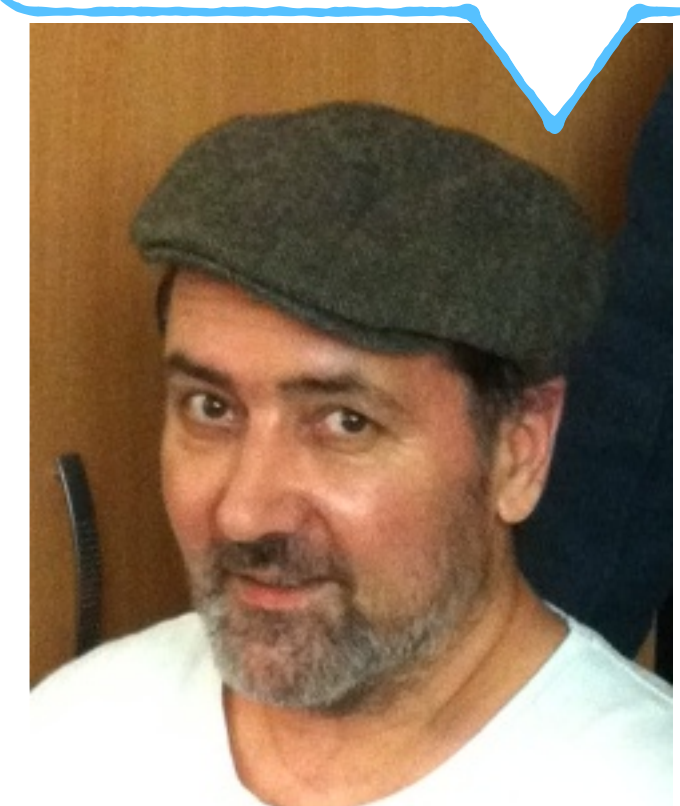

we are convinced that substantial progress in ITP will take time.

spectacular breakthroughs are unrealistic, in view of the enormous problems and the inherent difficulty of inductive theorem proving.

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Strategic Issues, Problems and Challenges in Inductive Theorem Proving

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ITP (Inductive Theorem Proving) problems are at the heart verification and reasoning tasks in

Challenge accepted!

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Why in

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problems are at the heart
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The time has come!

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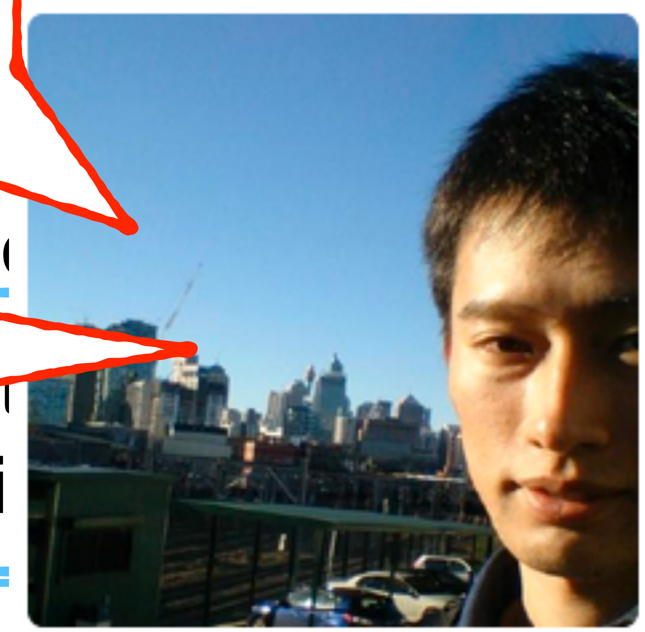

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Strategic Issues, Problems and Challenges in Inductive Theorem Proving

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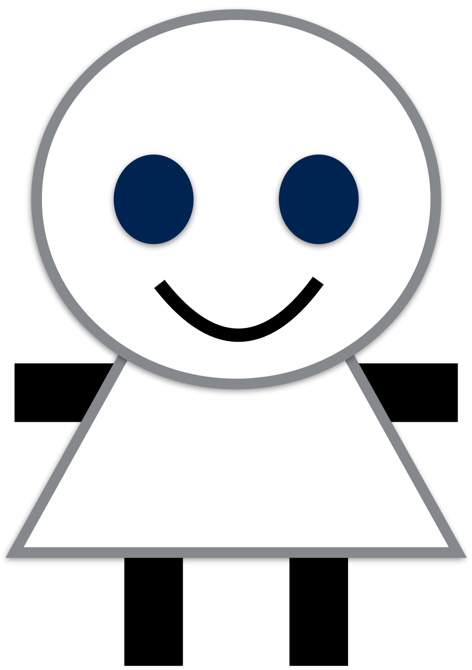
Interactive theorem proving with Isabelle/HOL



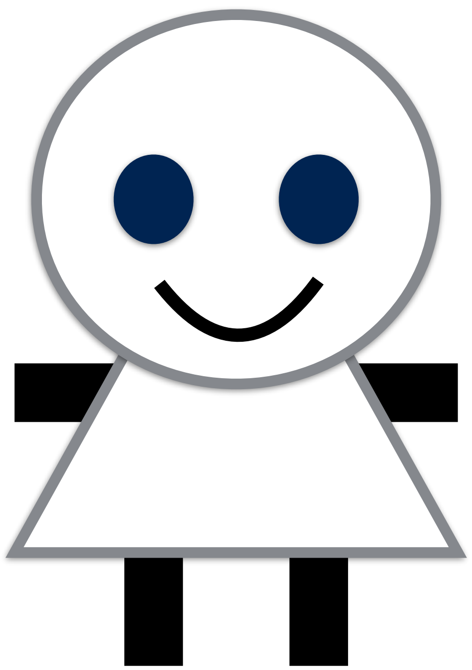
git clone https://github.com/data61/PSL

Interactive theorem proving with Isabelle/HOL

proof goal

context

tactic / proof method



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Interactive theorem proving with Isabelle/HOL

proof goal

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tactic / proof method

error-message

subgoals

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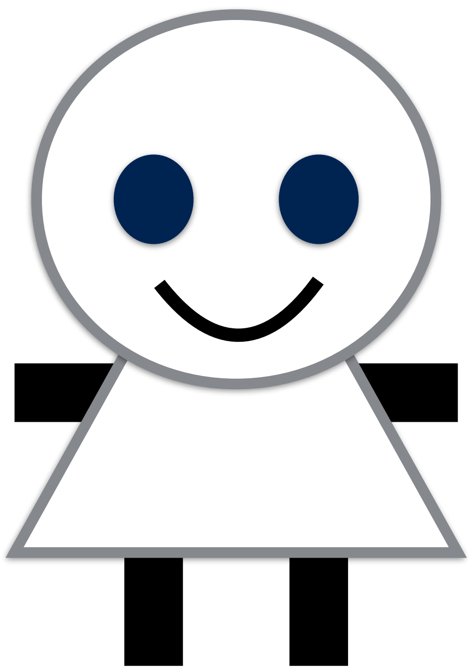
Interactive theorem proving with Isabelle/HOL

proof goal **context**

tactic / proof method



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Interactive theorem proving with Isabelle/HOL

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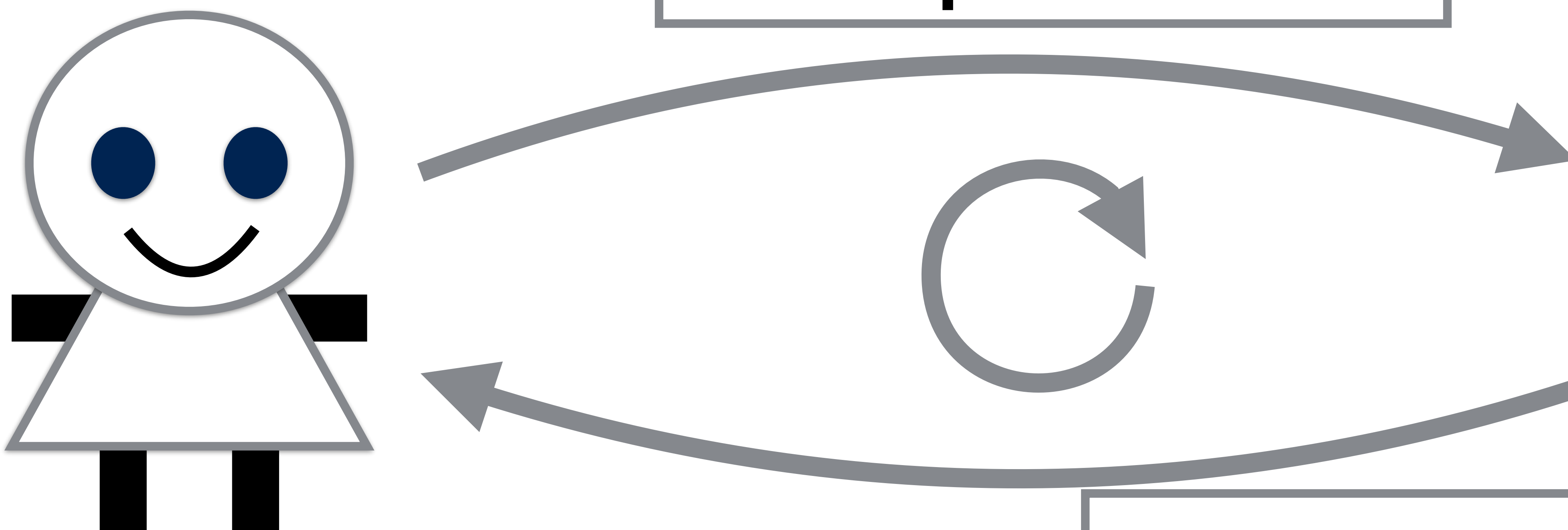


error-message

subgoals

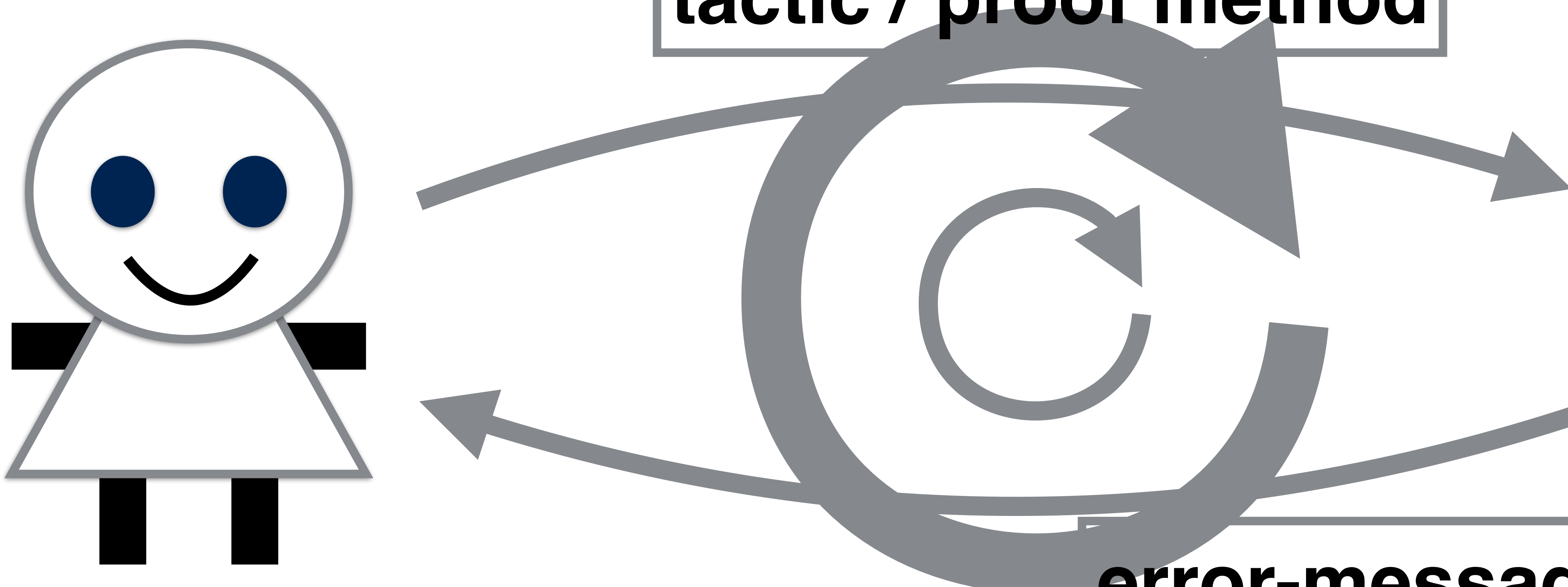
no sub-goal!

git clone https://github.com/data61/PSL

Interactive theorem proving with Isabelle/HOL

proof goal **context**

tactic / proof method



error-message

subgoals **no sub-goal!**

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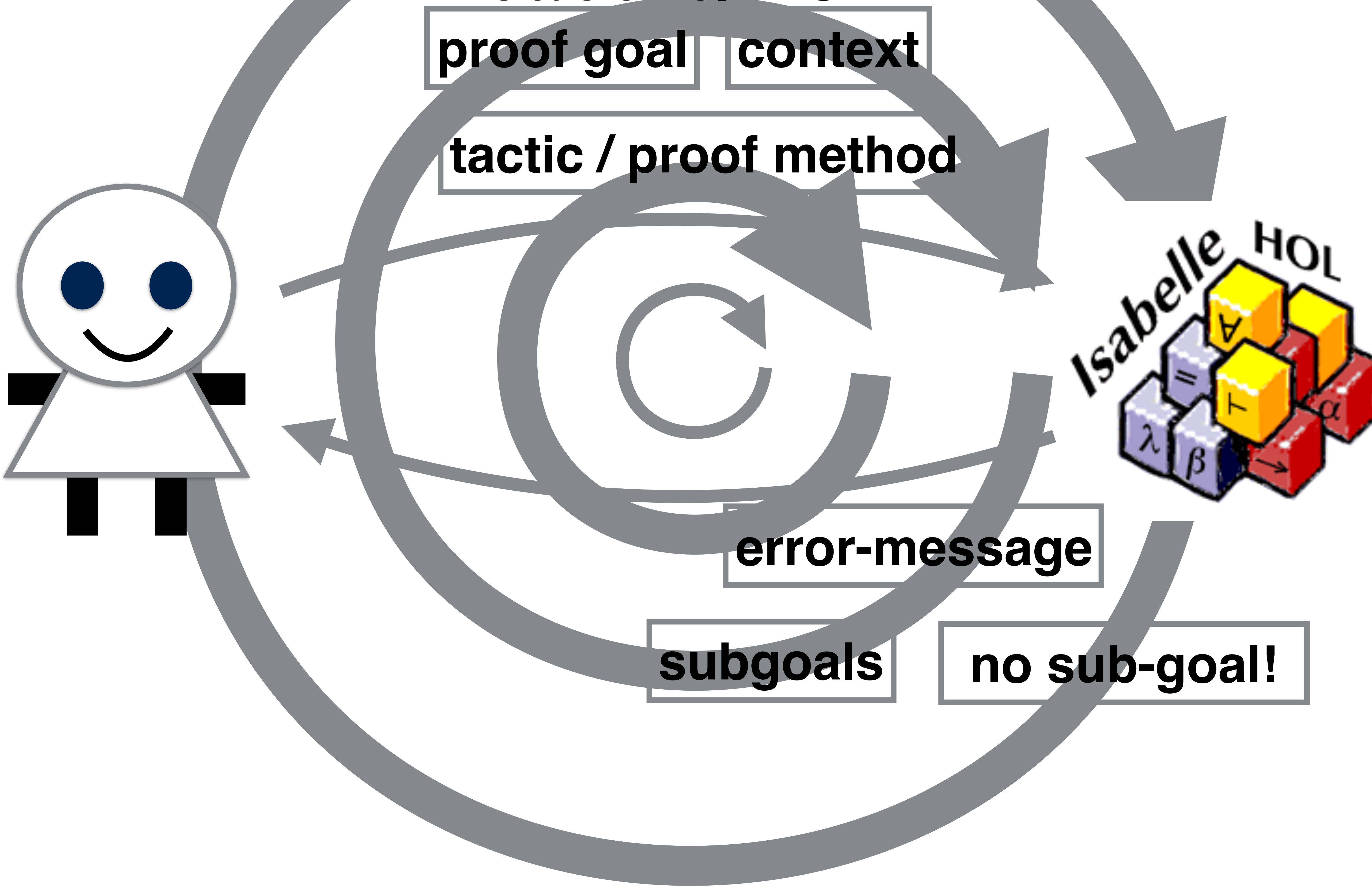

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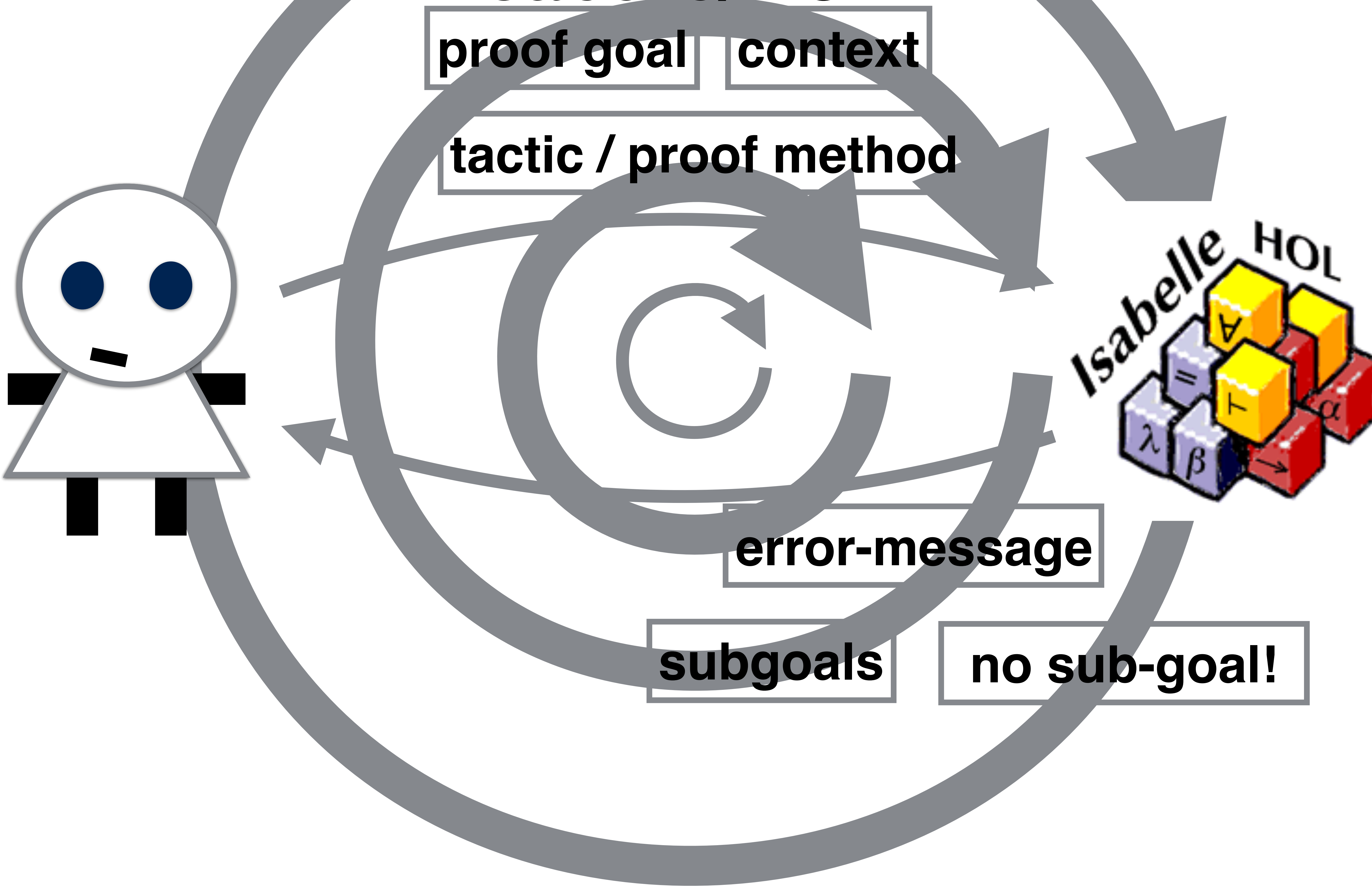

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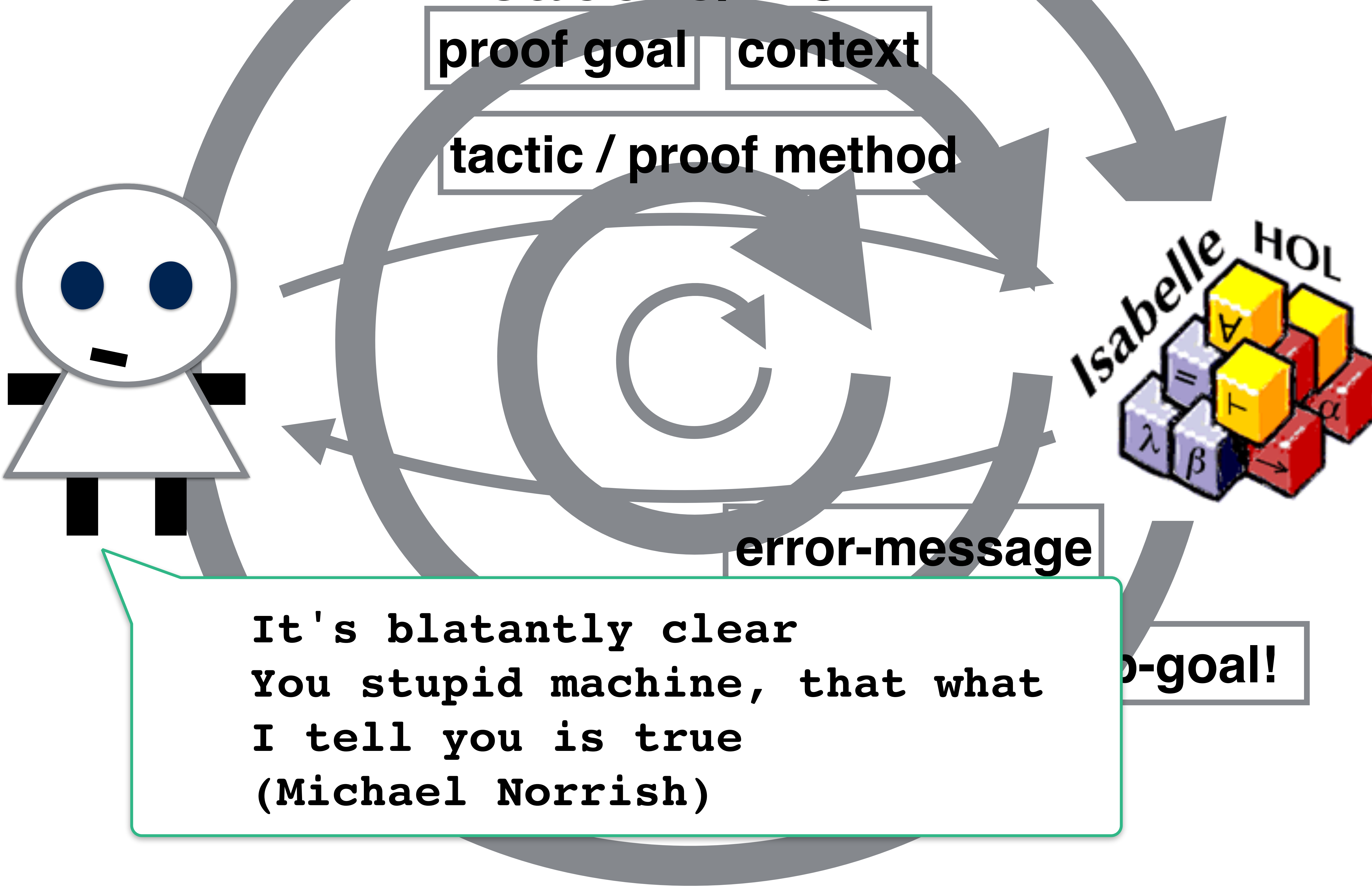

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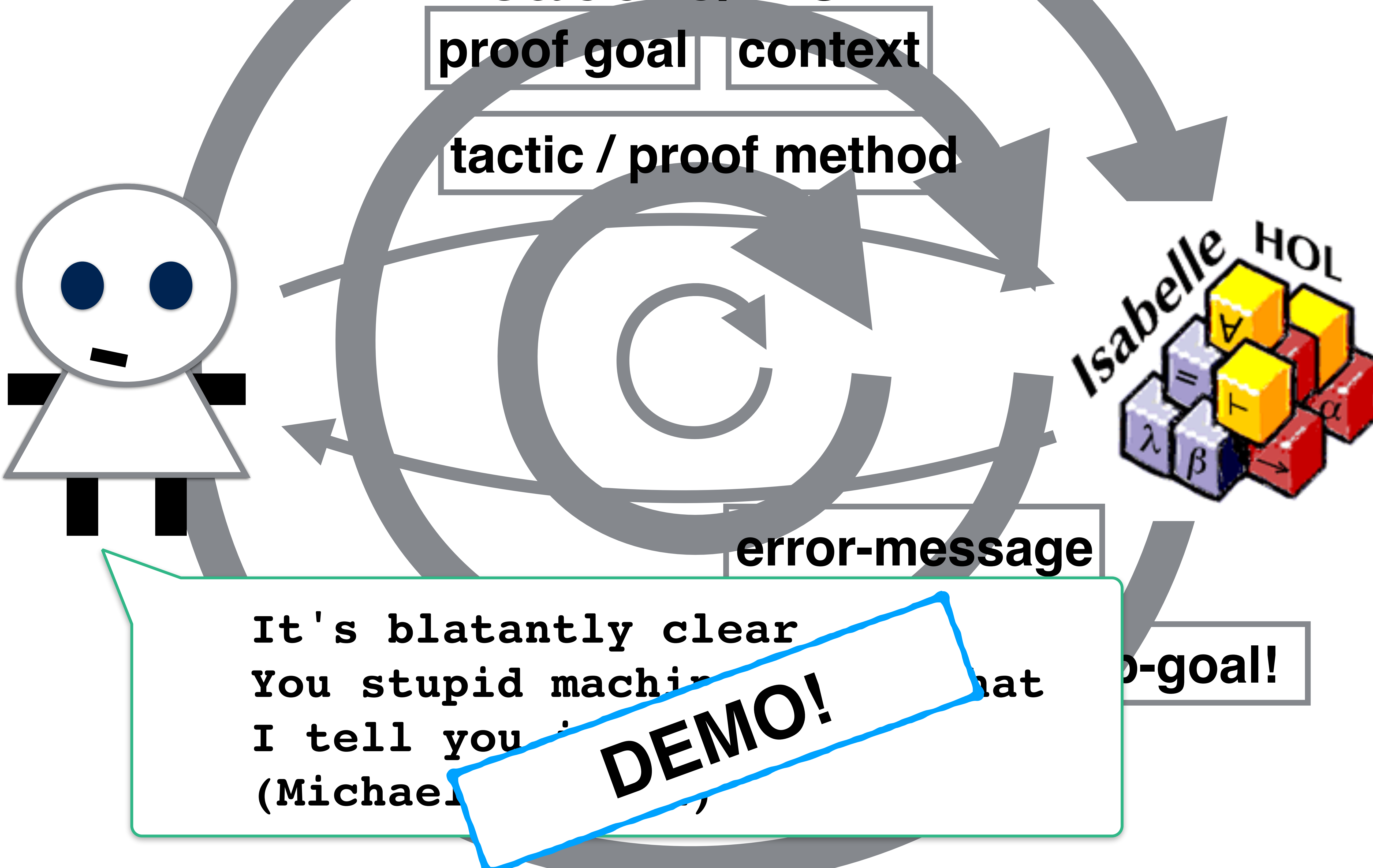

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find_proof DInd(*= Thens [Dynamic (Induct), Auto, IsSolved]*)
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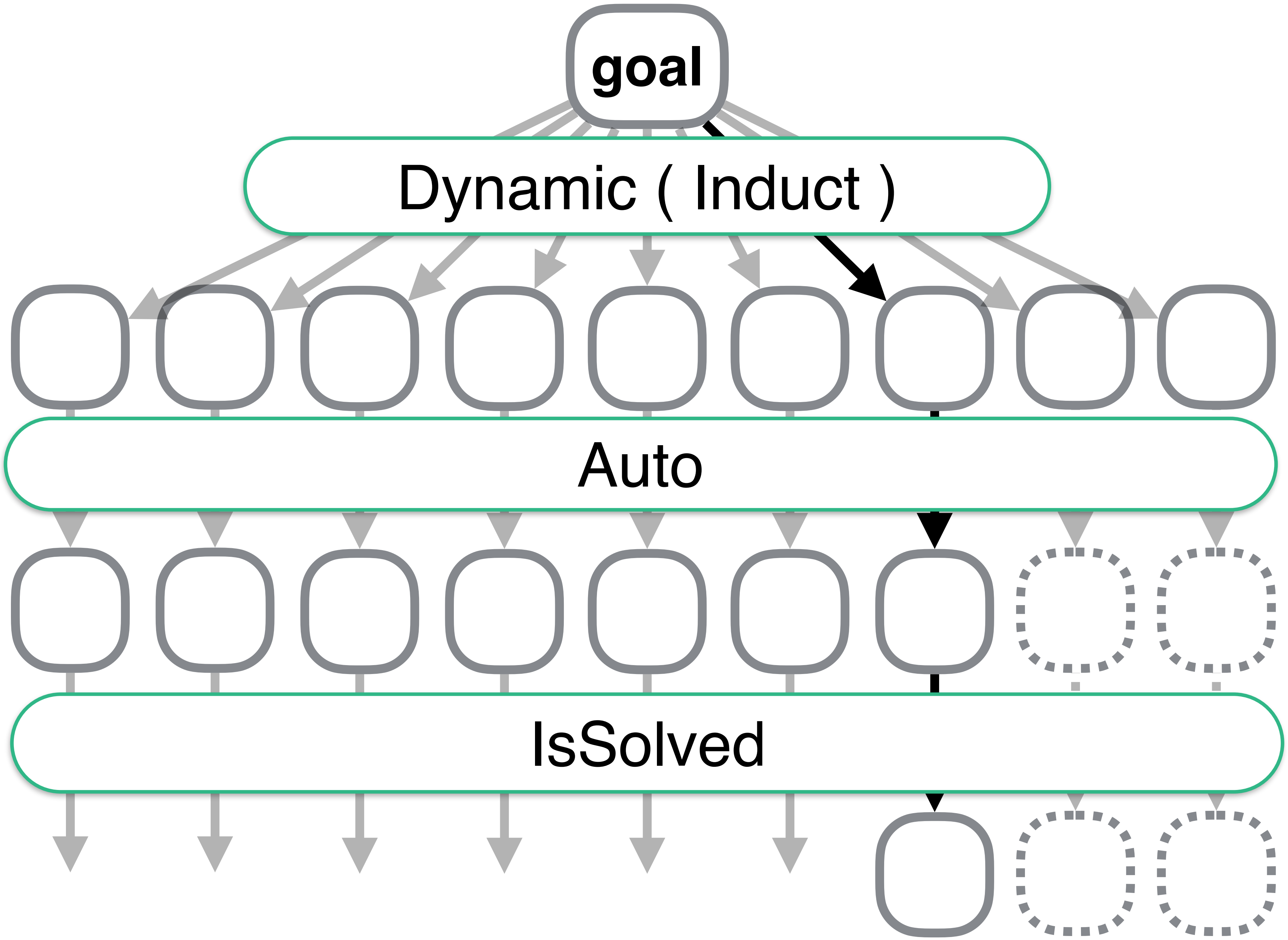

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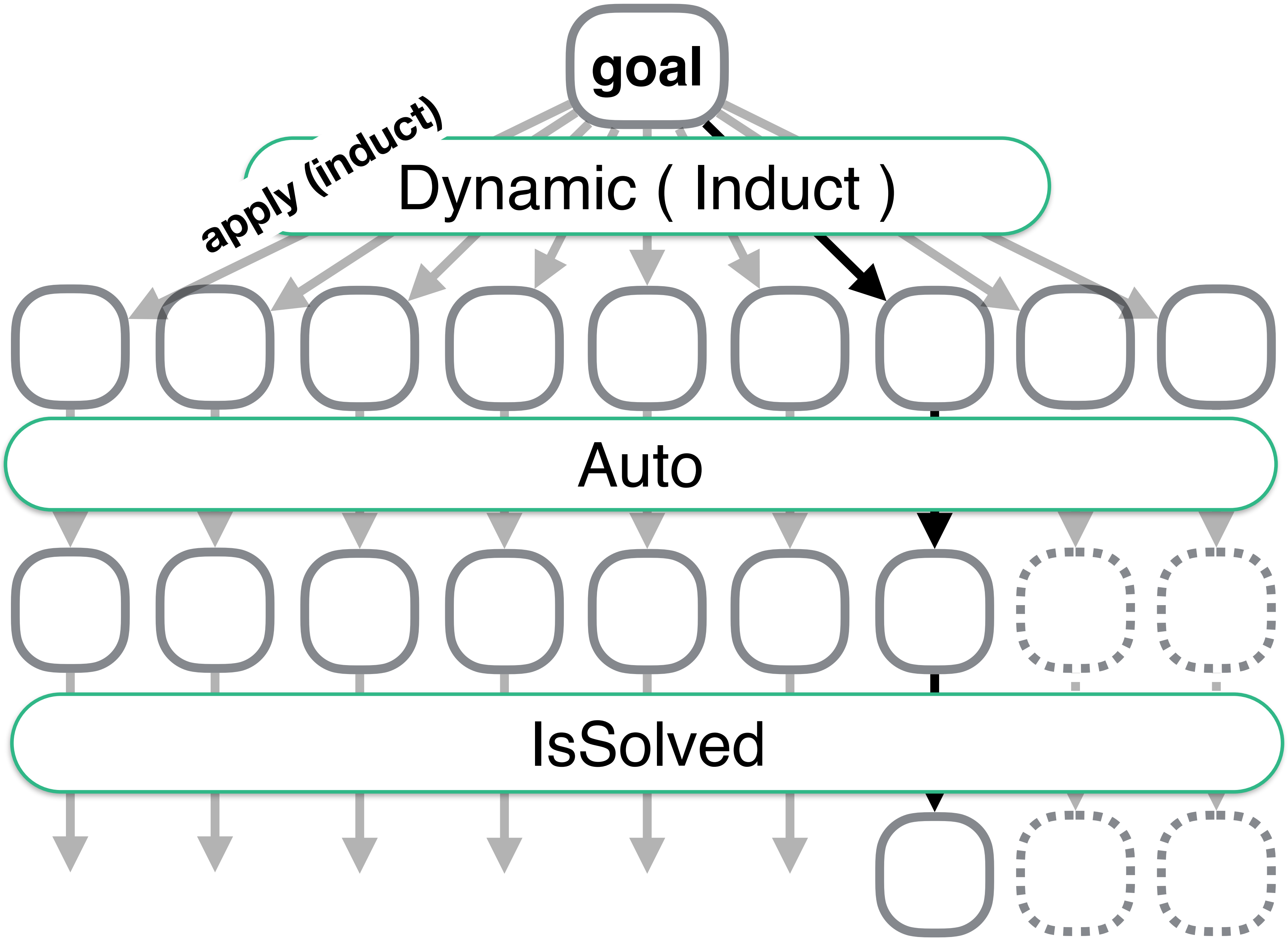

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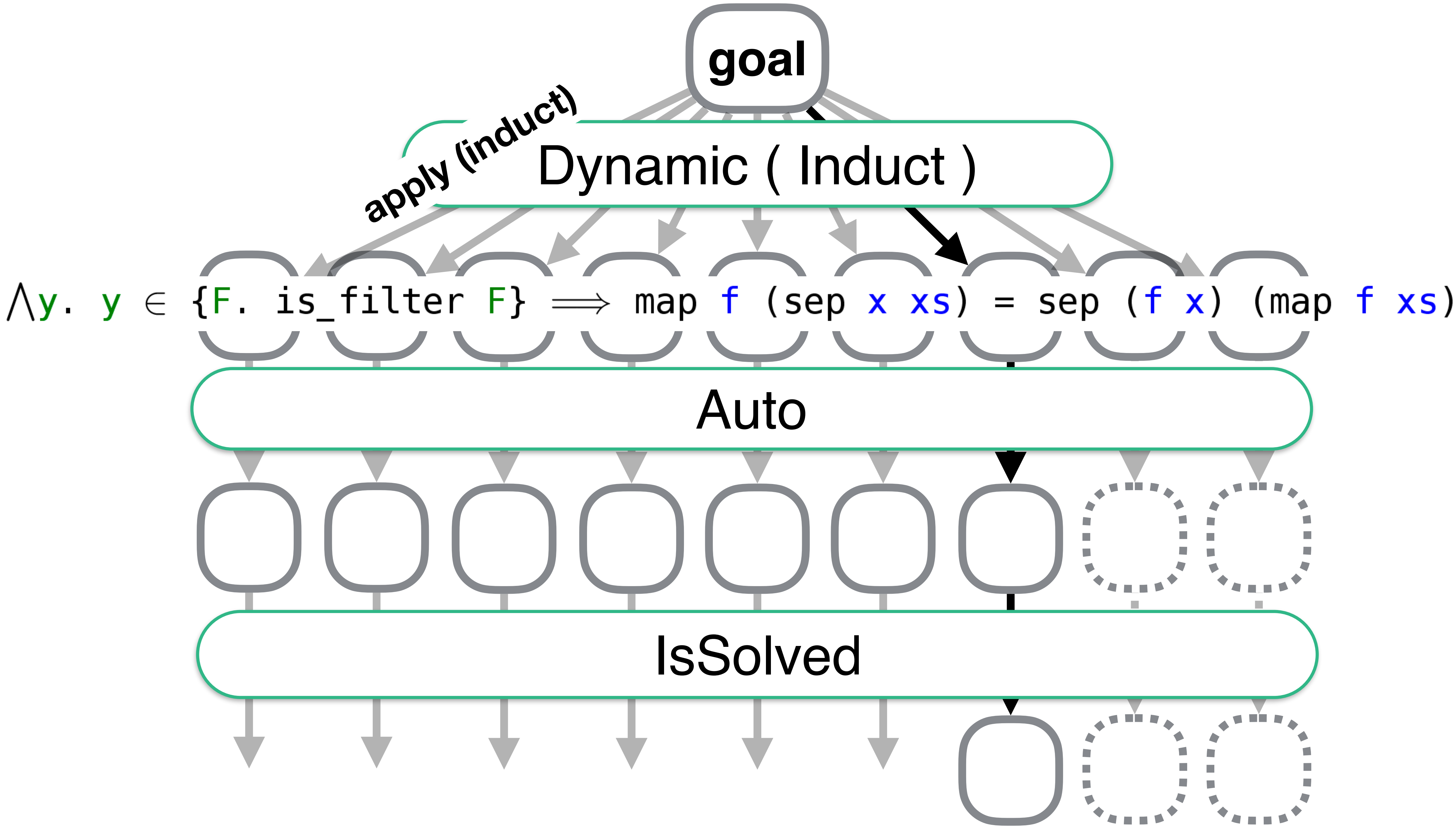

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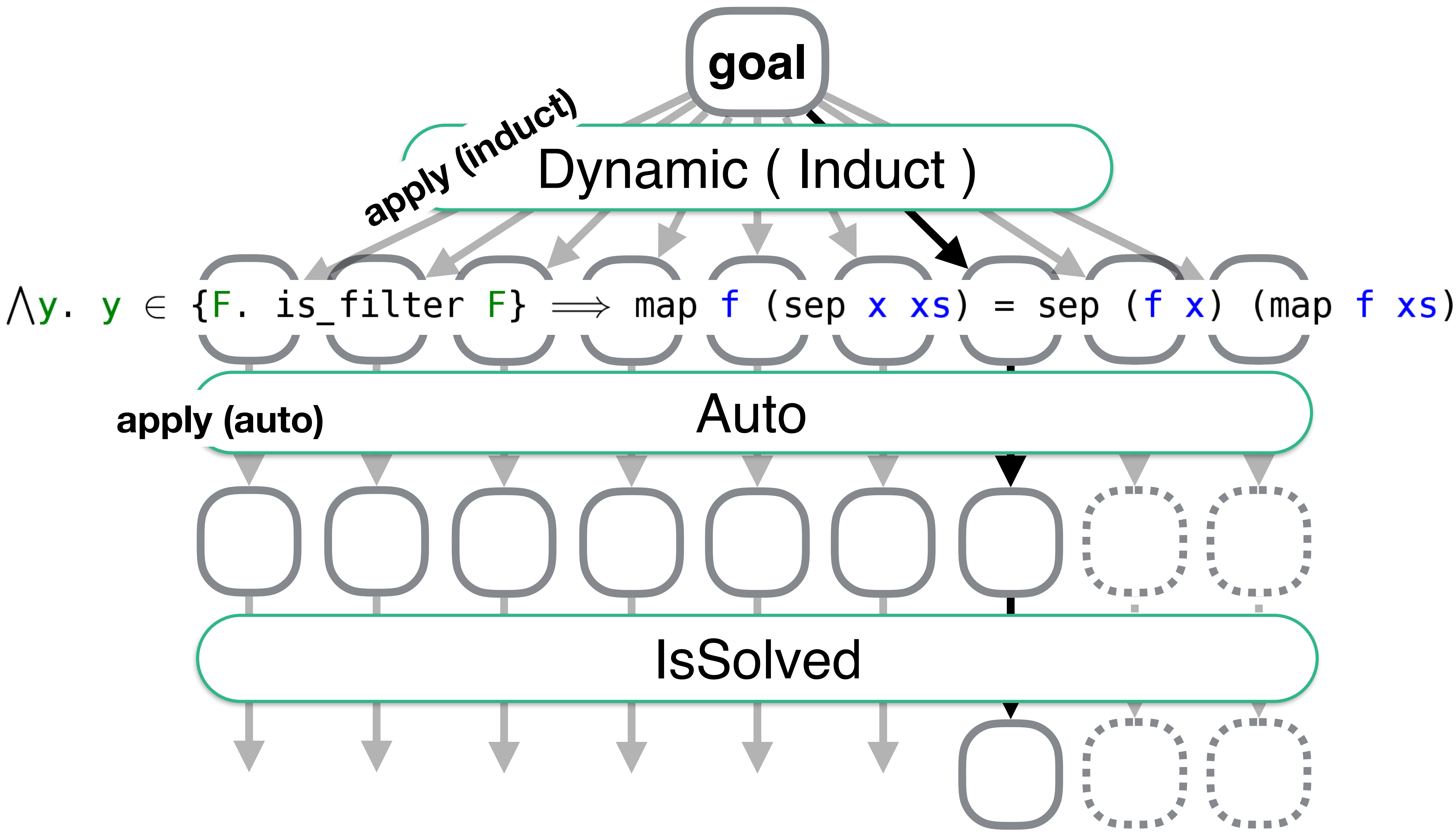

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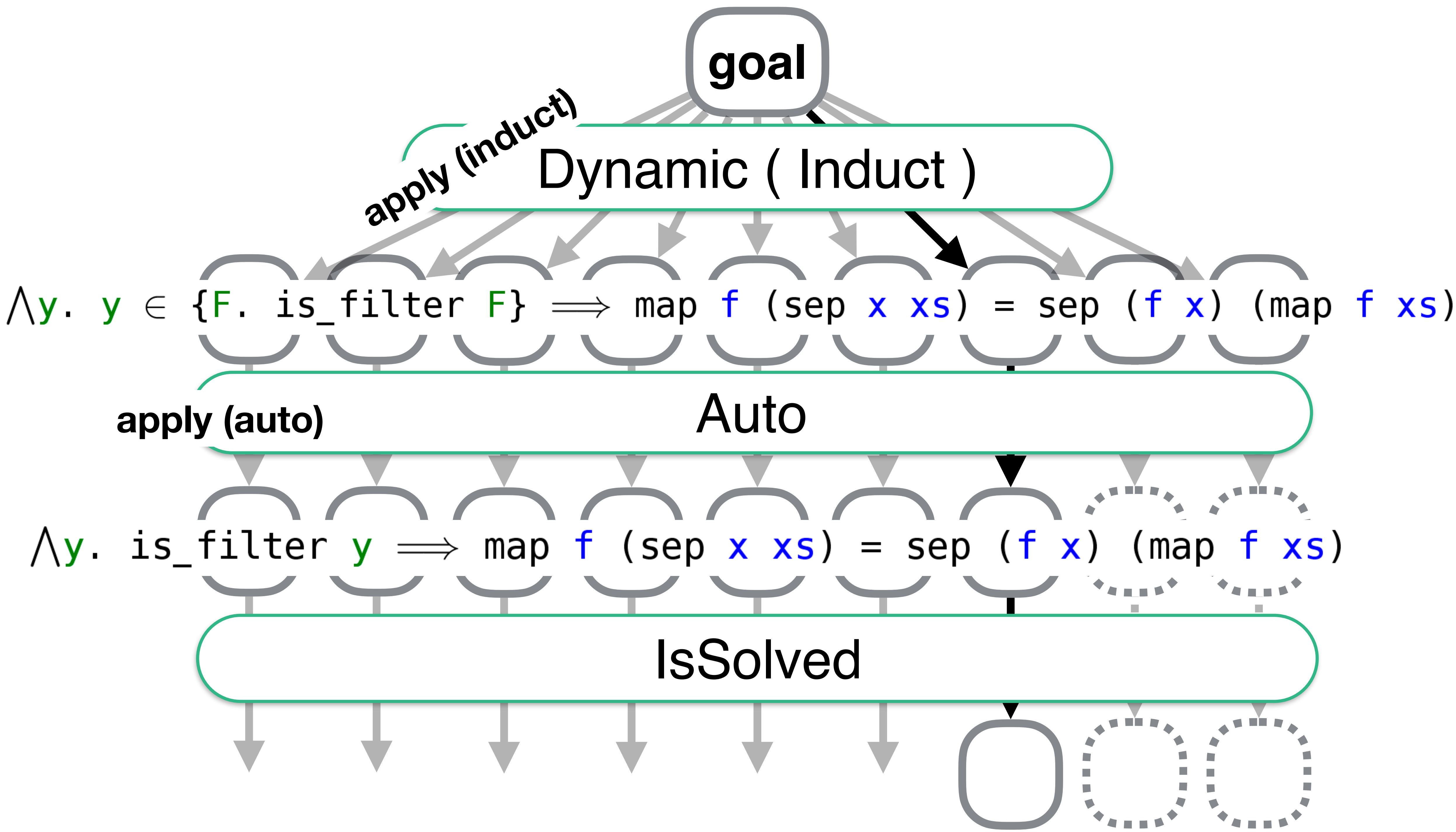

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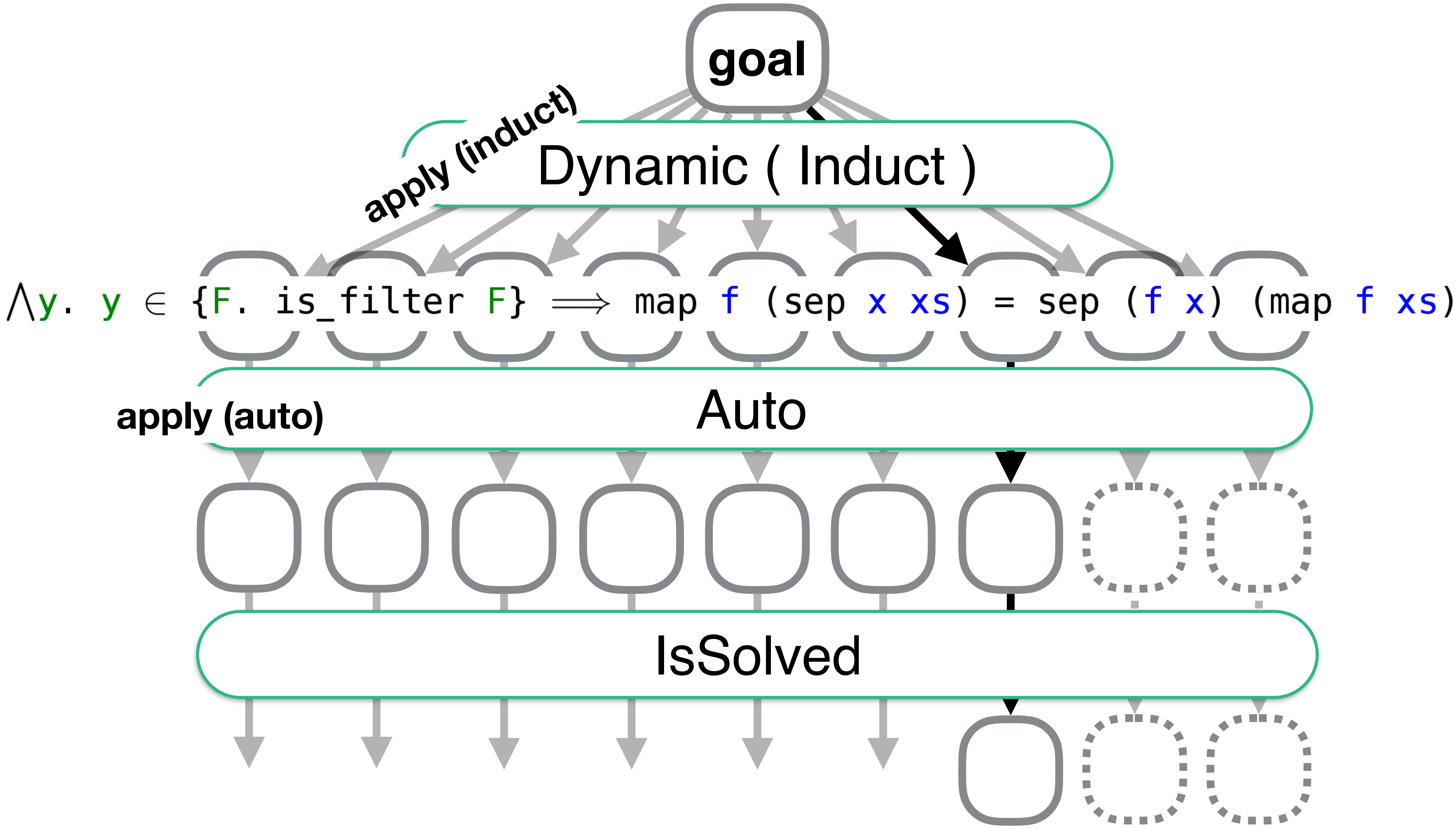

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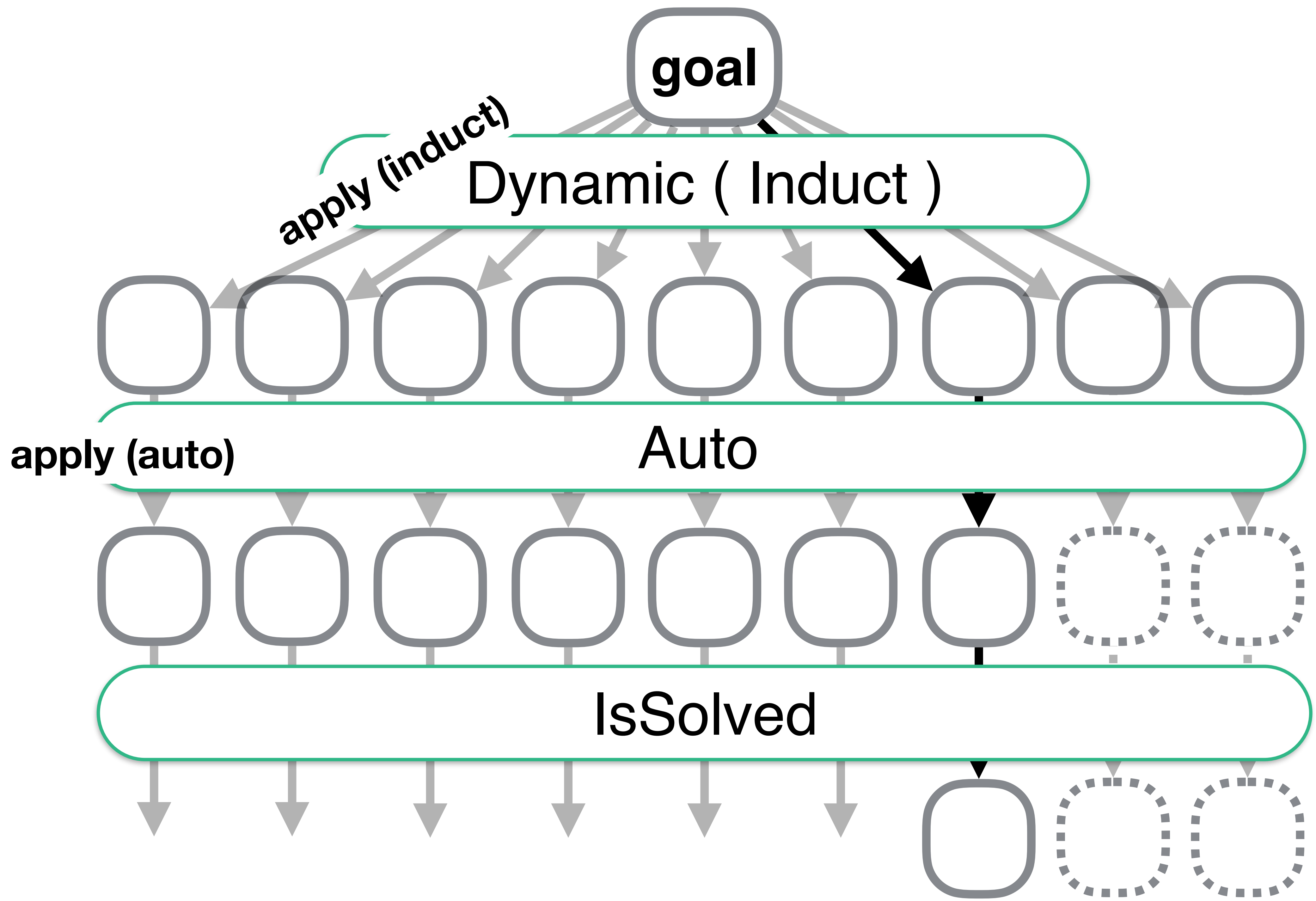

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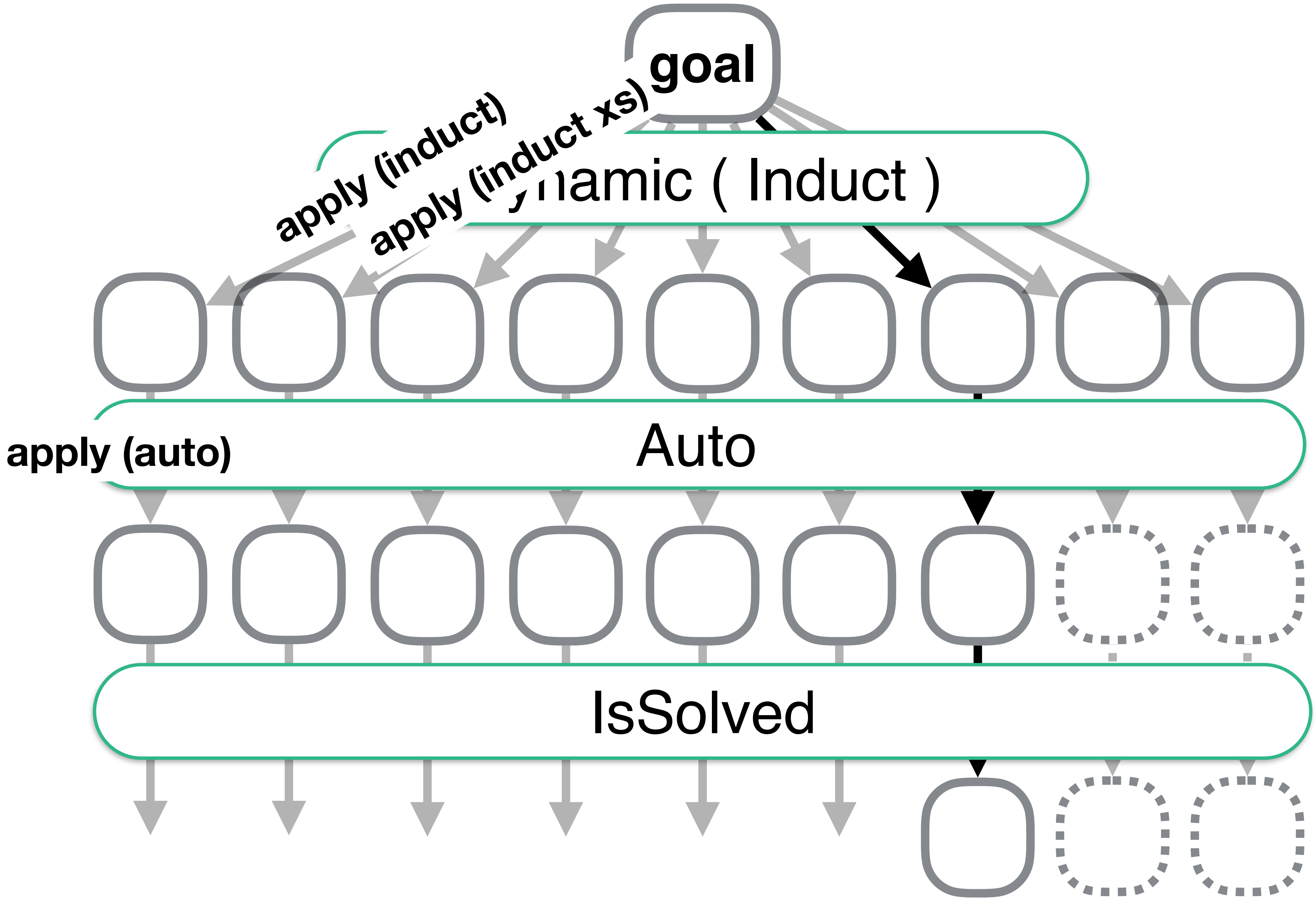

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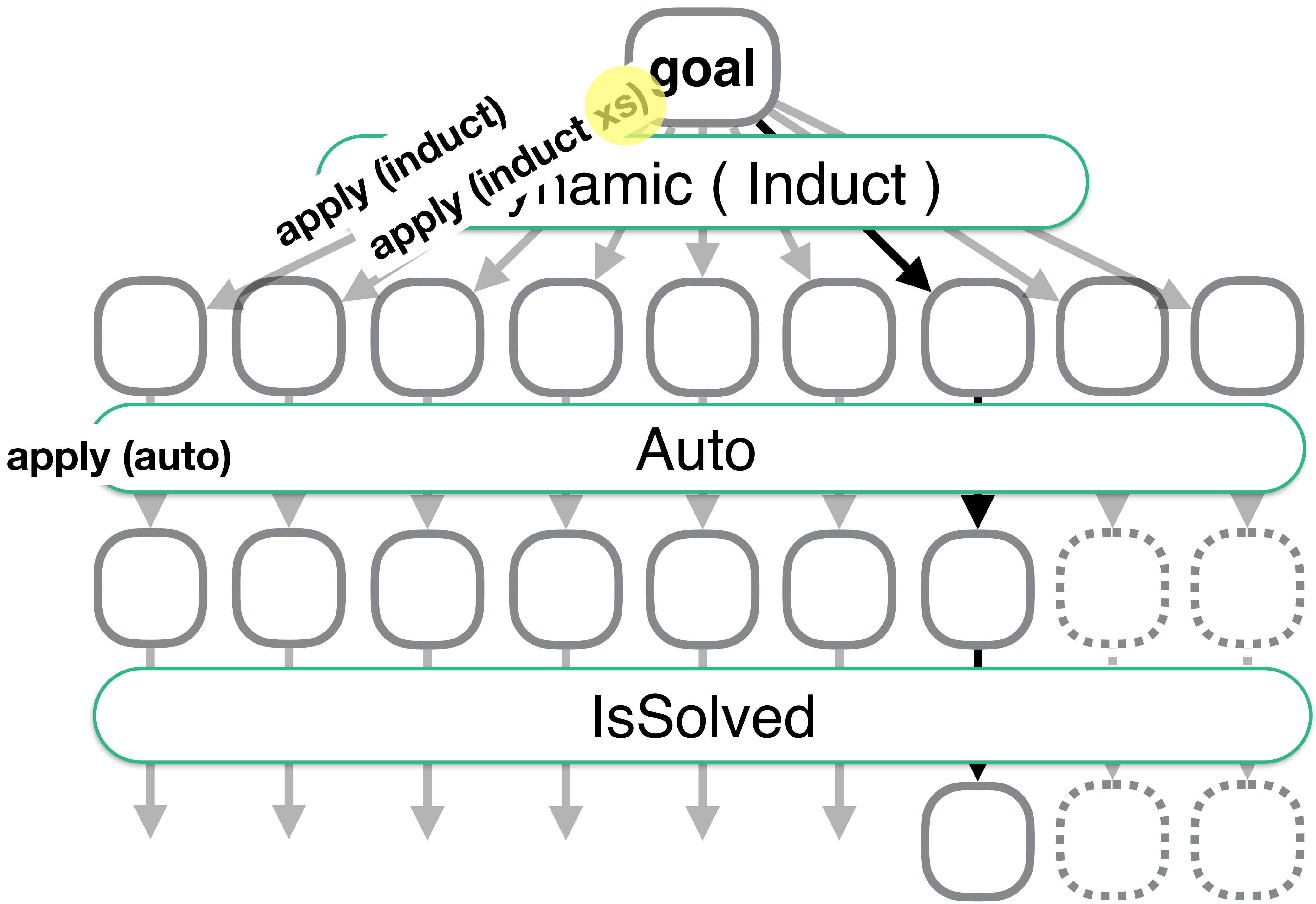

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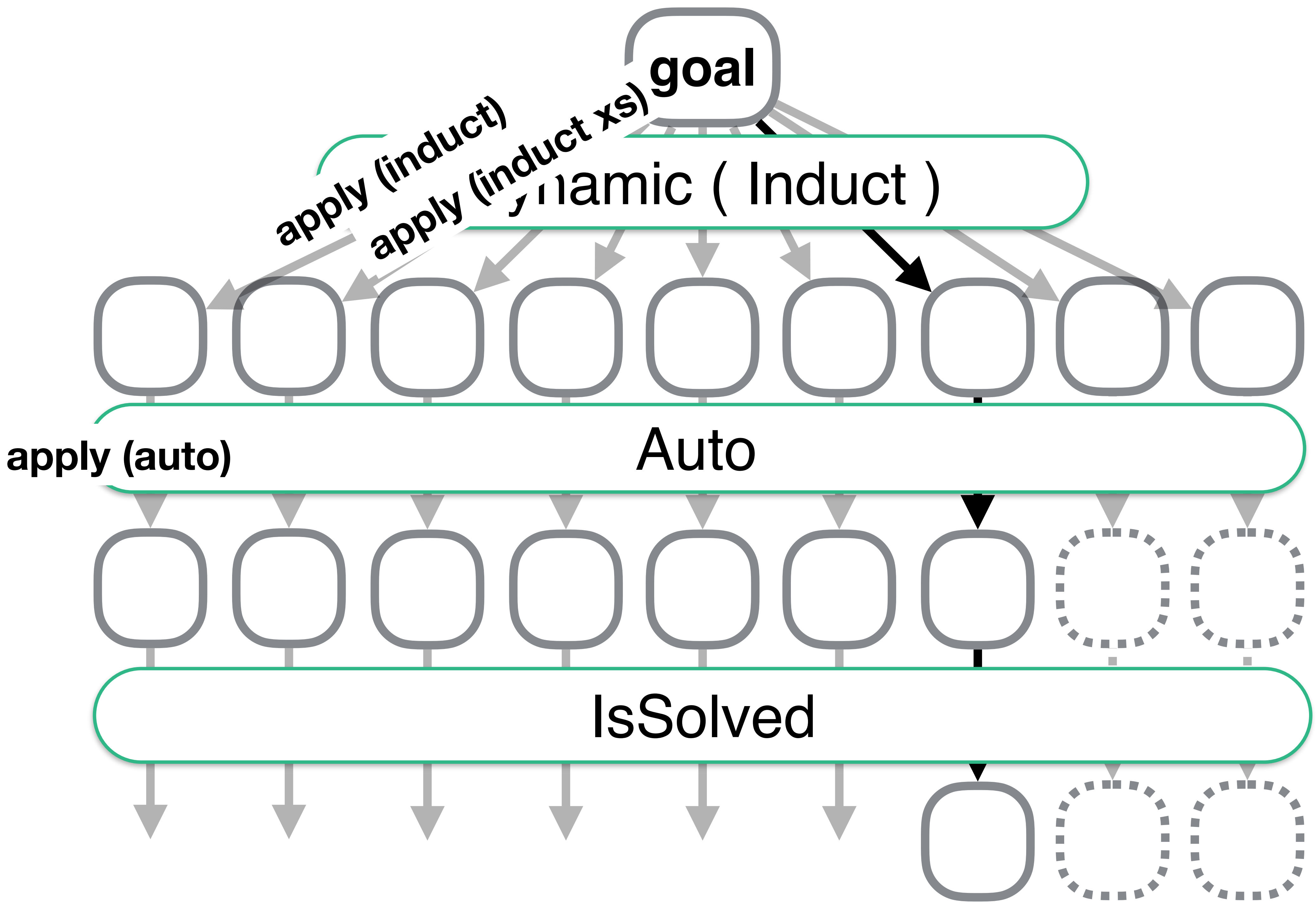

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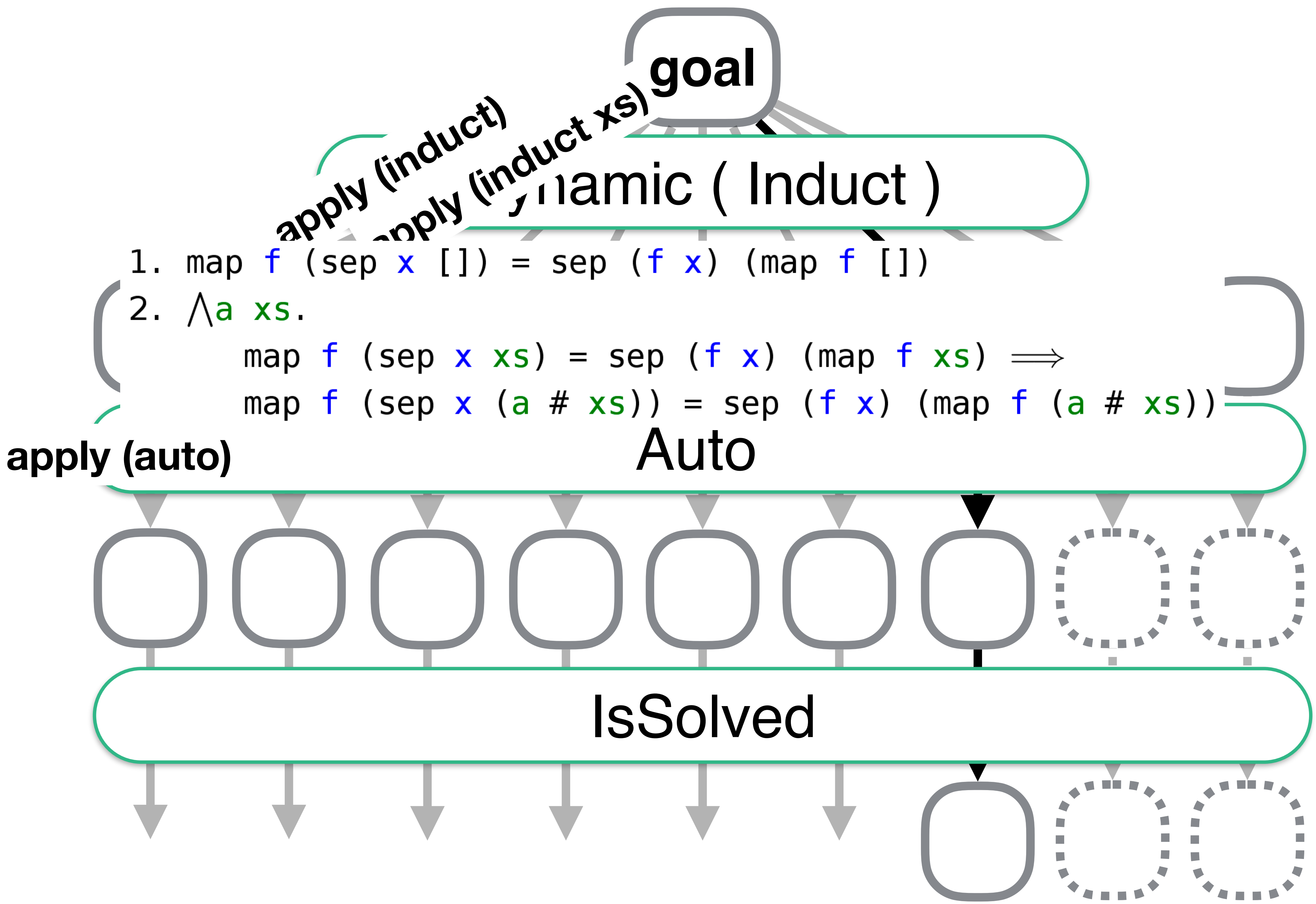

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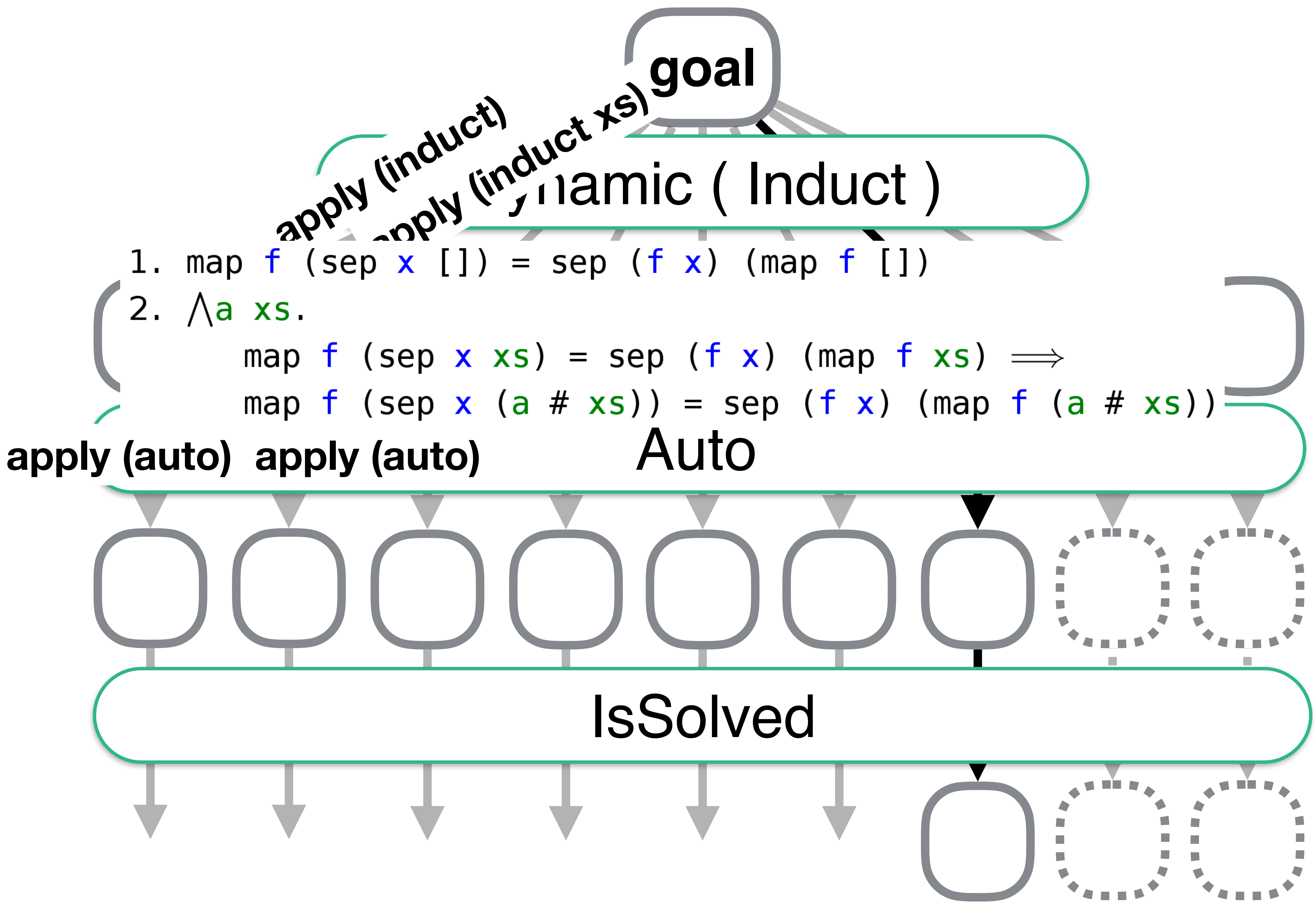

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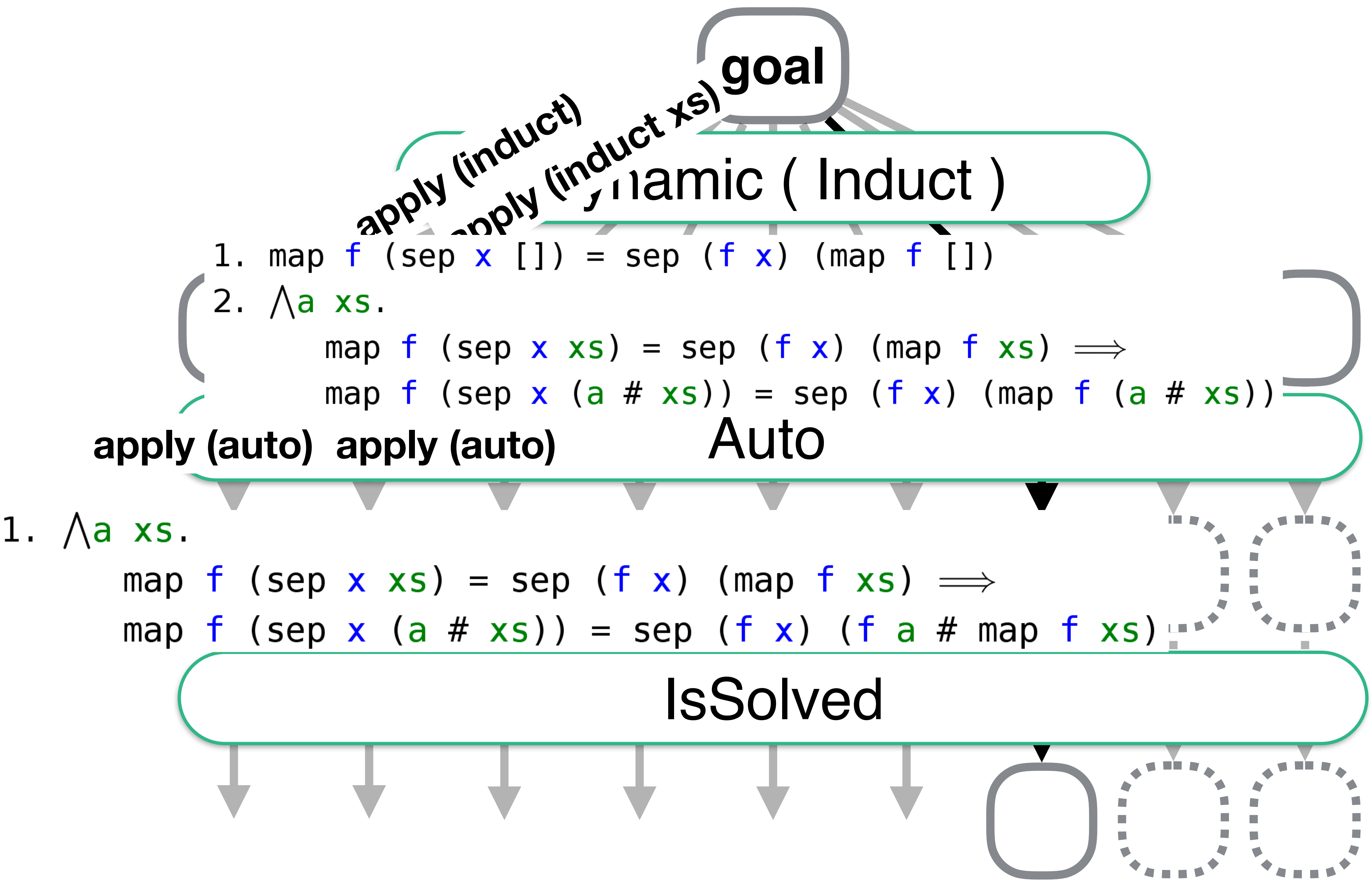

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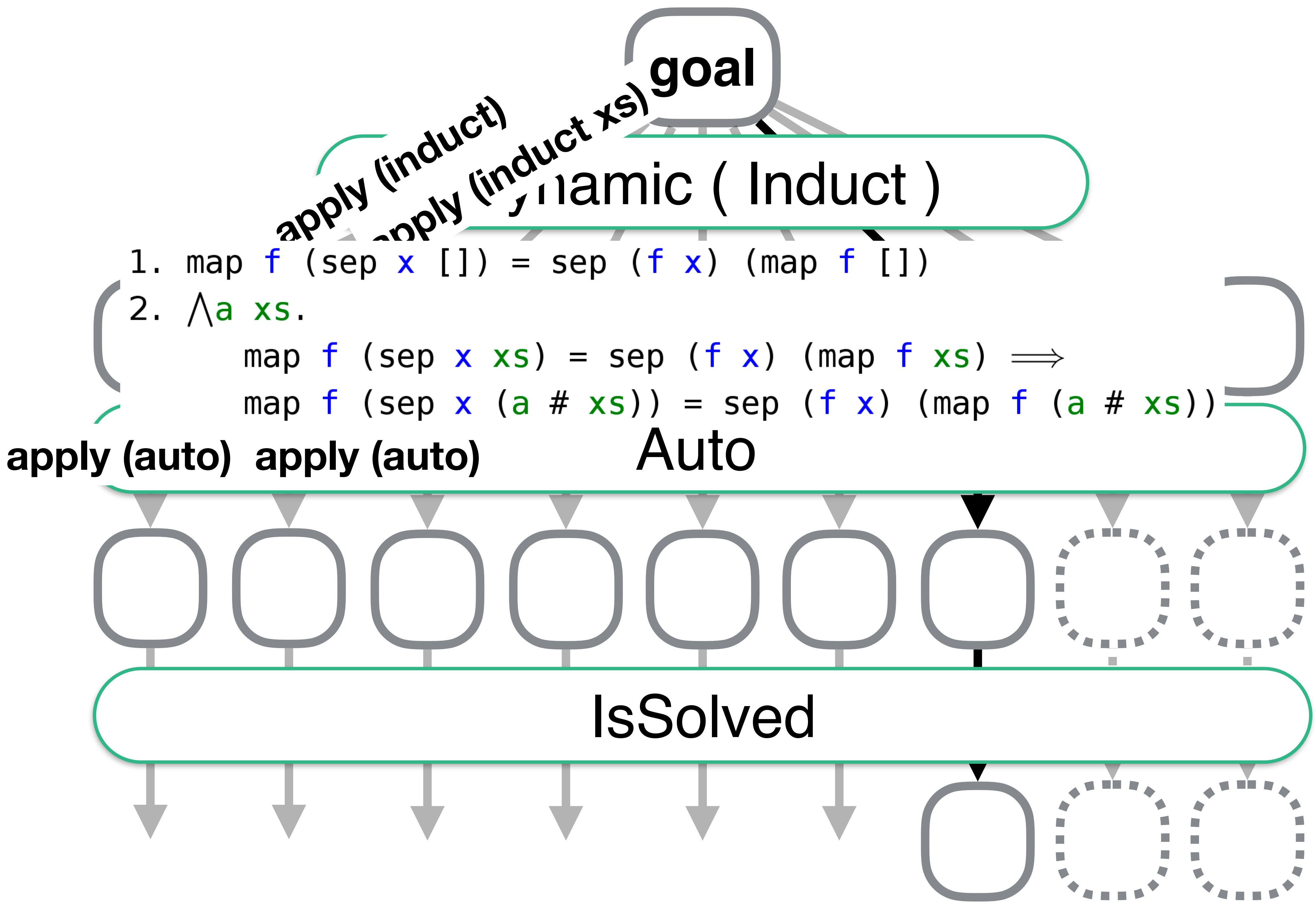

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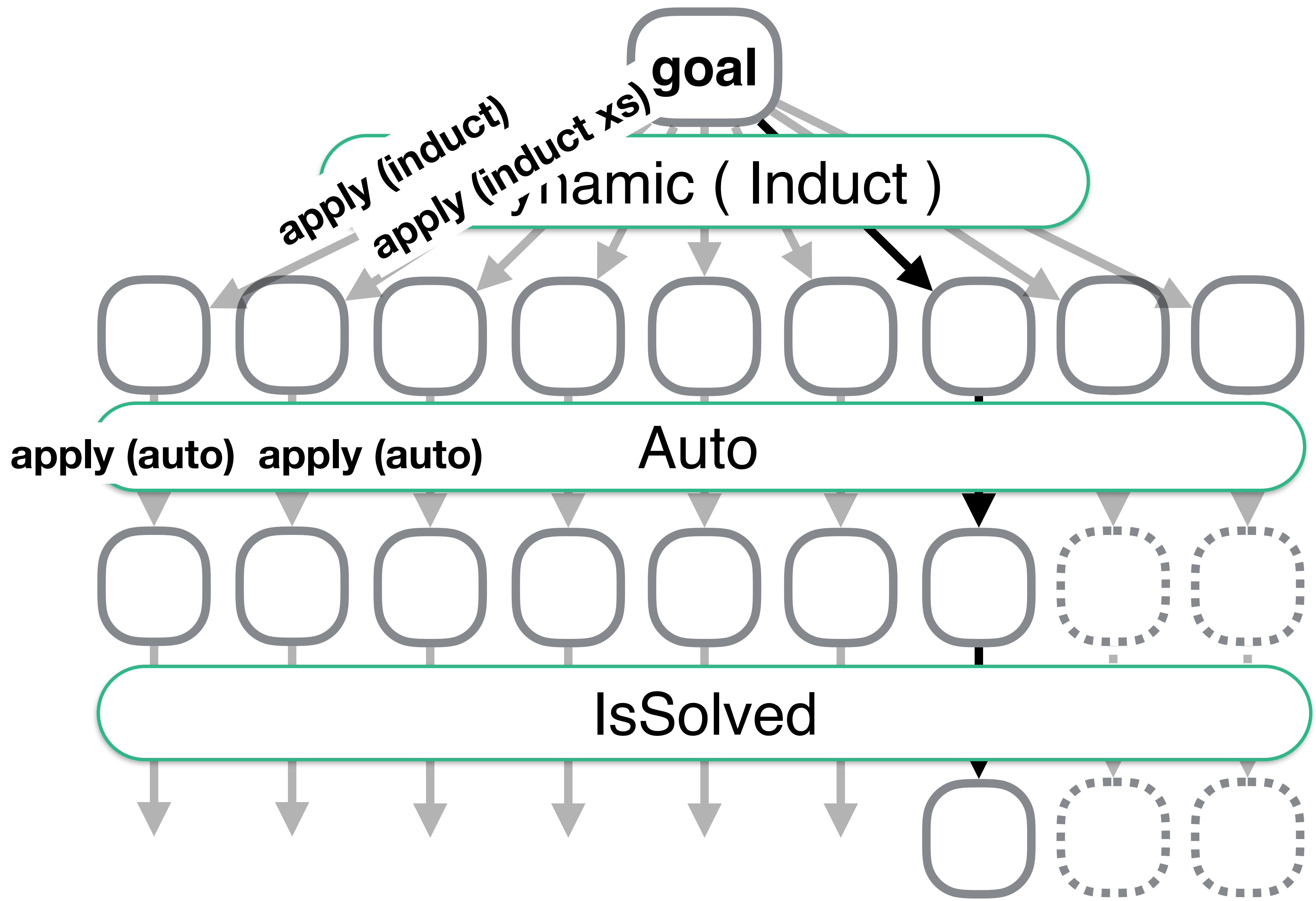

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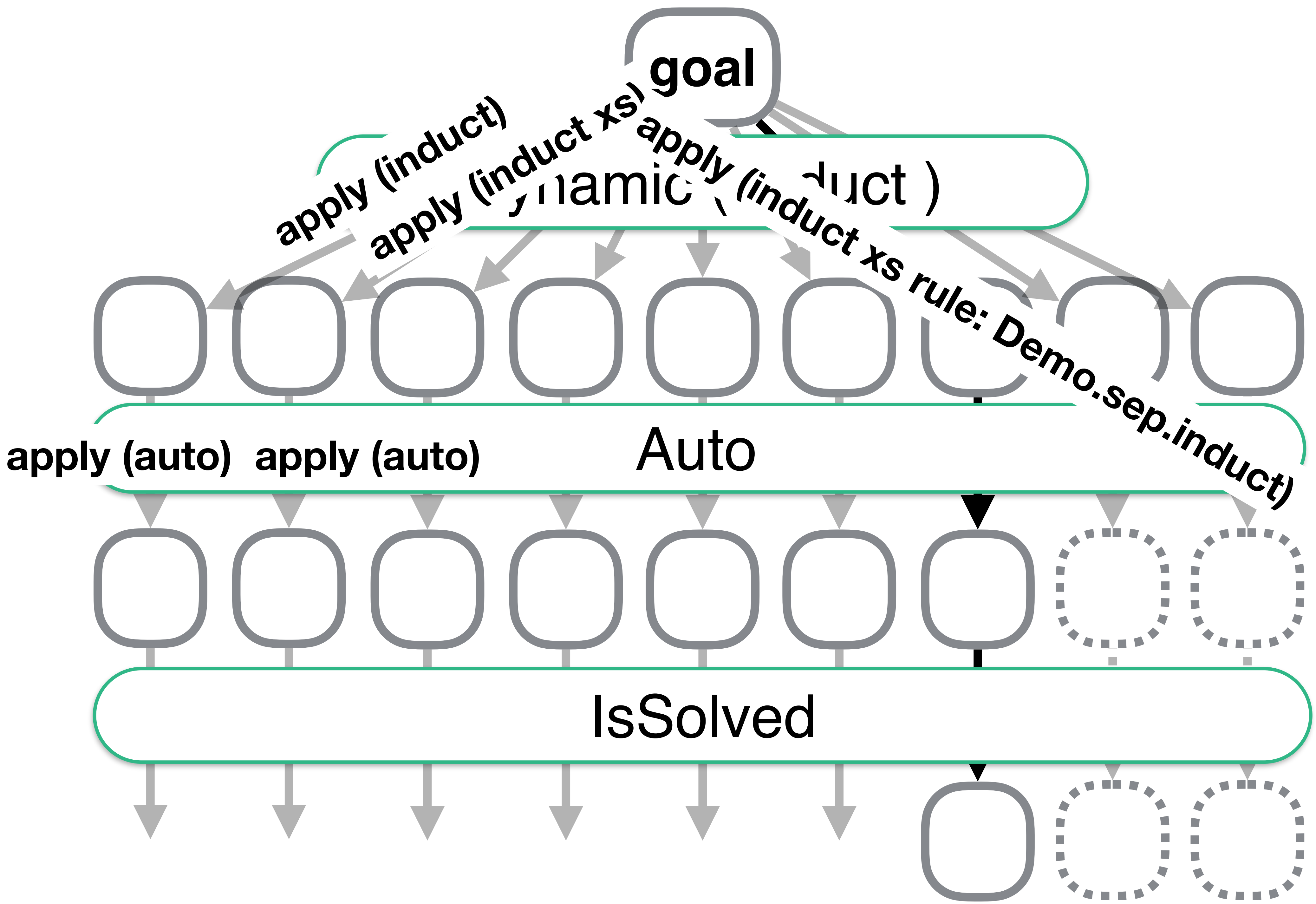

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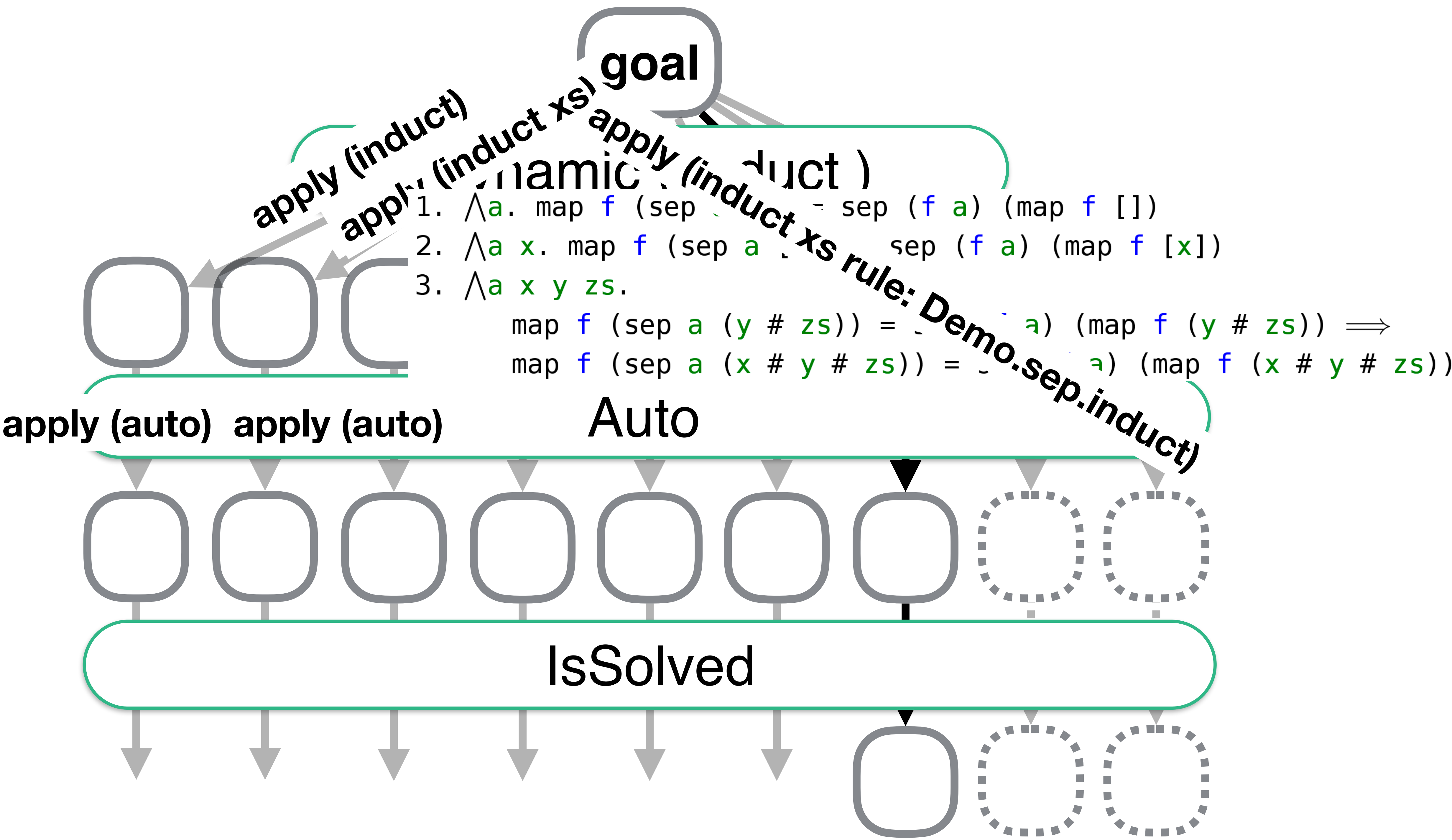

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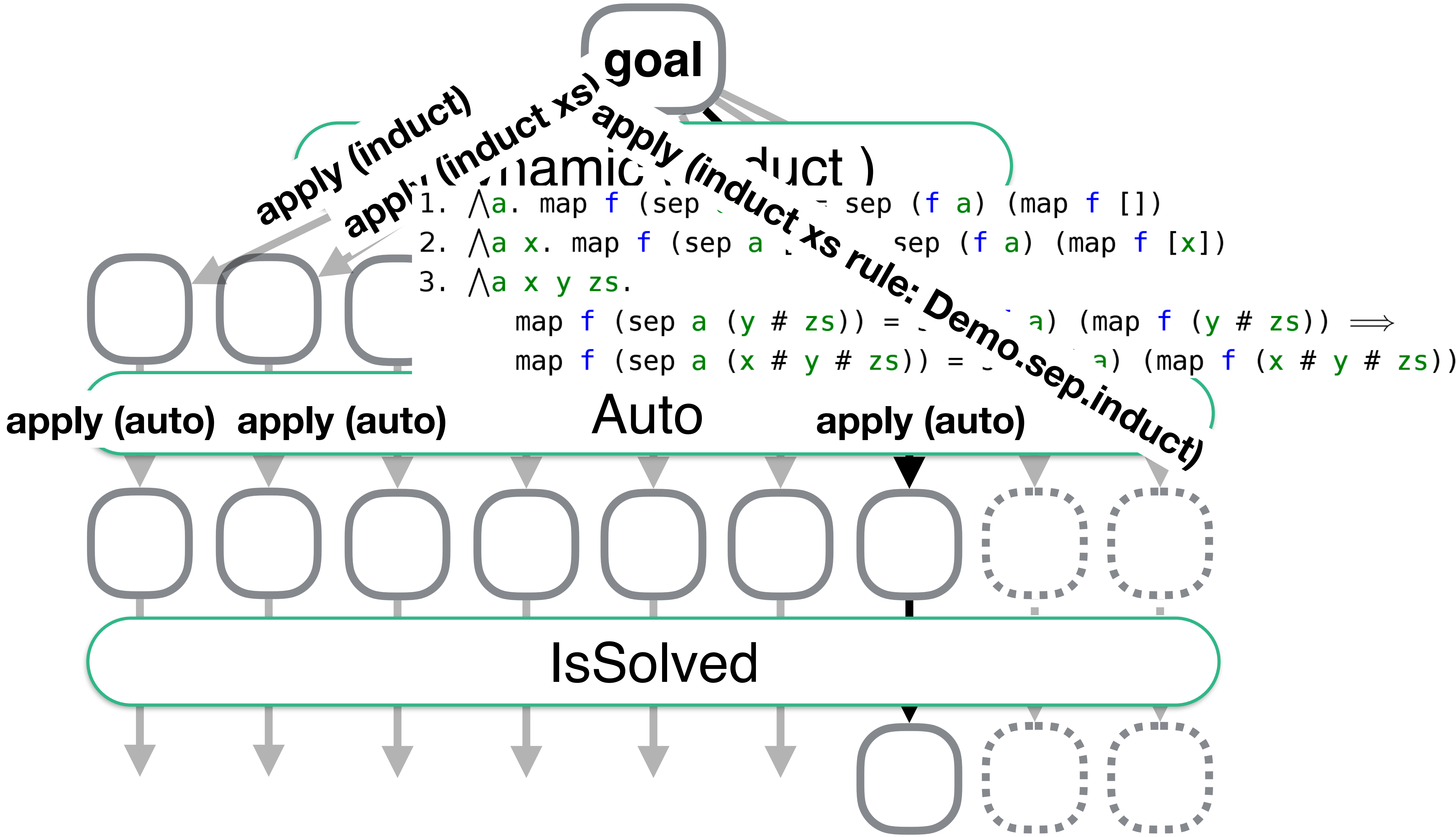

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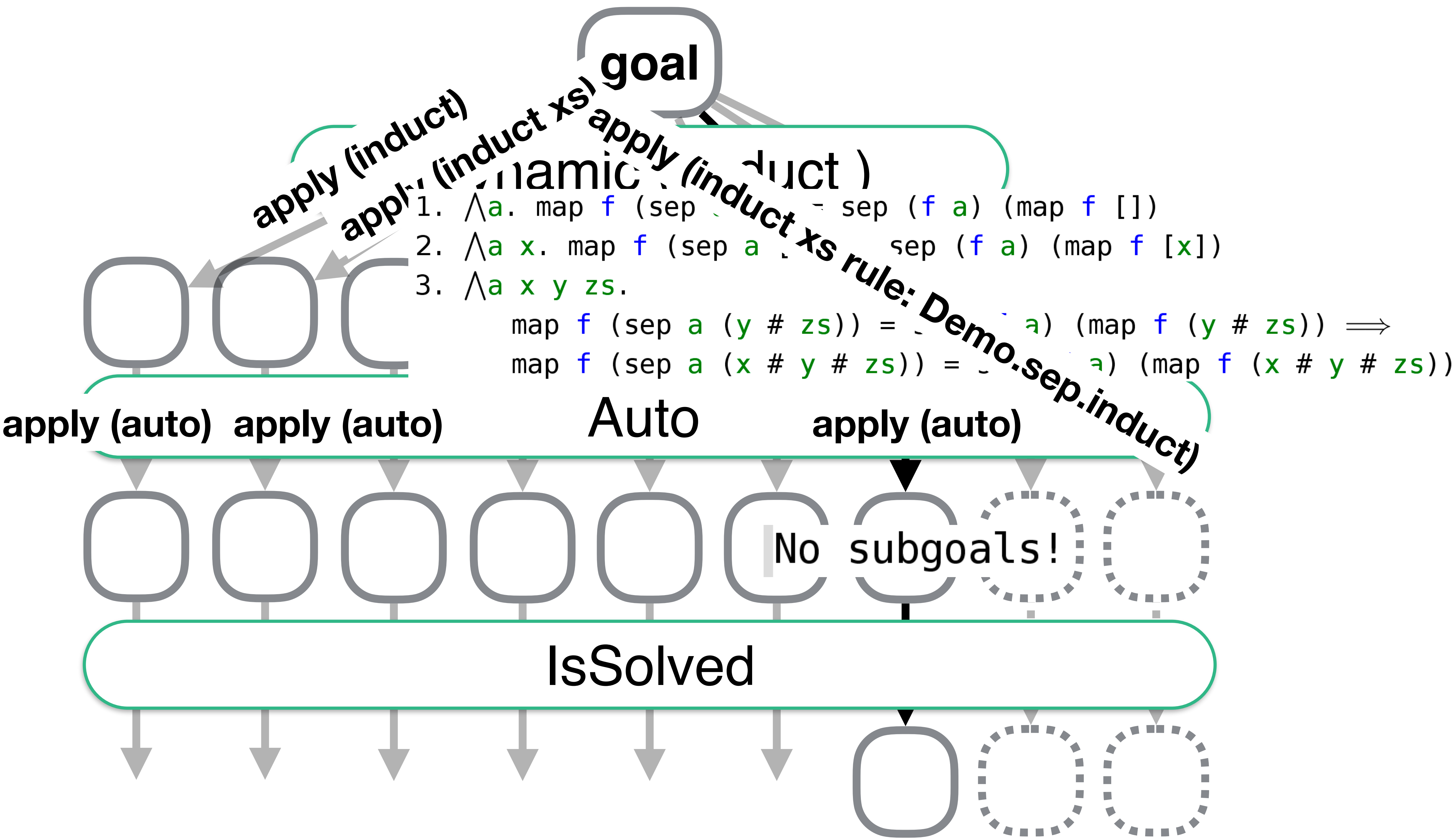

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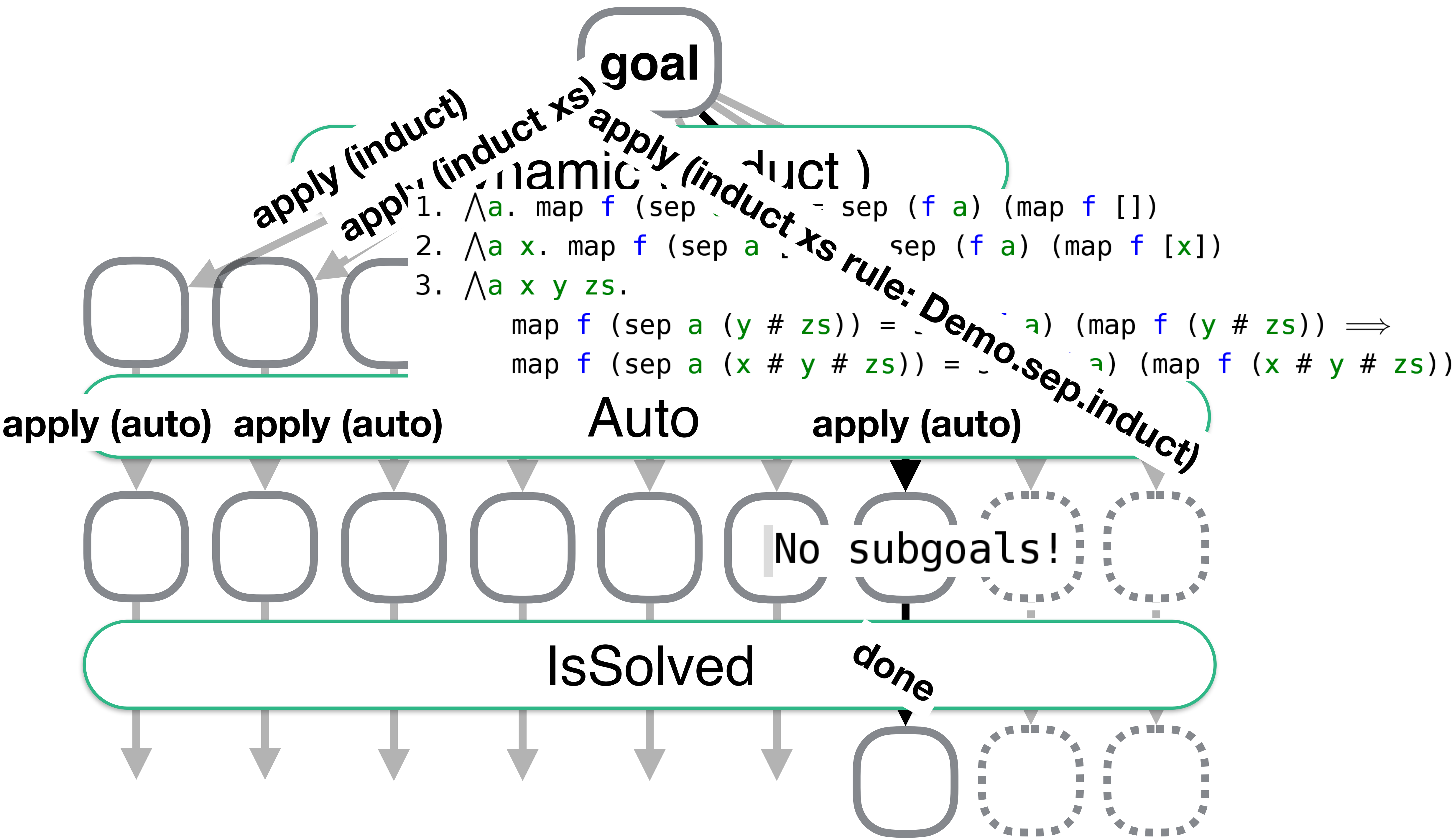

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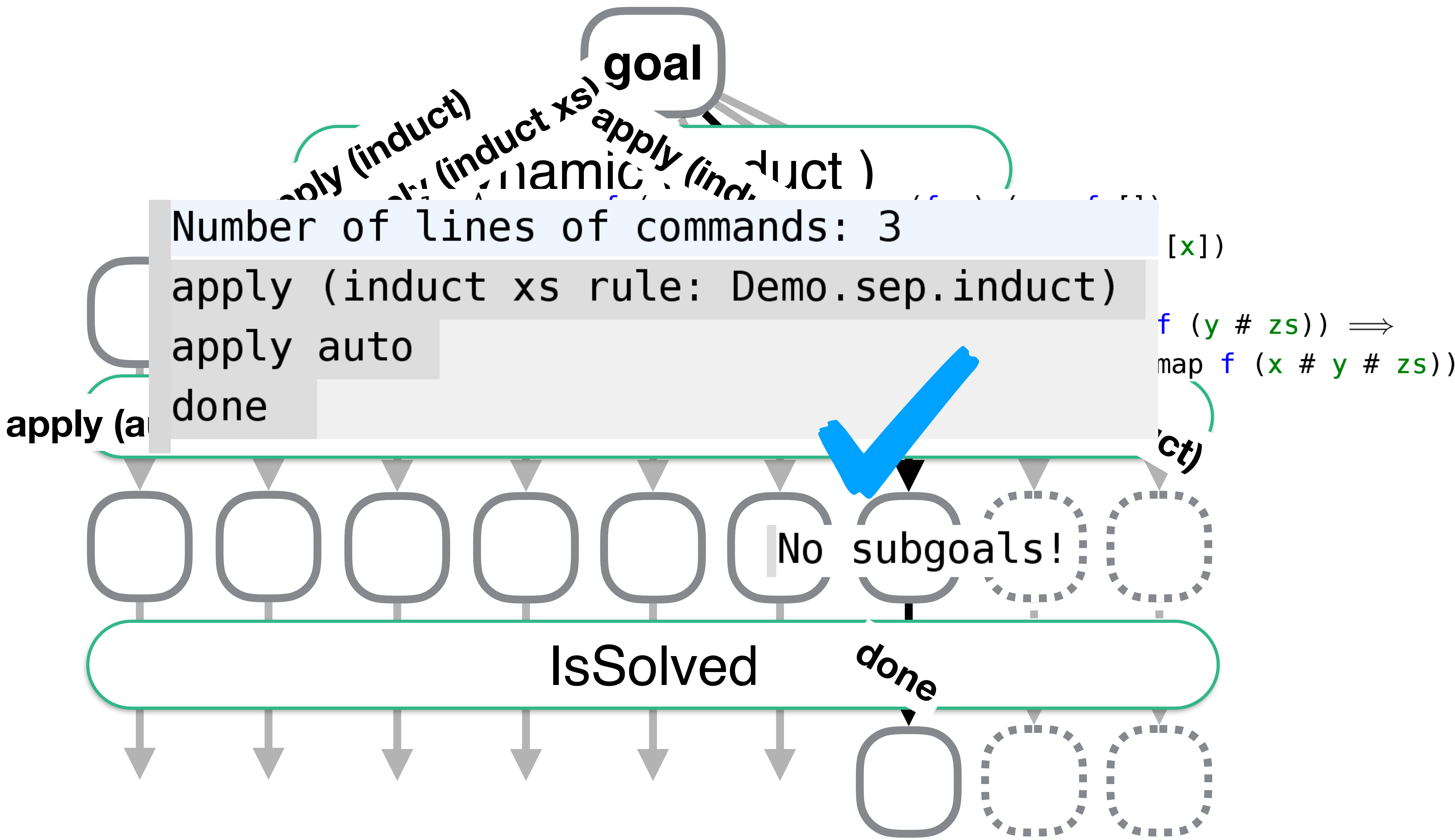


git clone https://github.com/data61/PSL

Try_Hard: the default strategy

```
strategy Try_Hard =
Ors [Thens [Subgoal, Basic],
     Thens [DInductTac, Auto_Solve],
     Thens [DCaseTac, Auto_Solve],
     Thens [Subgoal, Advanced],
     Thens [DCaseTac, Solve_Many],
     Thens [DInductTac, Solve_Many] ]
```

```
strategy Basic =
 Ors [
   Auto_Solve,
   Blast_Solve,
   FF_Solve,
   Thens [IntroClasses, Auto_Solve],
   Thens [Transfer, Auto_Solve],
   Thens [Normalization, IsSolved],
   Thens [DInduct, Auto_Solve],
   Thens [Hammer, IsSolved],
   Thens [DCases, Auto_Solve],
   Thens [DCoinduction, Auto_Solve],
   Thens [Auto, RepeatN(Hammer), IsSolved],
   Thens [DAuto, IsSolved]]
```

16 percentage point performance improvement compared to sledgehammer

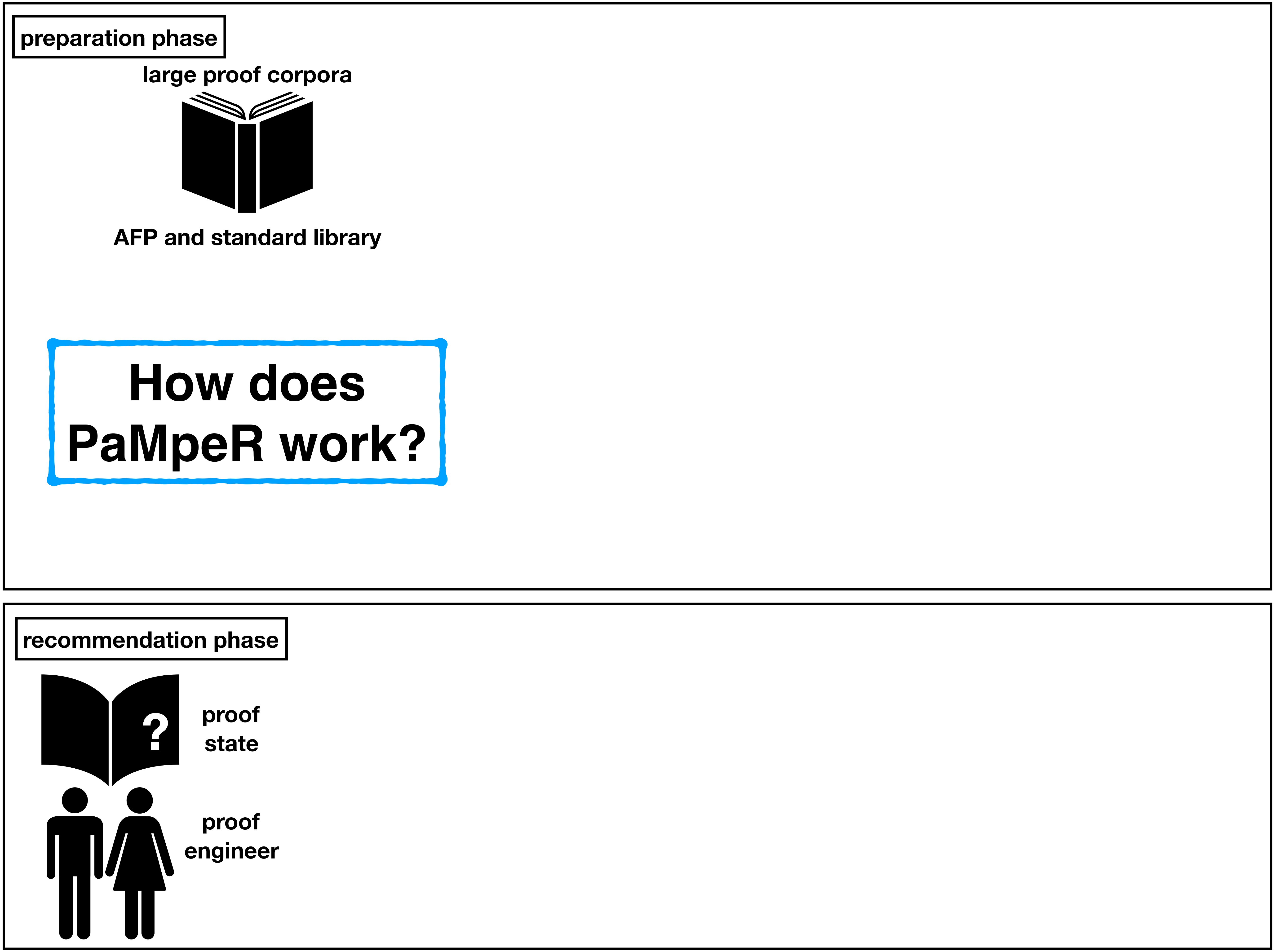
but the search space explodes

PaMpeR: Proof Method Recommendation

preparation phase

How does PaMpeR work?

recommendation phase


preparation phase
large proof corpora
AFP and standard library
How does PaMpeR work?
recommendation phase
proof state
proof engineer

preparation phase

large proof corpora

AFP and standard library

Statistics

Archive of Formal Proofs (https://www.isa-afp.org)

Statistics

Number of Articles:	468
Number of Authors:	313
Number of lemmas:	~128,900
Lines of Code:	~2,170,300

Most used AFP articles:

	Name	Used by ? articles
1.	Collections	15
2.	List-Index	14
3.	Coinductive	12

preparation phase

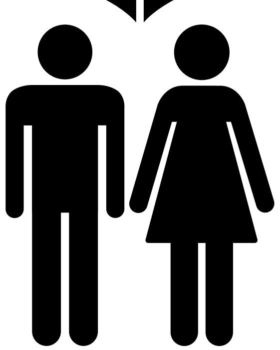
large proof corpora

AFP and standard library

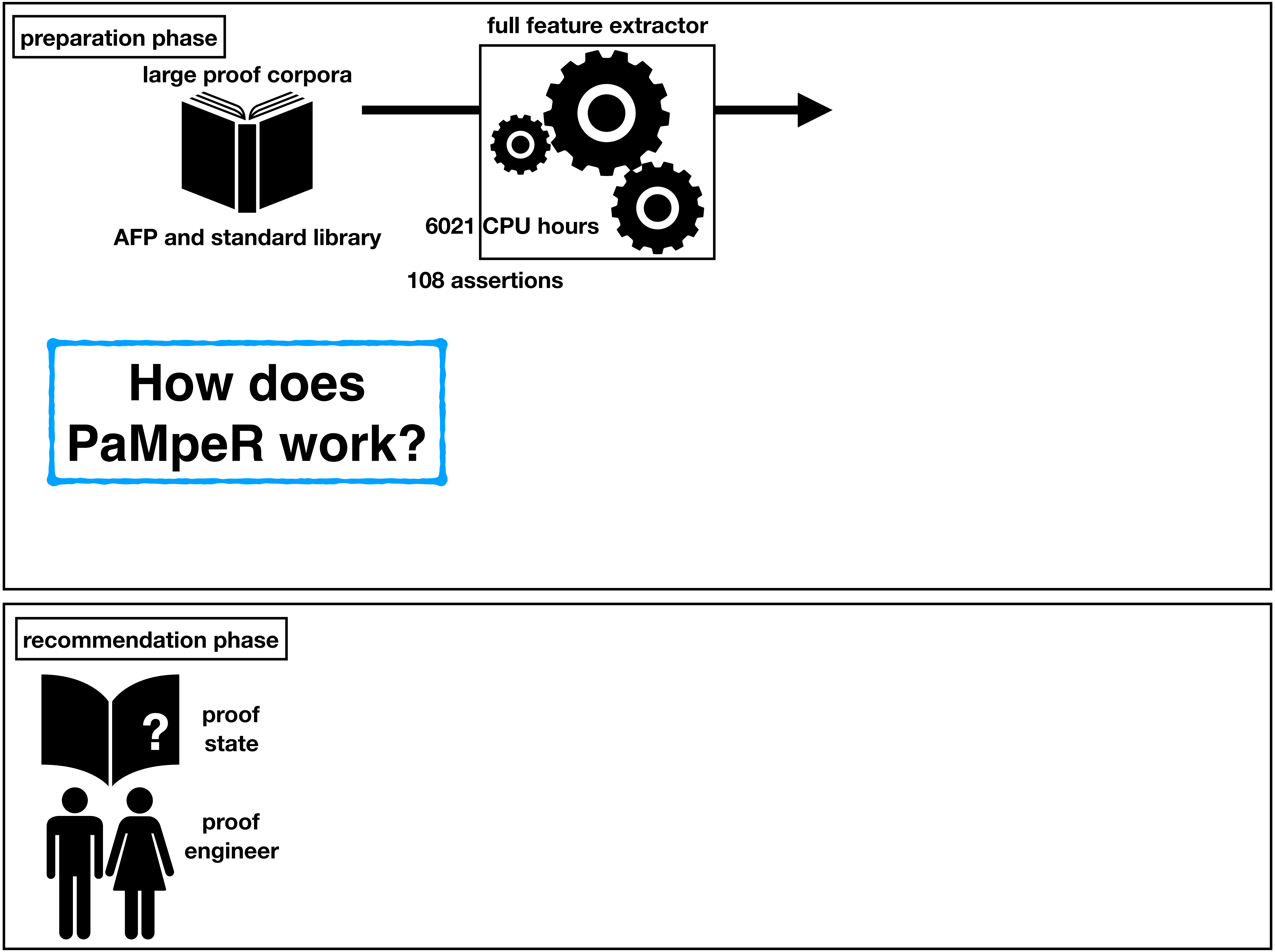
How does PaMpeR work?

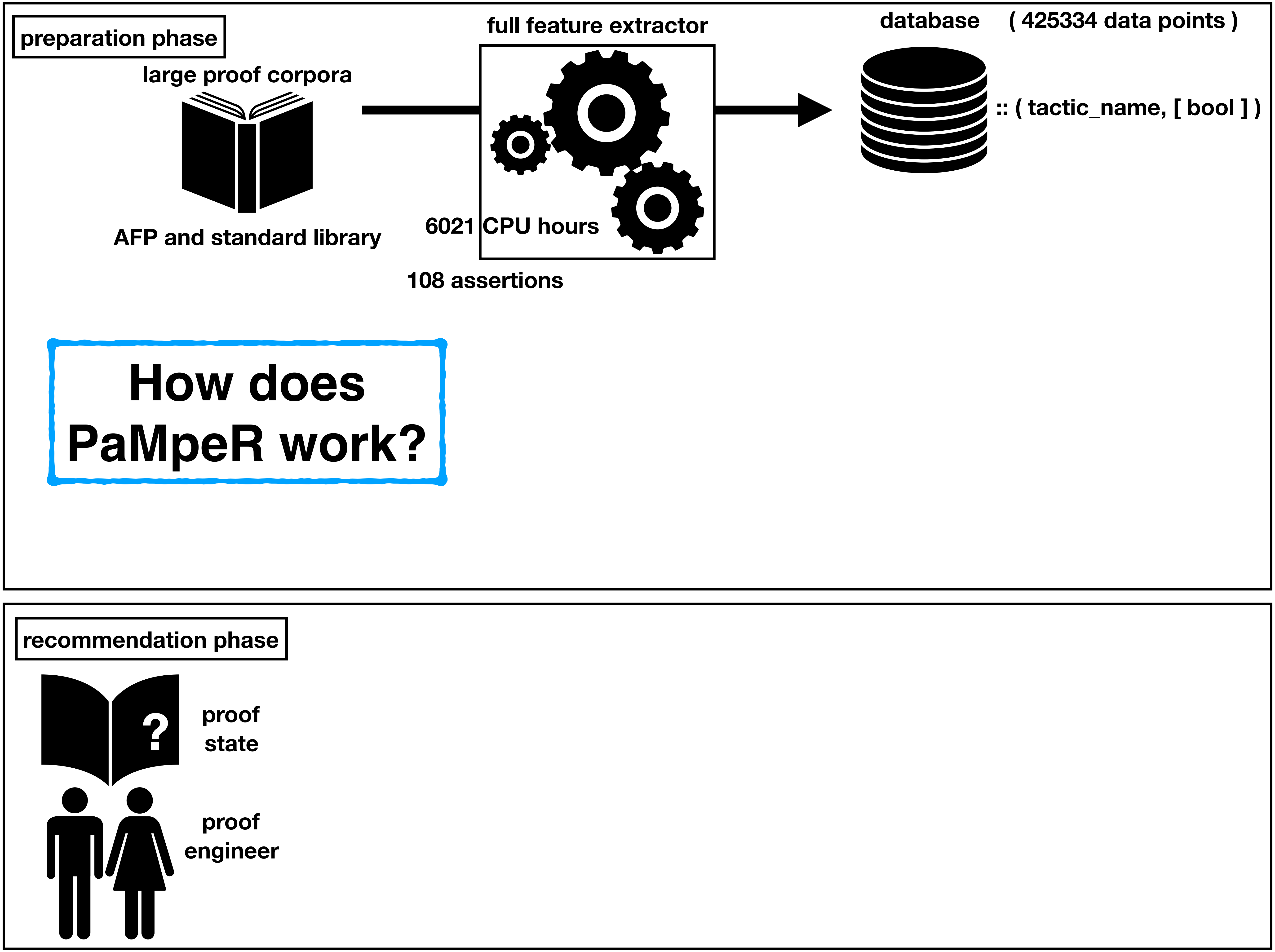
recommendation phase

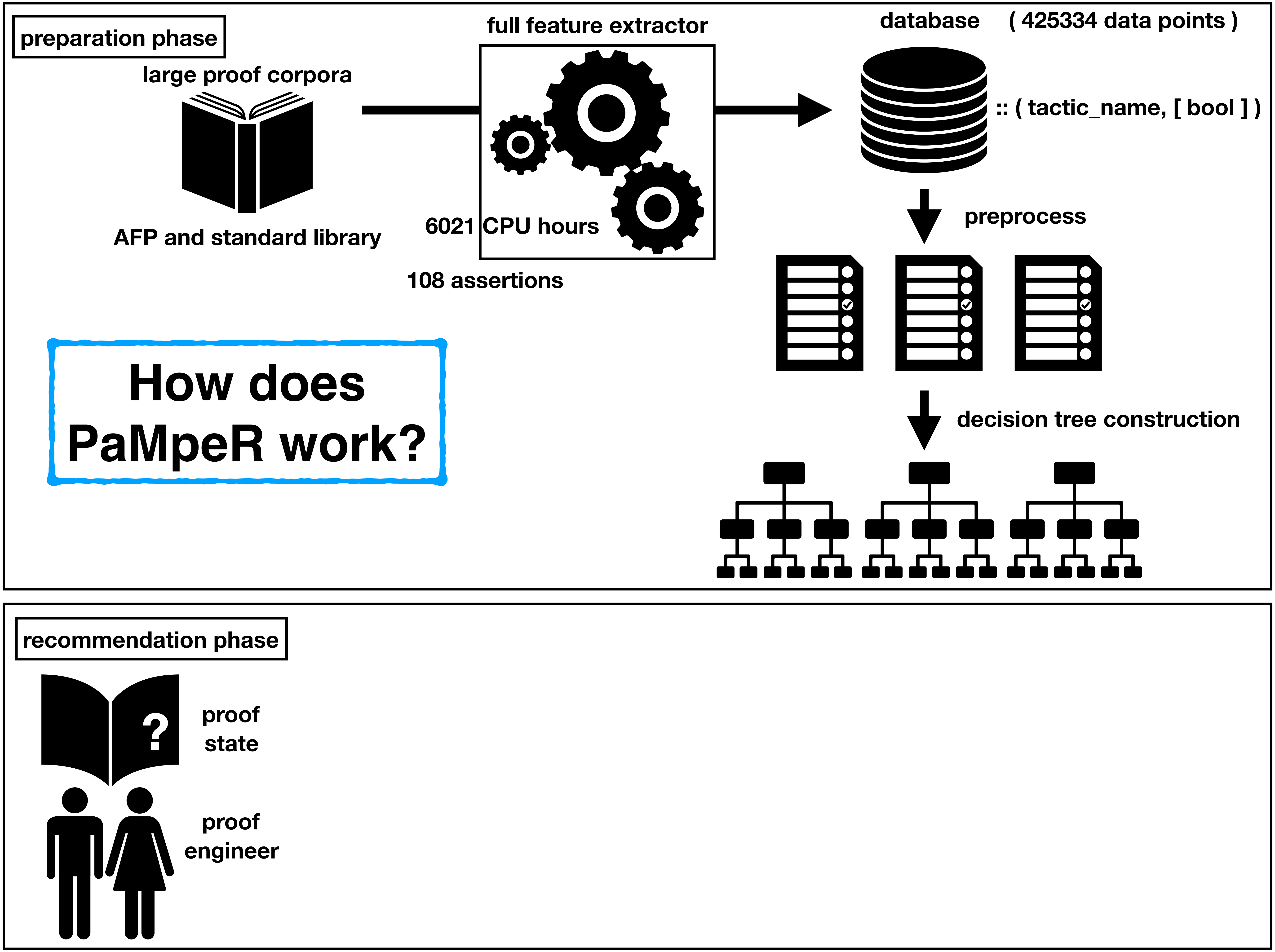
proof state

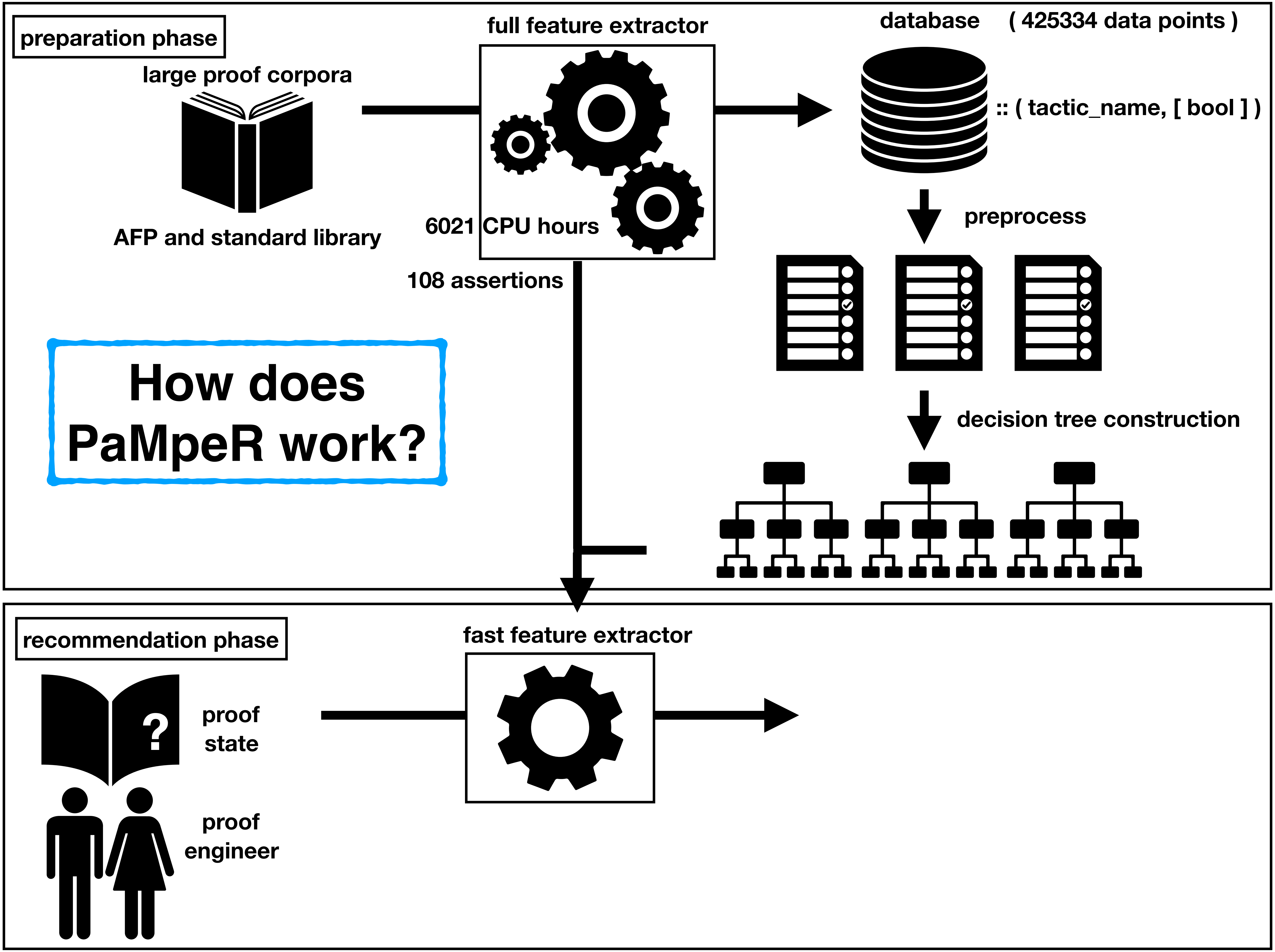


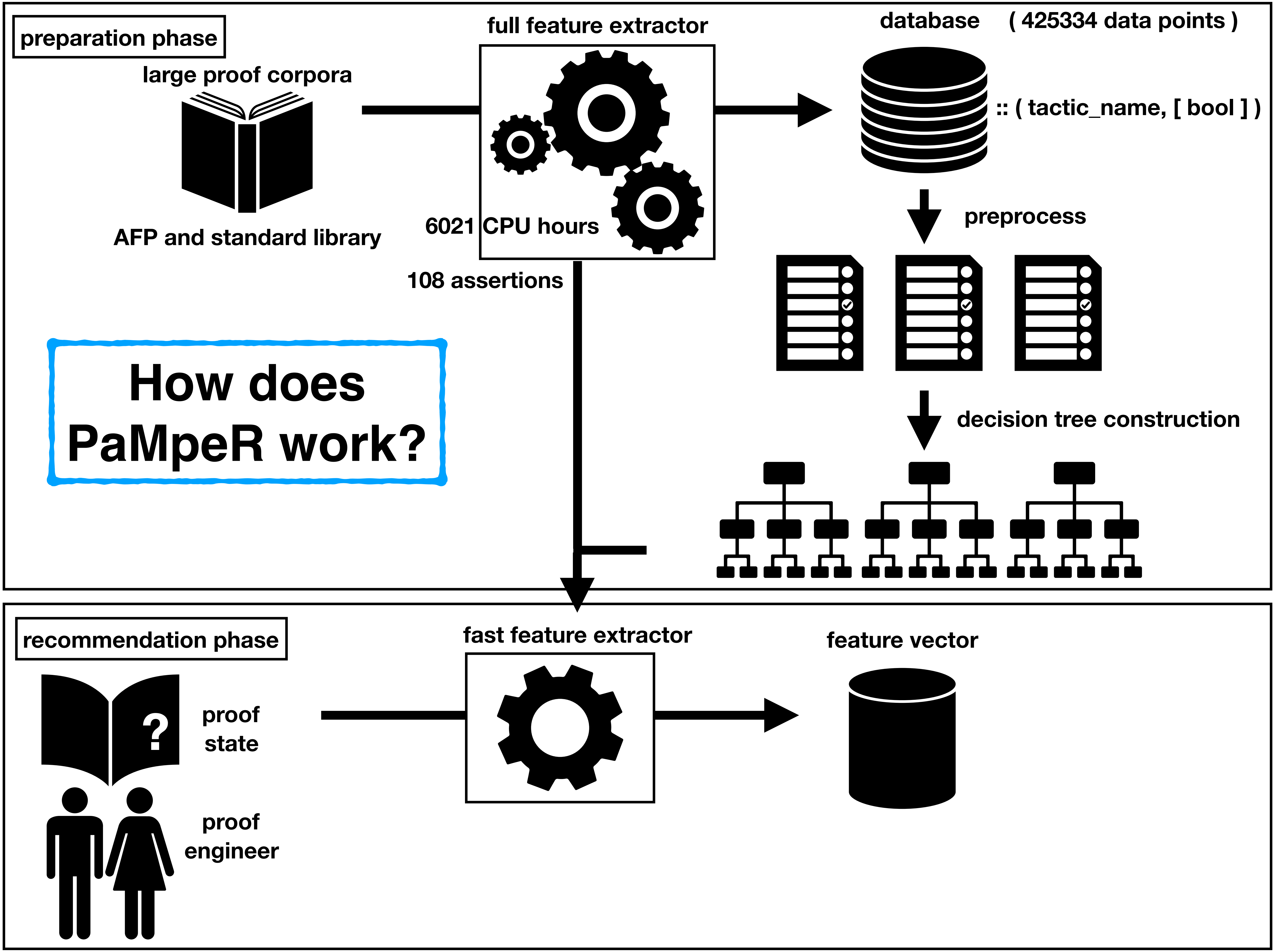
proof engineer


preparation phase
large proof corpora
AFP and standard library
full feature extractor
6021 CPU hours
108 assertions
How does PaMpeR work?
recommendation phase
proof state
proof engineer


preparation phase
large proof corpora
AFP and standard library
full feature extractor
6021 CPU hours
108 assertions
database (425334 data points)
:: (tactic_name, [bool])
How does PaMpeR work?
recommendation phase
proof state
proof engineer


preparation phase
large proof corpora
AFP and standard library
full feature extractor
6021 CPU hours
108 assertions
database
(425334 data points)
:: (tactic_name, [bool])
preprocess
decision tree construction
How does PaMpeR work?
recommendation phase
proof state
proof engineer


preparation phase
large proof corpora
AFP and standard library
full feature extractor
6021 CPU hours
108 assertions
database
(425334 data points)
:: (tactic_name, [bool])
preprocess
decision tree construction
How does PaMpeR work?
recommendation phase
proof state
proof engineer
fast feature extractor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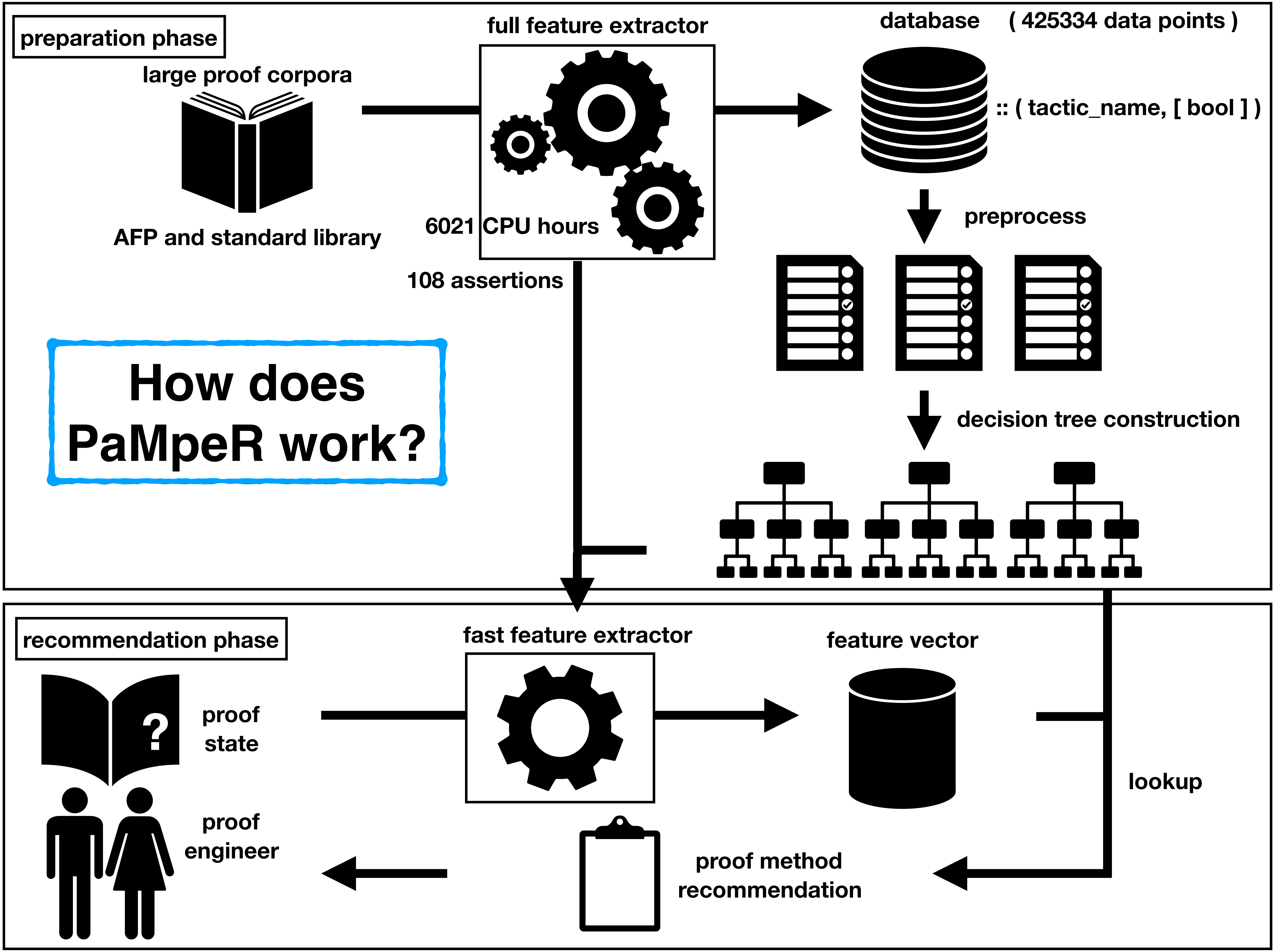
recommendation phase
proof
state
proof
engineer
fast feature extractor
feature vector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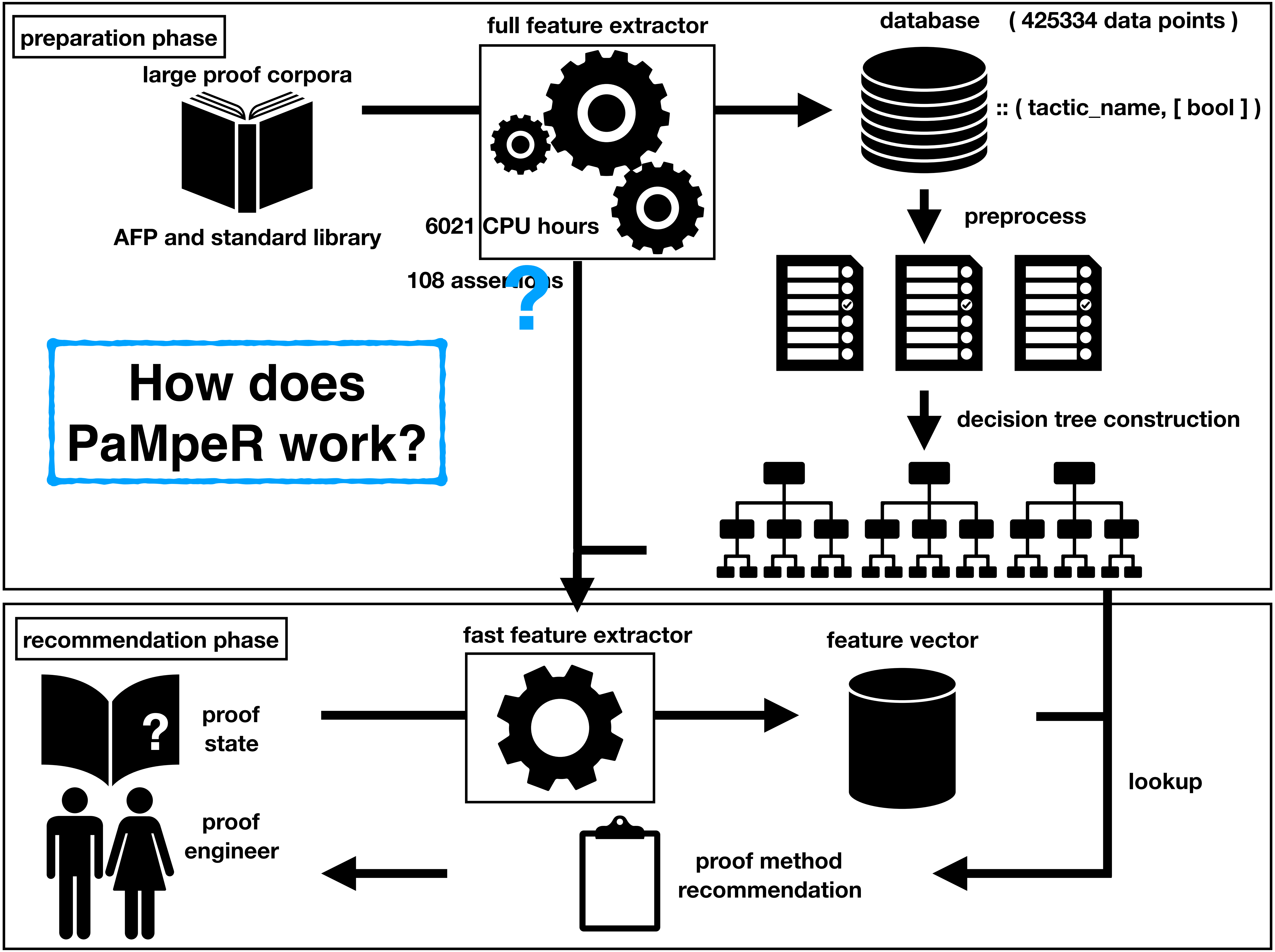
How does PaMpeR work?
recommendation phase
proof state
proof engineer
fast feature extractor
feature vector
lookup
proof method recommendation



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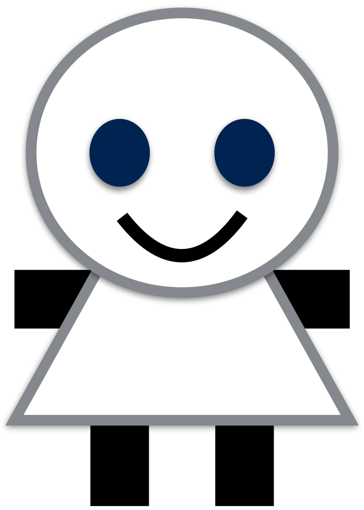
git clone https://github.com/data61/PSL

AITP2018 review



anonymous reviewer

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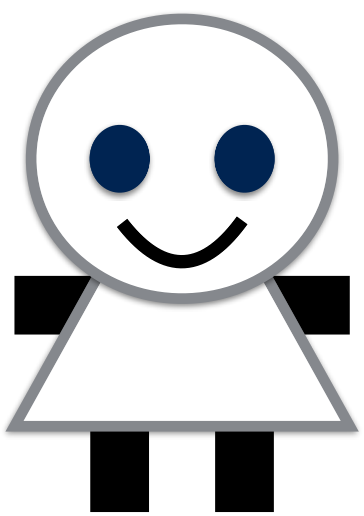
AITP2018 review

Proof Method Recommendation, PaMpeR!



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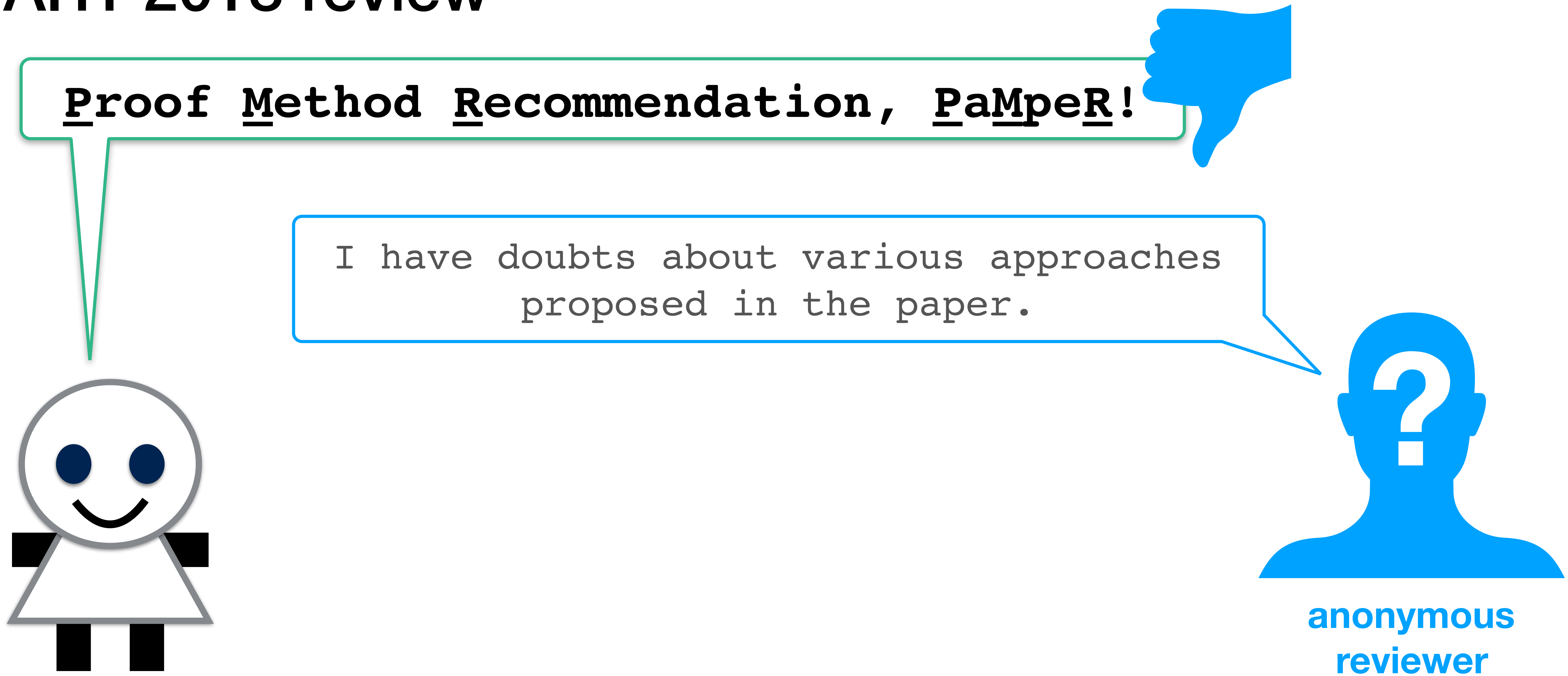
AITP2018 review



~~A~~ITP2018 review

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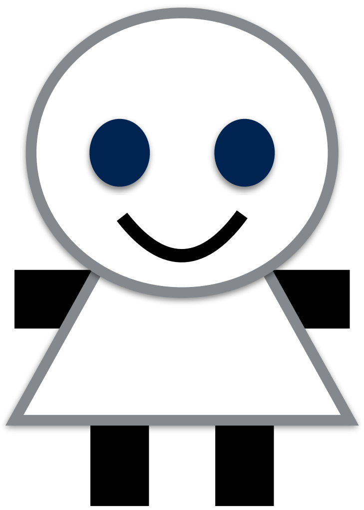
Proof Method Recommendation, PaMpeR!

I have doubts about various approaches proposed in the paper.



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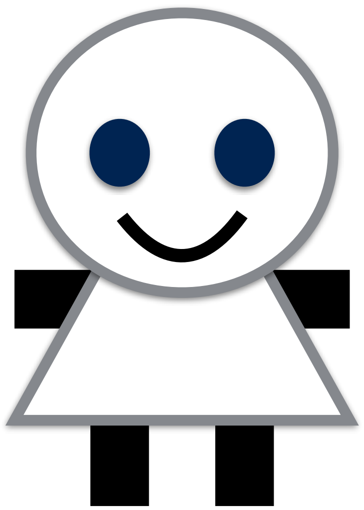

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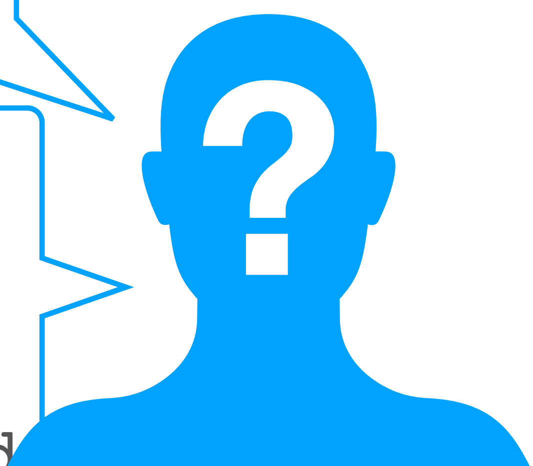
New users of Isabelle are facing many challenges from
- writing their first definitions,
- stating suitable theorem statements, and
- producing properly structured proofs.



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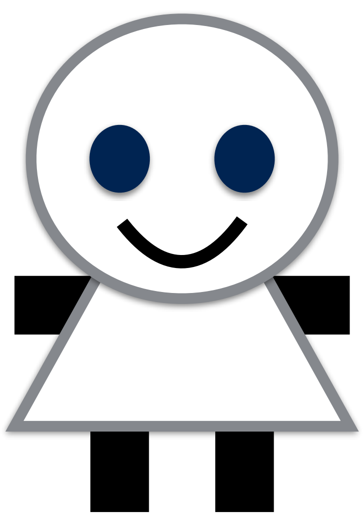

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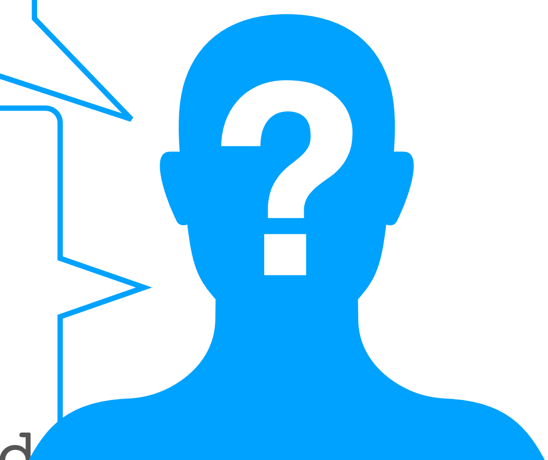

anonymous reviewer

Proof methods are merely the bits at the bottom of that.

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~~A~~ITP2018 review

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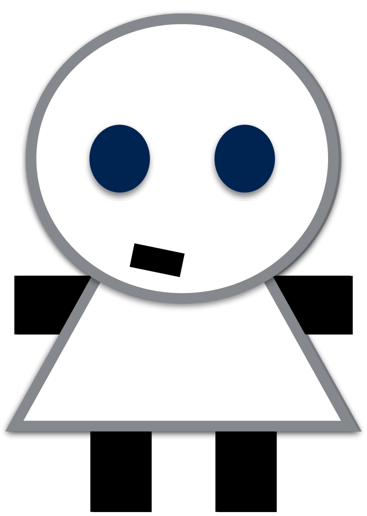

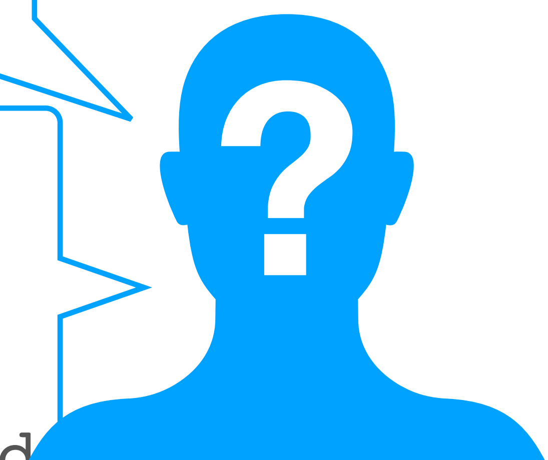

Proof methods are merely the bits at the bottom of that.

I was writing how to prove not how to specify!

~~A~~ITP2018 review

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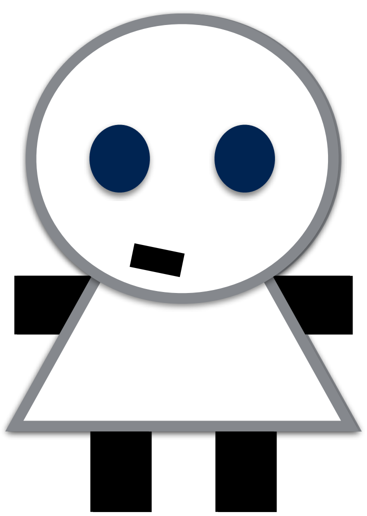

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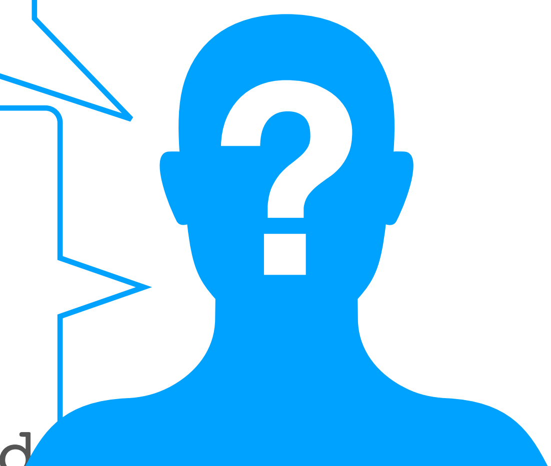

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ITP2018 review

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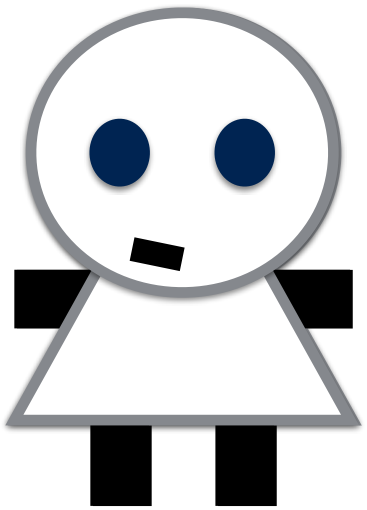

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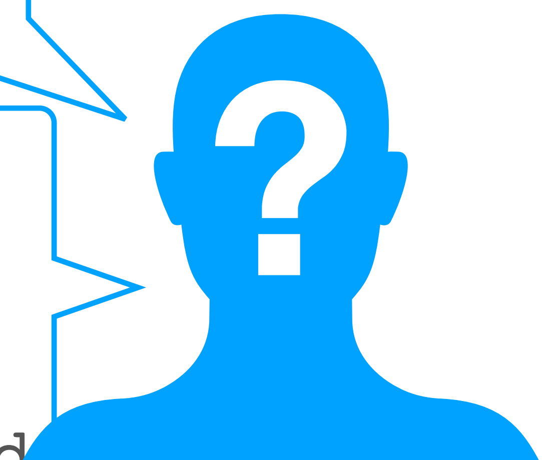


Proof methods are merely the bits at the bottom of that.

I was writing how to prove not how to specify!

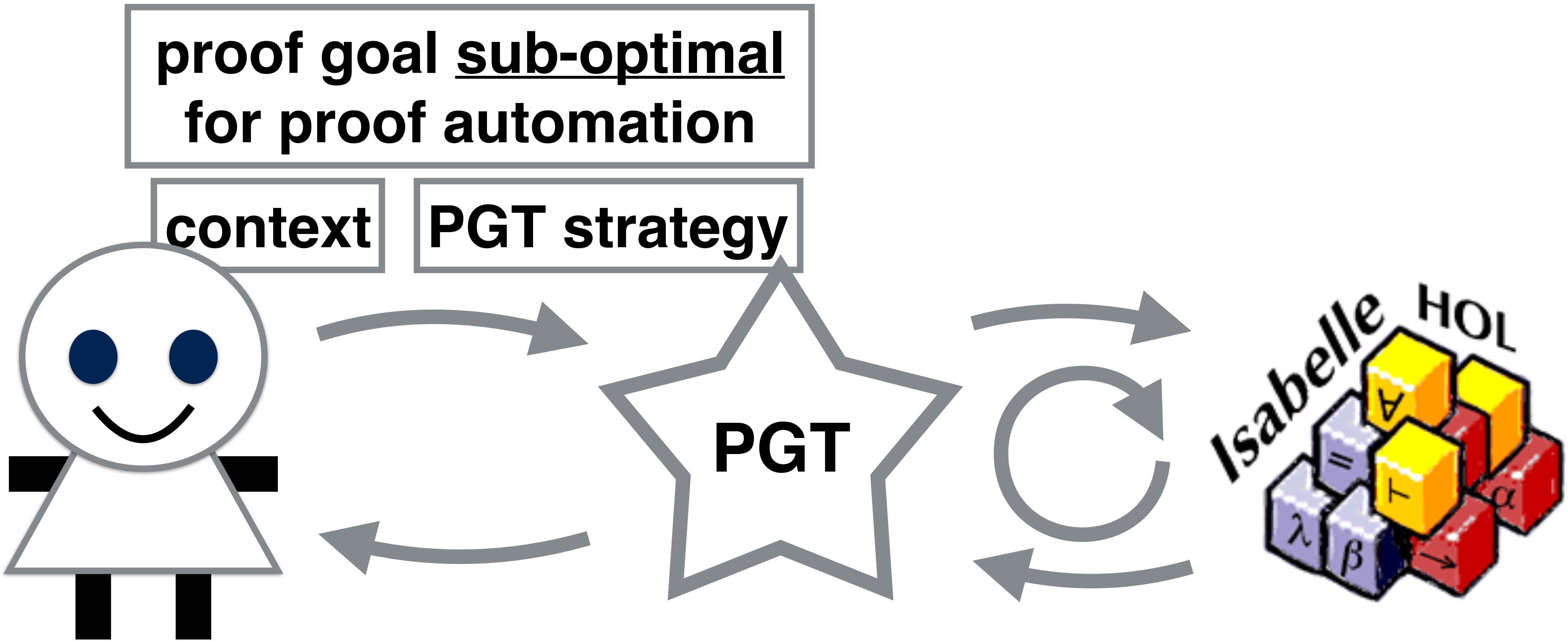
Proof Goal Transformer, PGT!

git clone https://github.com/data61/PSL

PSL with PGT

git clone https://github.com/data61/PSL

PSL with PGT



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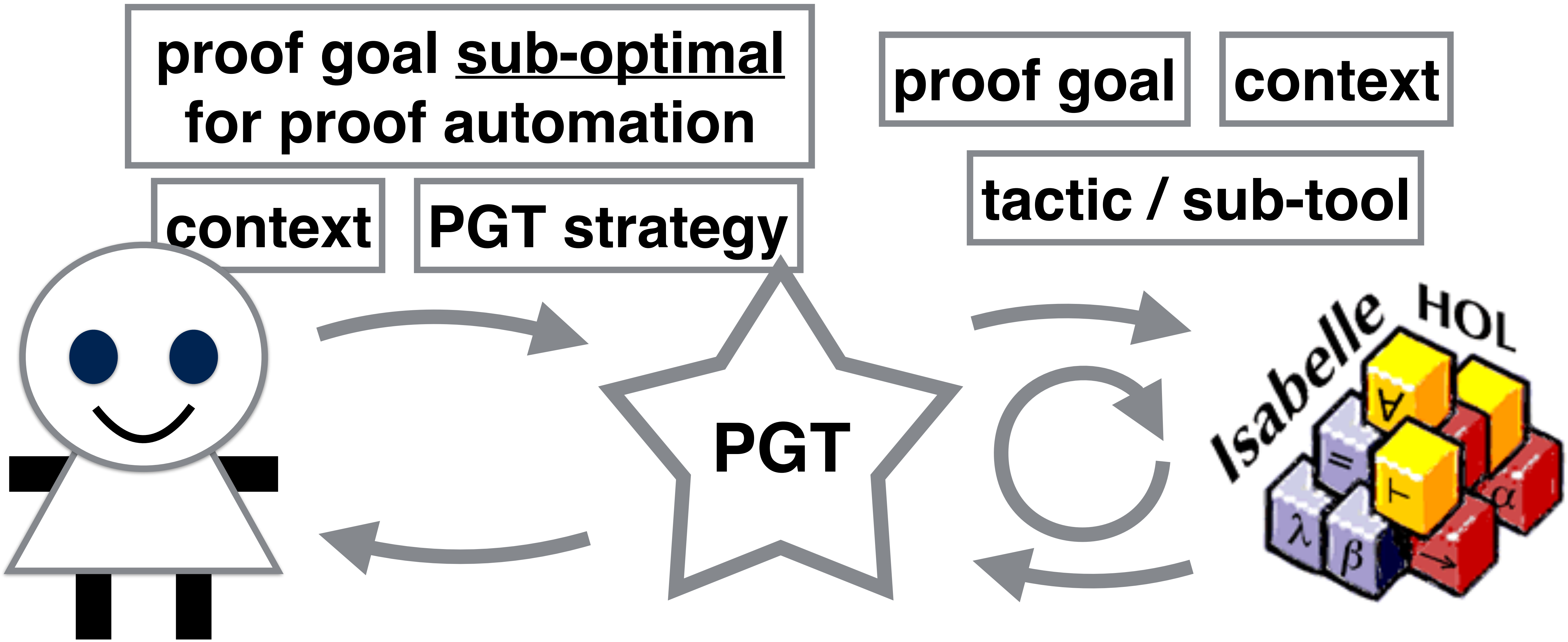
PSL with PGT



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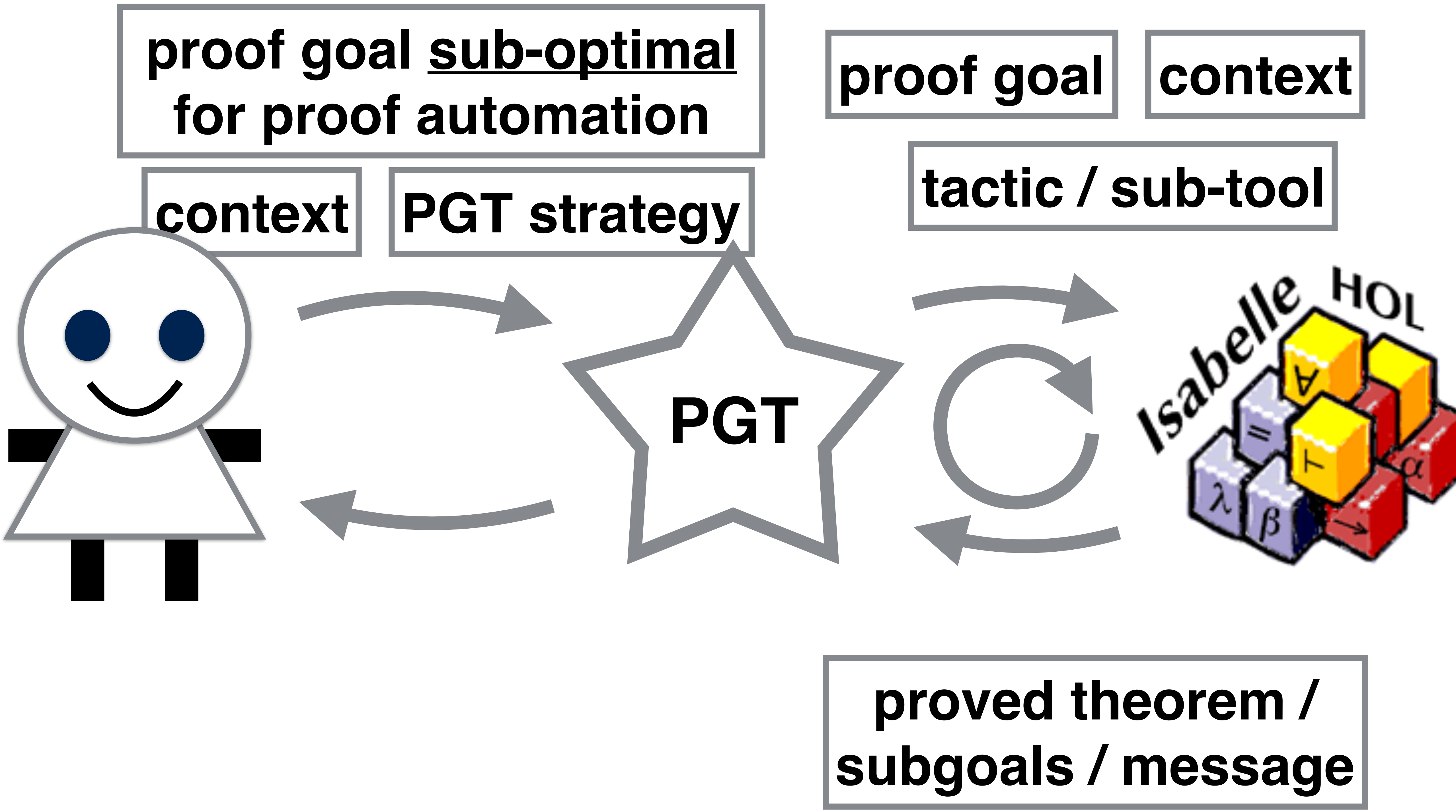
PSL with PGT



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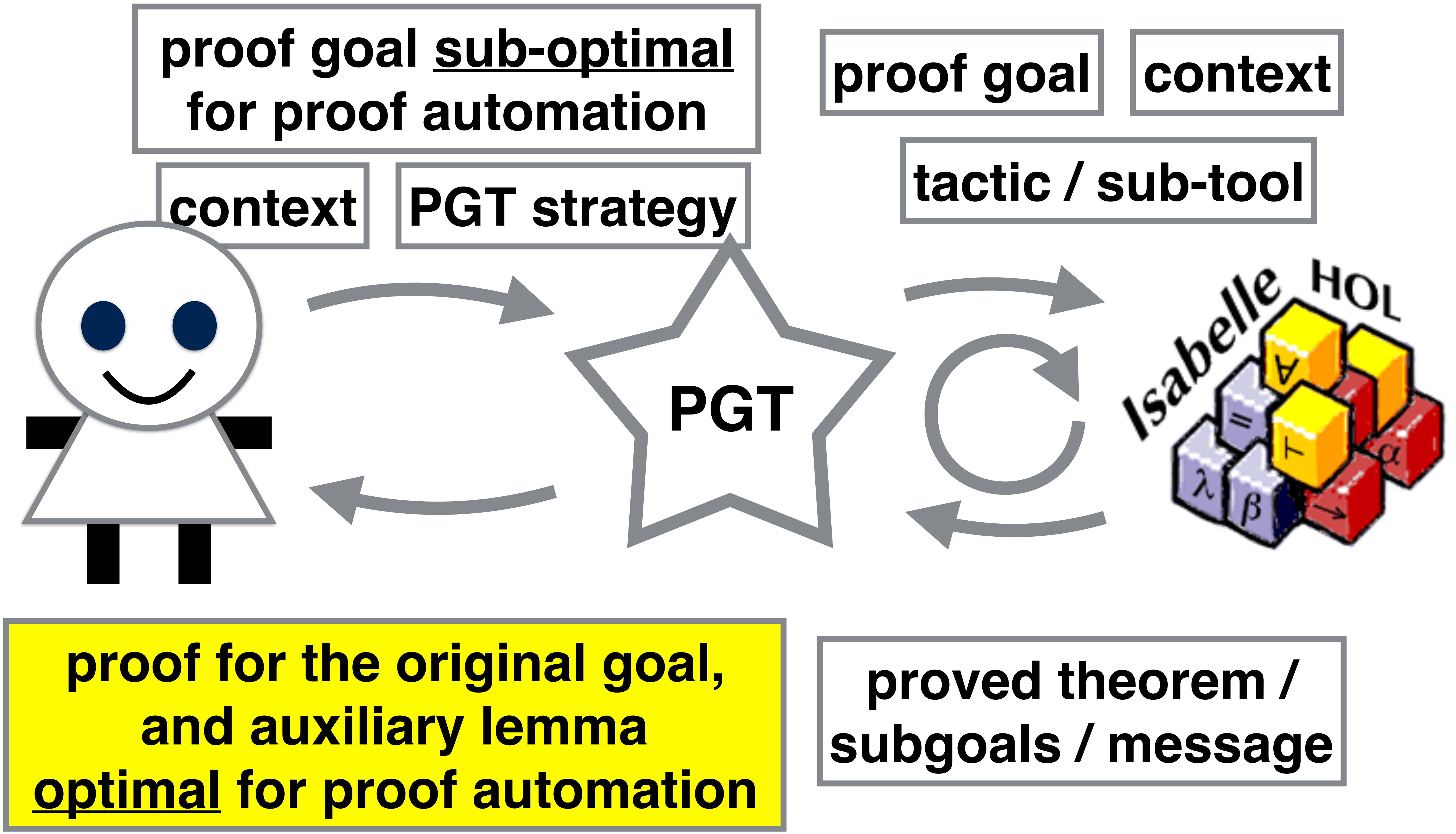
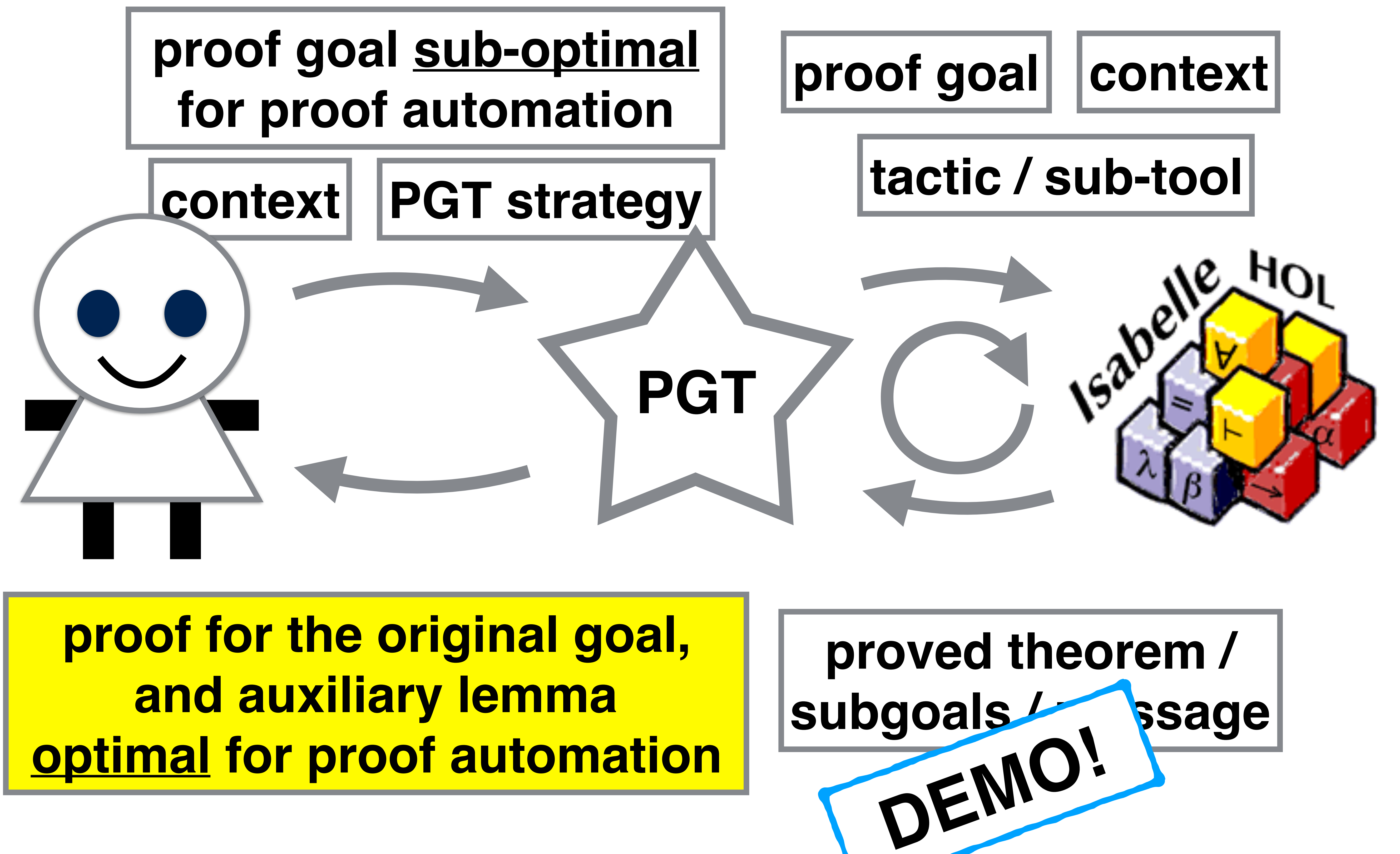
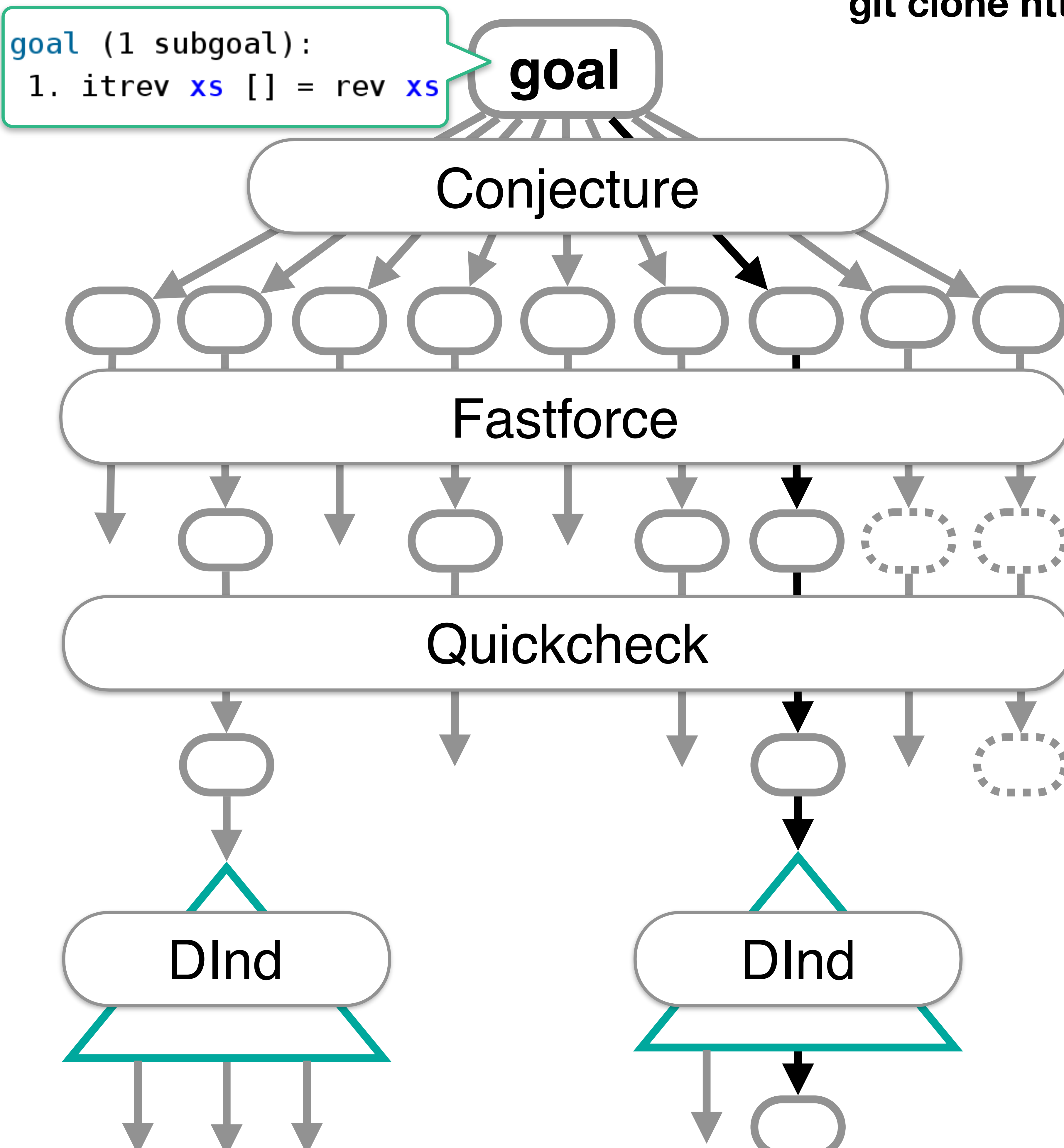
PSL with PGT

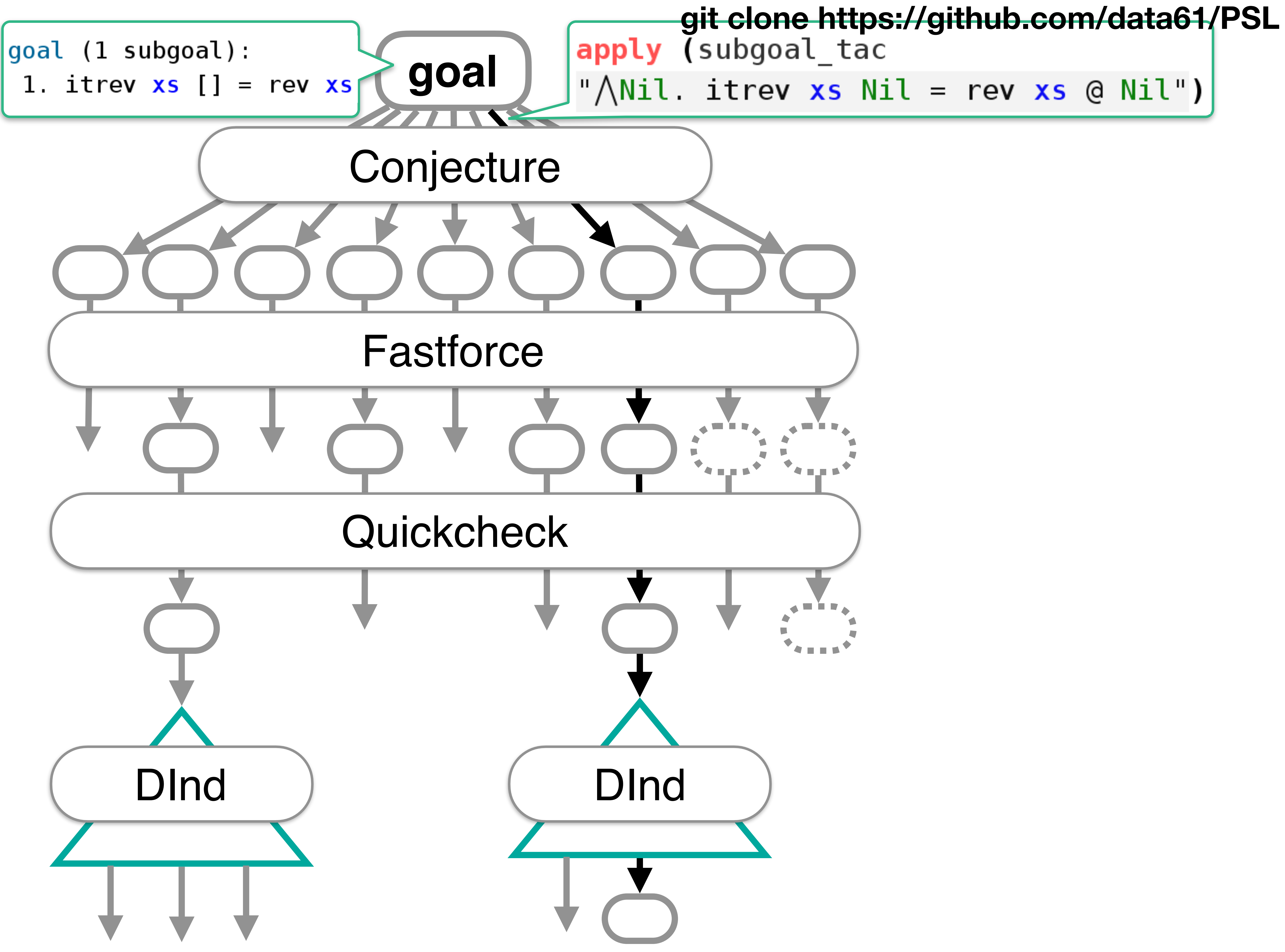


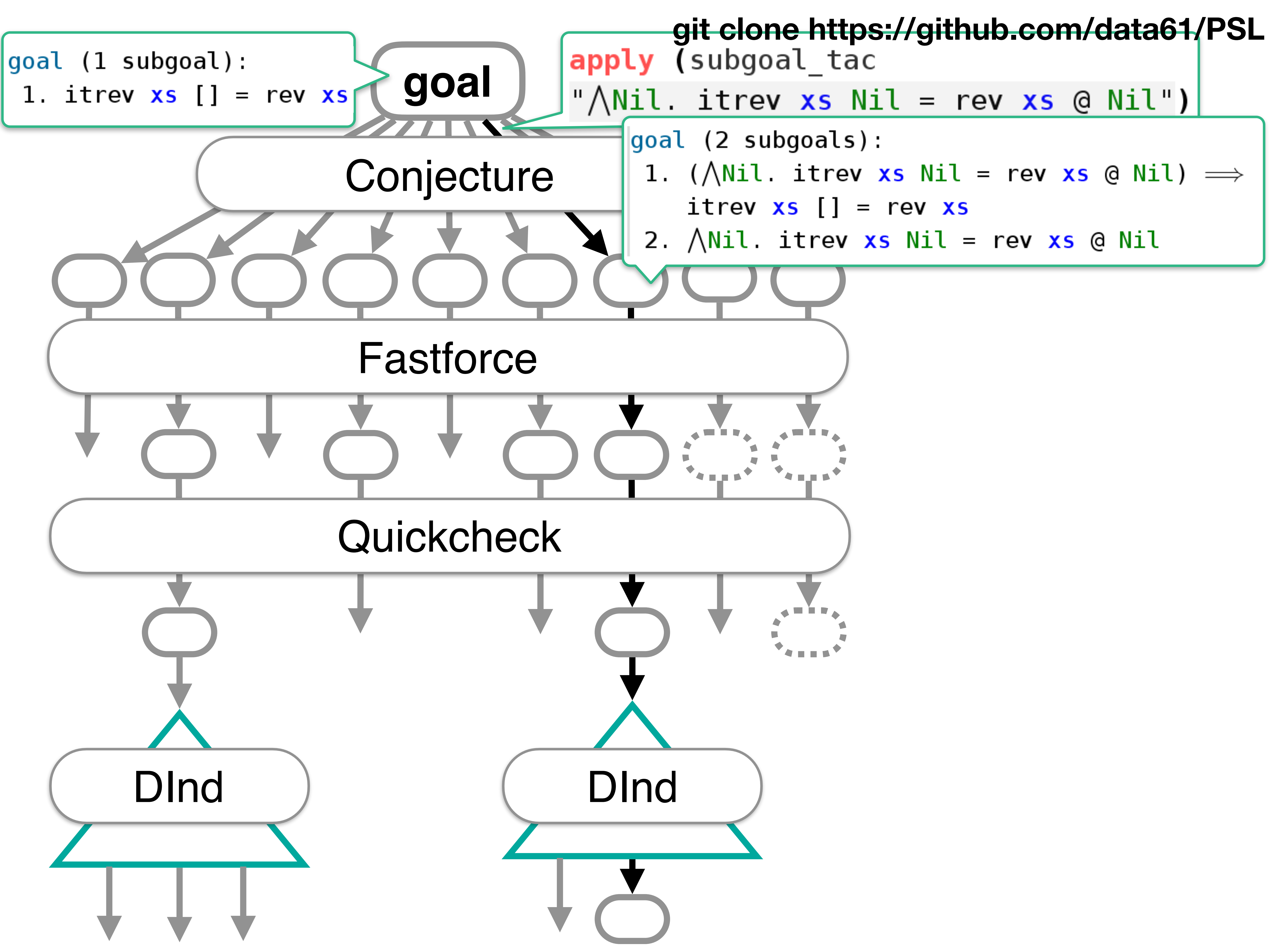
PSL with PGT


proof goal sub-optimal
for proof automation
context
PGT strategy
PGT
proof goal
context
tactic / sub-tool
Isabelle
HOL
proof for the original goal,
and auxiliary lemma
optimal for proof automation
proved theorem /
subgoals /
ssage
DEMO!

git clone https://github.com/data61/PSL




git clone https://github.com/data61/PSL
goal (1 subgoal):
1. itrev xs [] = rev xs
goal
apply (subgoal_tac
"⋀Nil. itrev xs Nil = rev xs @ Nil")
Conjecture
Fastforce
Quickcheck
DInd
DInd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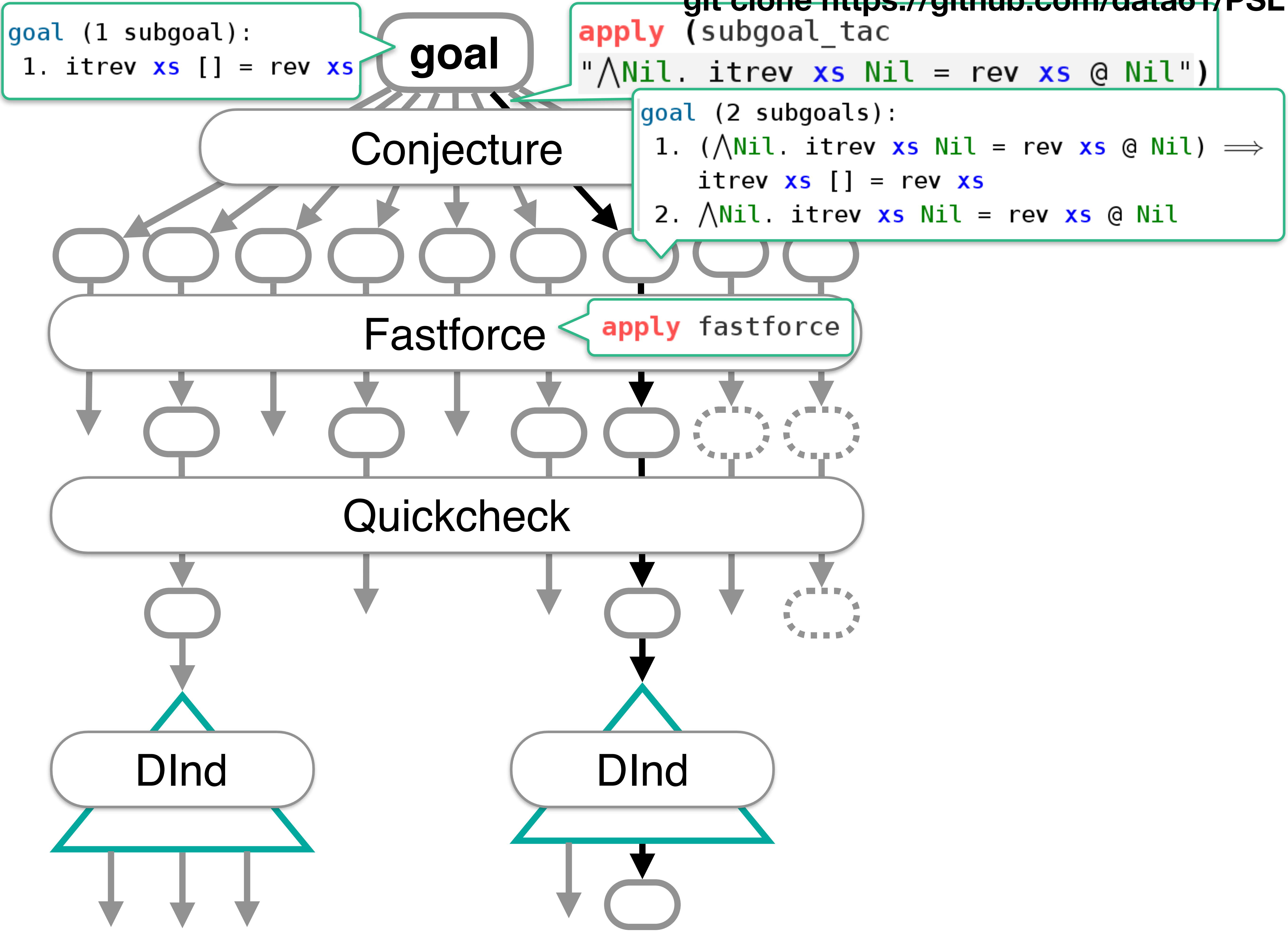

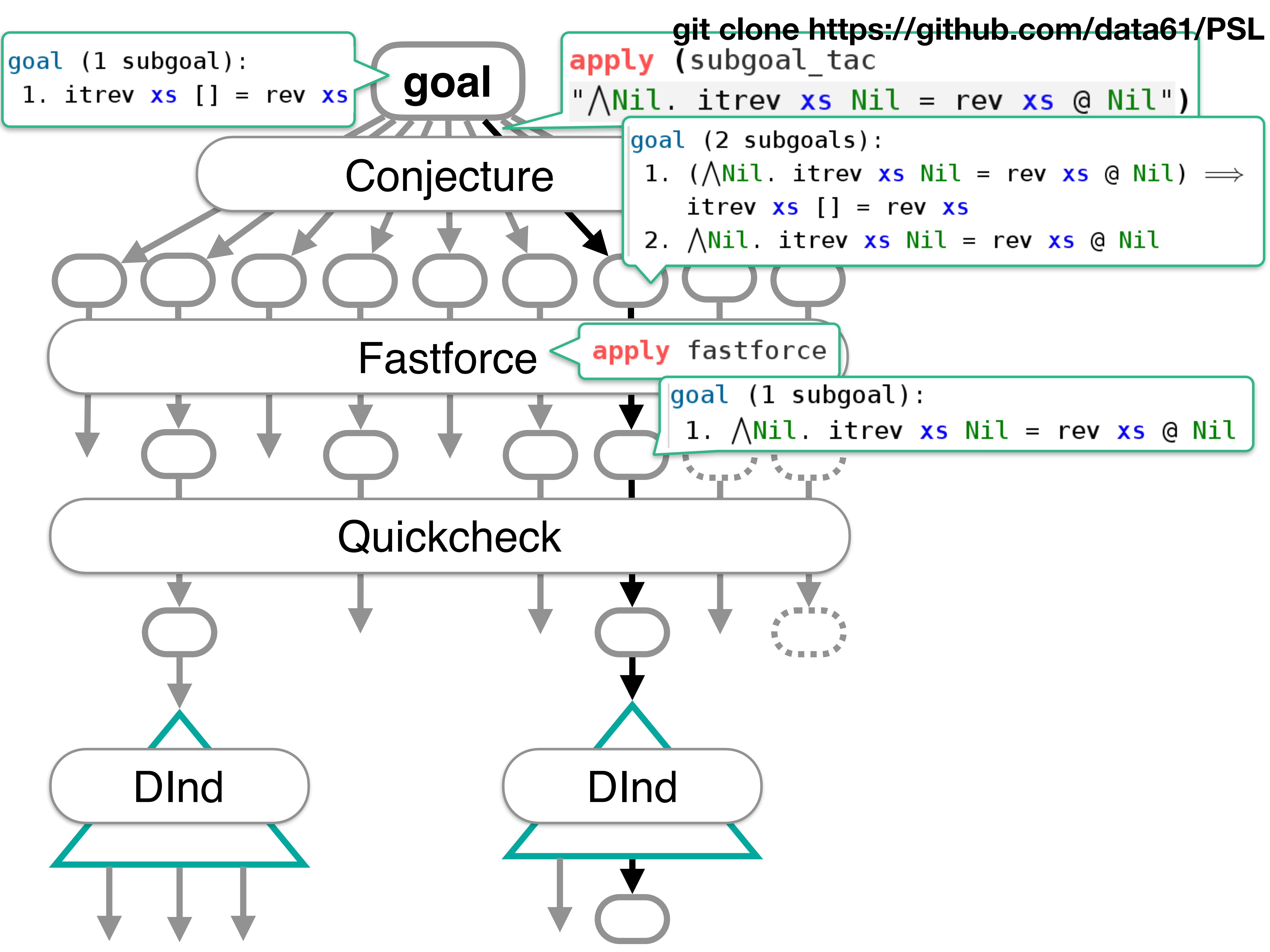
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apply fastforce
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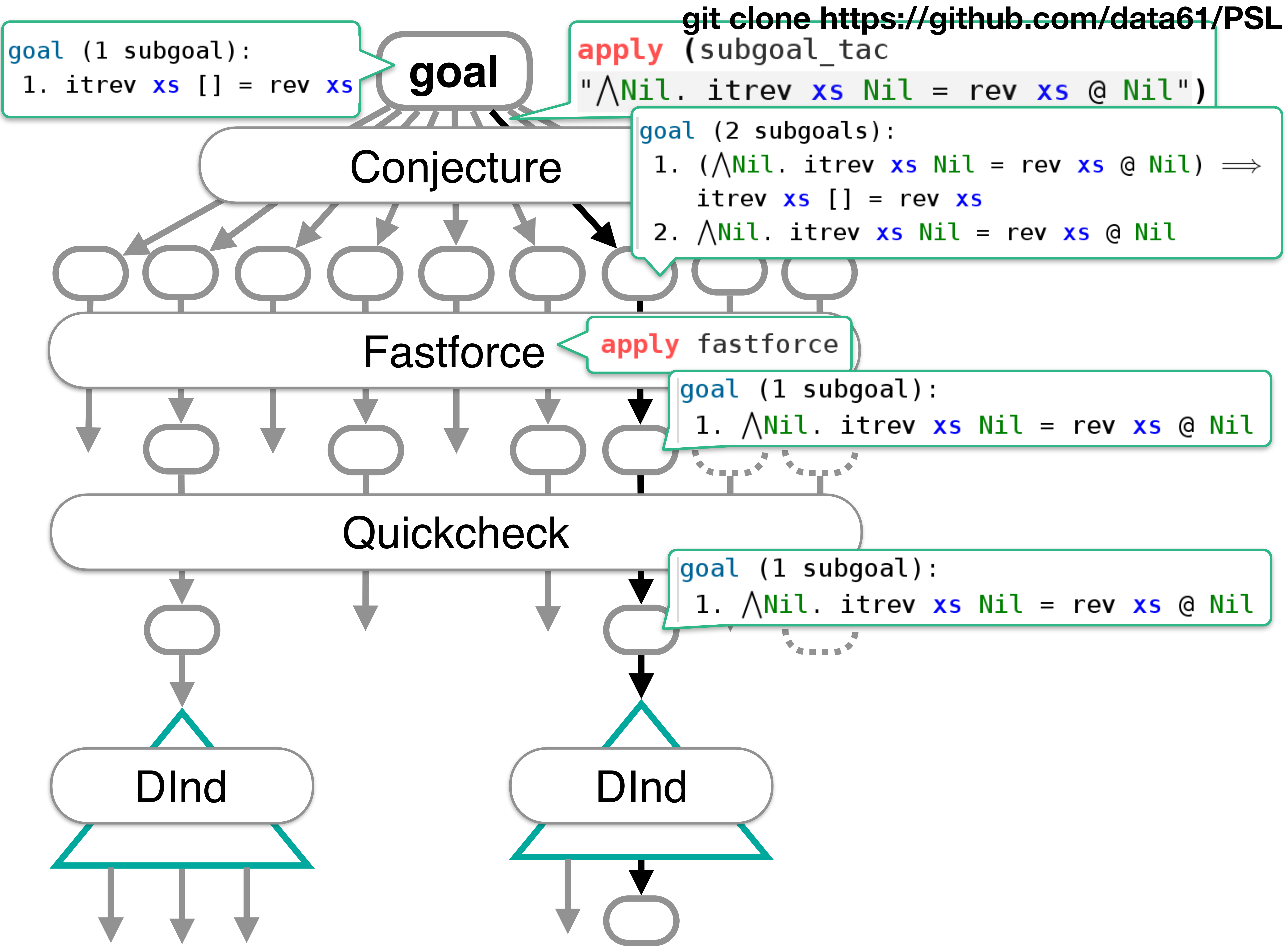
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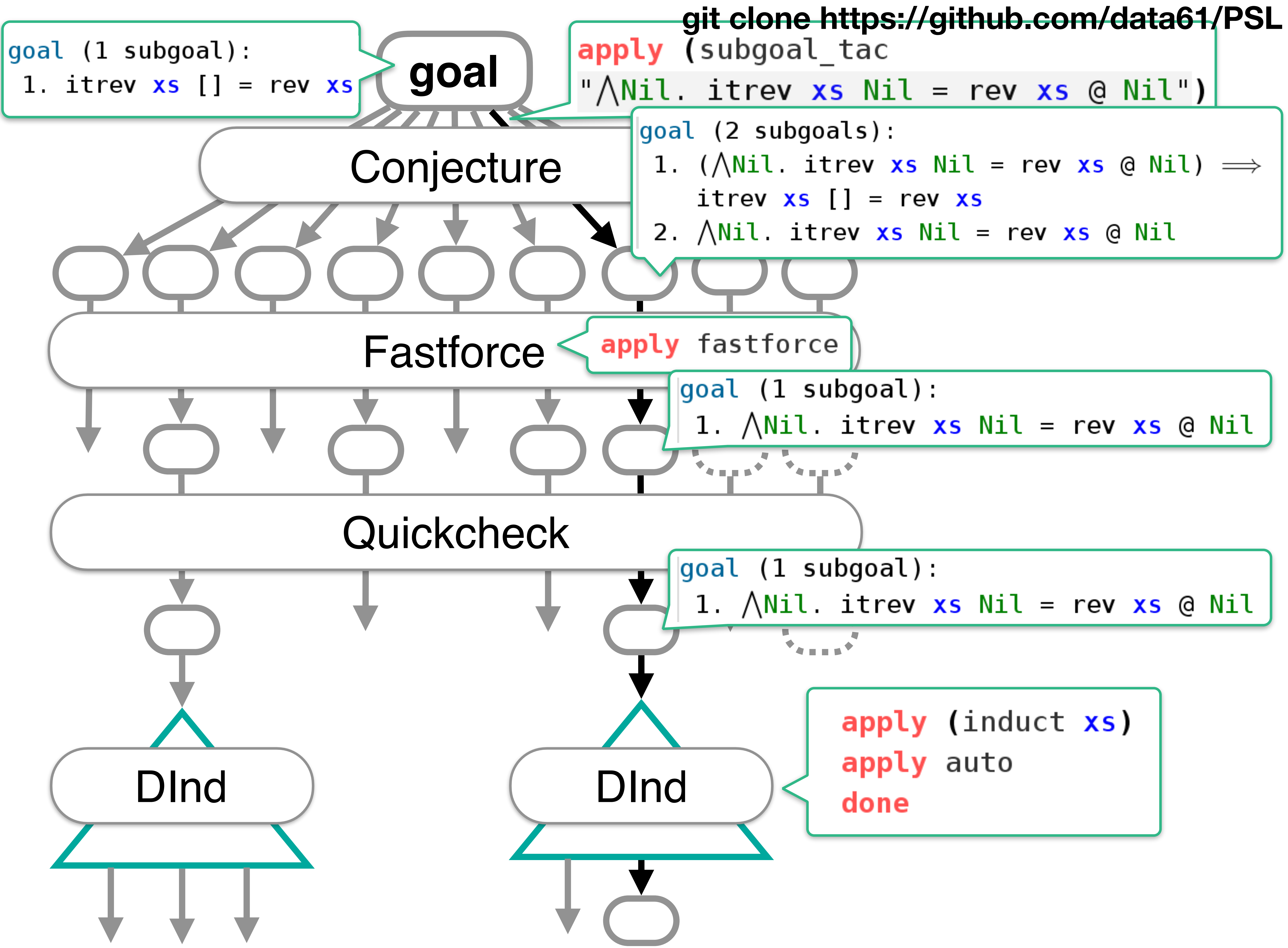

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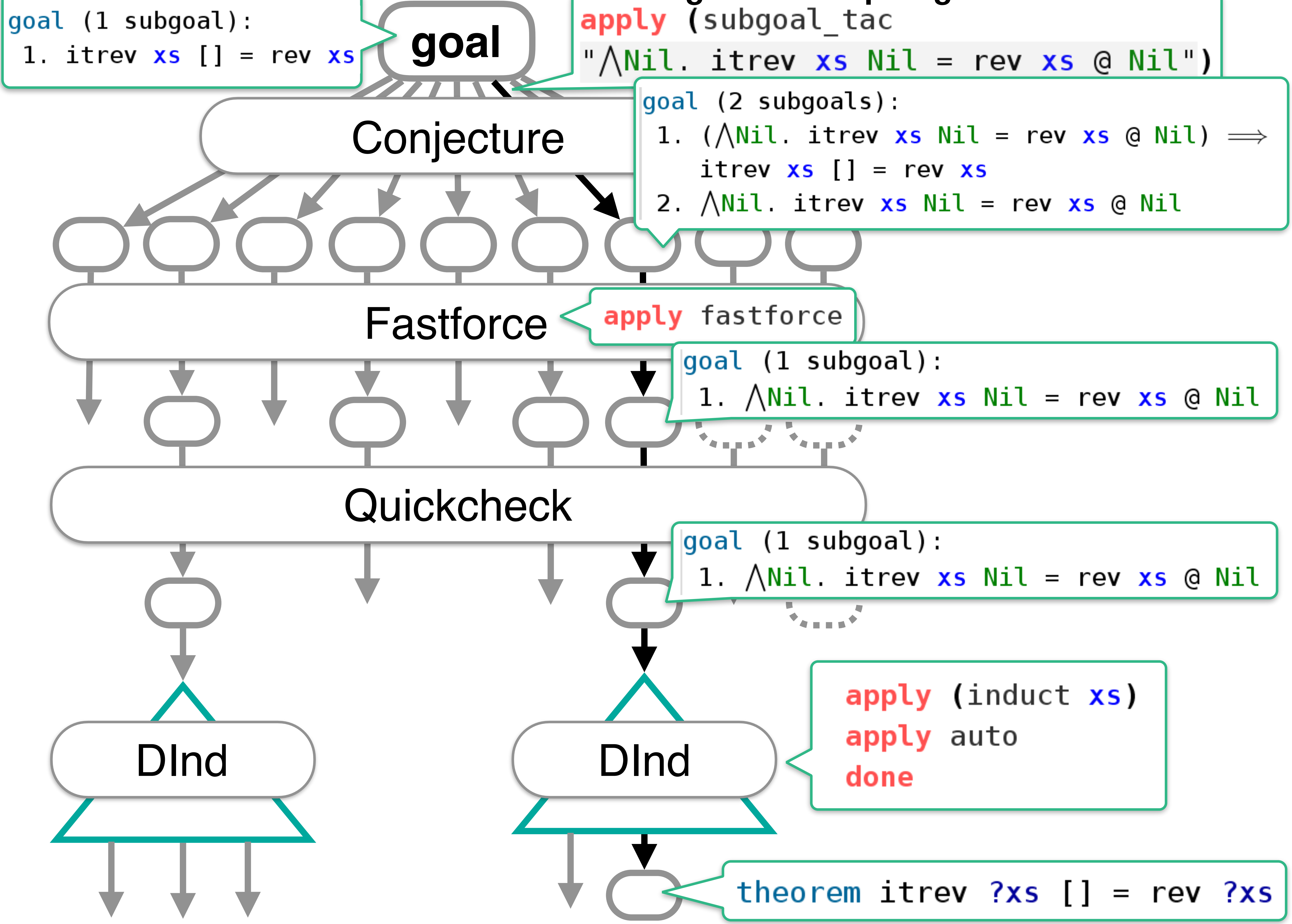
Conjecture
Fastforce
apply fastforce
goal (1 subgoal):
1. ⋀Nil. itrev xs Nil = rev xs @ Nil
Quickcheck
goal (1 subgoal):
1. ⋀Nil. itrev xs Nil = rev xs @ Nil
DInd
DInd
apply (induct xs)
apply auto
done

git clone https://github.com/data61/PSL



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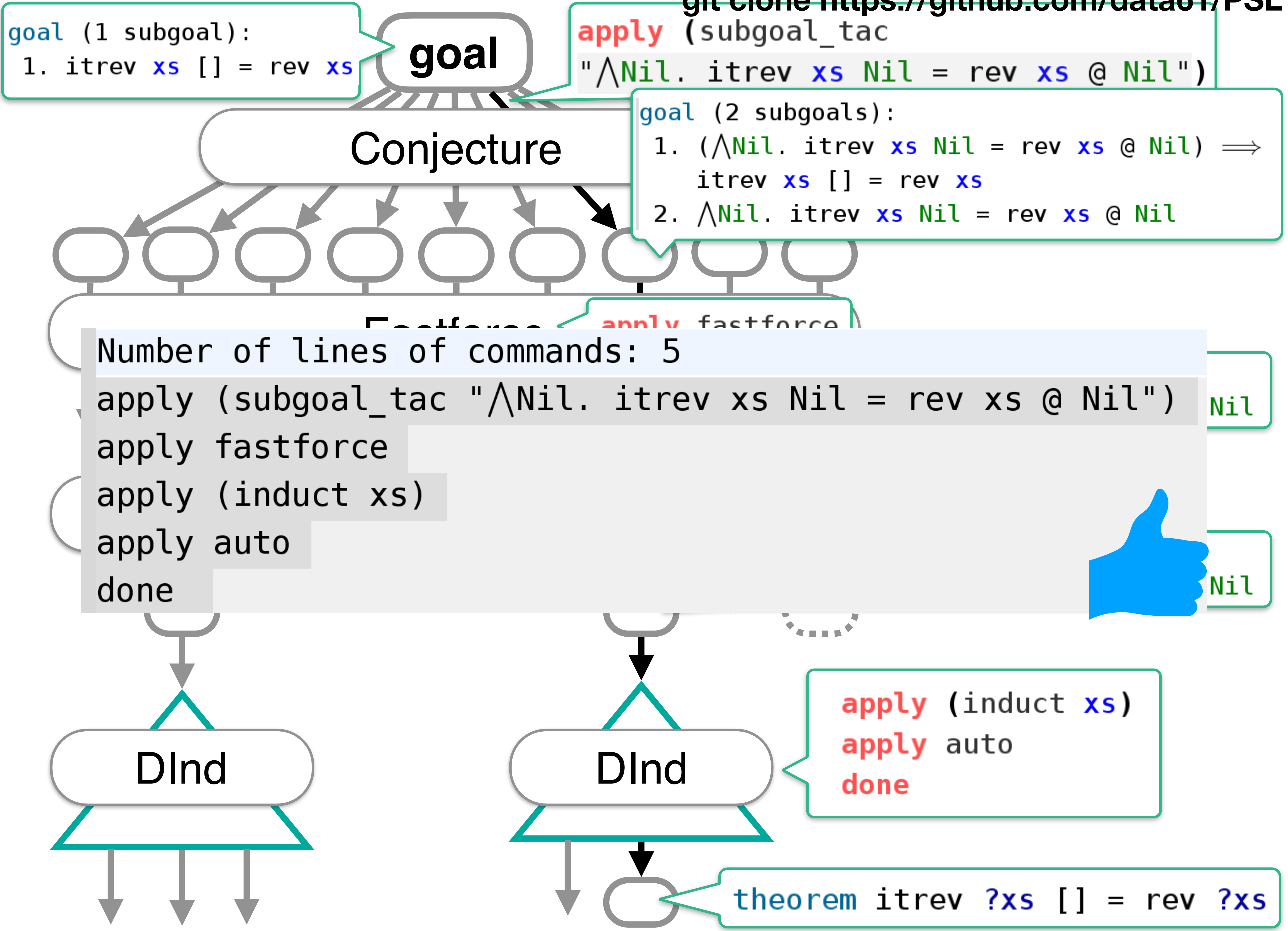

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Success story

PSL can find how to apply induction for easy problems.

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PaMpeR recommends which proof methods to use.

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Success story

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PaMpeR recommends which proof methods to use.

PGT produces useful auxiliary lemmas.

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Success story

PSL can find how to apply induction for easy problems.

CADE2017

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Success story

PSL can find how to apply induction for easy problems.

CADE2017

PaMpeR recommends which proof methods to use.

ASE2018

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CICM2018 (best system award)

Too good to be true?

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Too good to be true?

PSL can find how to apply induction for easy problems.

only if PSL completes a proof search

PaMpeR recommends which proof methods to use.

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only if PSL with PGT completes a proof search

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Too good to be true?

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PaMpeR recommends which proof methods to use.

but PaMpeR does not recommend arguments for proof methods

PGT produces useful auxiliary lemmas.

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Recommend how to apply induction without completing a proof.

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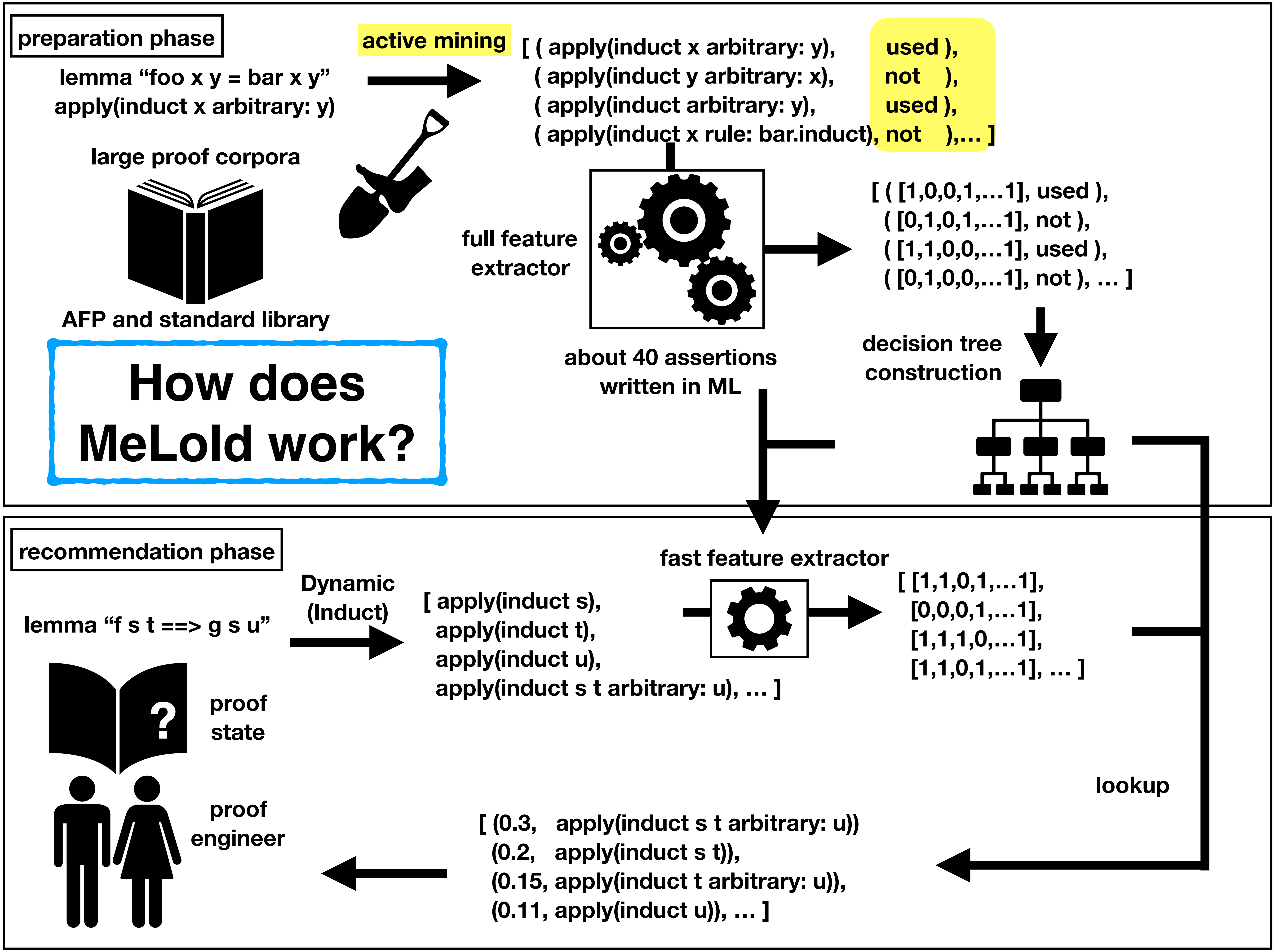
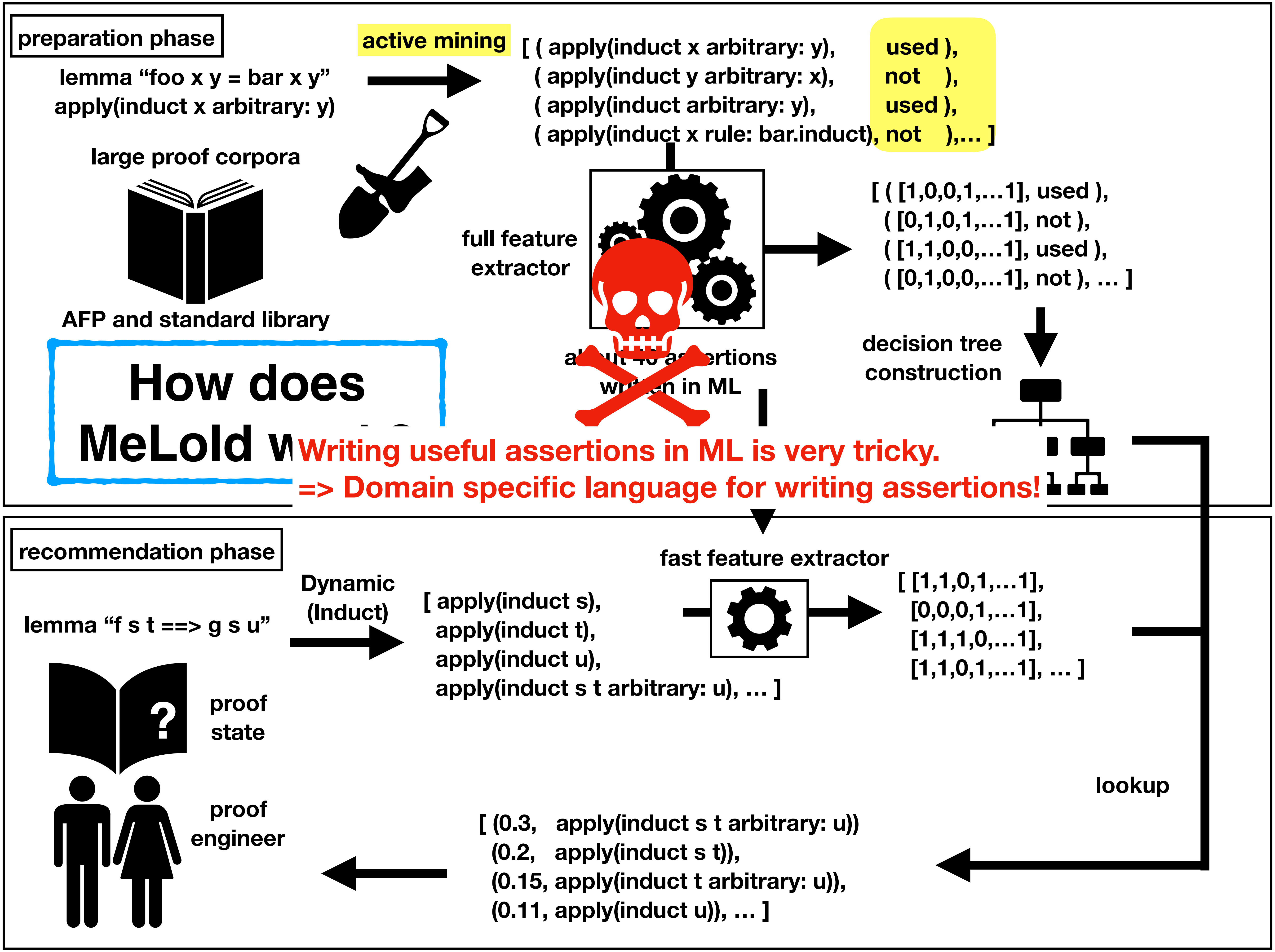
proof search

Recommend how to apply induction without completing a proof.

MeLoId: Machine Learning Induction


preparation phase
active mining
lemma “foo x y = bar x y”
apply(induct x arbitrary: y)
[(apply(induct x arbitrary: y), used),
(apply(induct y arbitrary: x), not),
(apply(induct arbitrary: y), used),
(apply(induct x rule: bar.induct), not),...]
large proof corpora
AFP and standard library
full feature extractor
about 40 assertions written in ML
[([1,0,0,1,...1], used),
([0,1,0,1,...1], not),
([1,1,0,0,...1], used),
([0,1,0,0,...1], not), ...]
decision tree construction
How does MeLold work?
recommendation phase
Dynamic (Induct)
lemma “f s t ==> g s u”
[apply(induct s),
apply(induct t),
apply(induct u),
apply(induct s t arbitrary: u), ...]
fast feature extractor
[[1,1,0,1,...1],
[0,0,0,1,...1],
[1,1,1,0,...1],
[1,1,0,1,...1], ...]
proof state
proof engineer
lookup
[(0.3, apply(induct s t arbitrary: u))
(0.2, apply(induct s t)),
(0.15, apply(induct t arbitrary: u)),
(0.11, apply(induct u)), ...]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([0,1,0,1,...1], not),
([1,1,0,0,...1], used),
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decision tree construction
How does
MeLold w
Writing useful assertions in ML is very tricky.
=> Domain specific language for writing assertions!
recommendation phase
Dynamic (Induct)
lemma “f s t ==> g s u”
[apply(induct s),
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proof state
proof engineer
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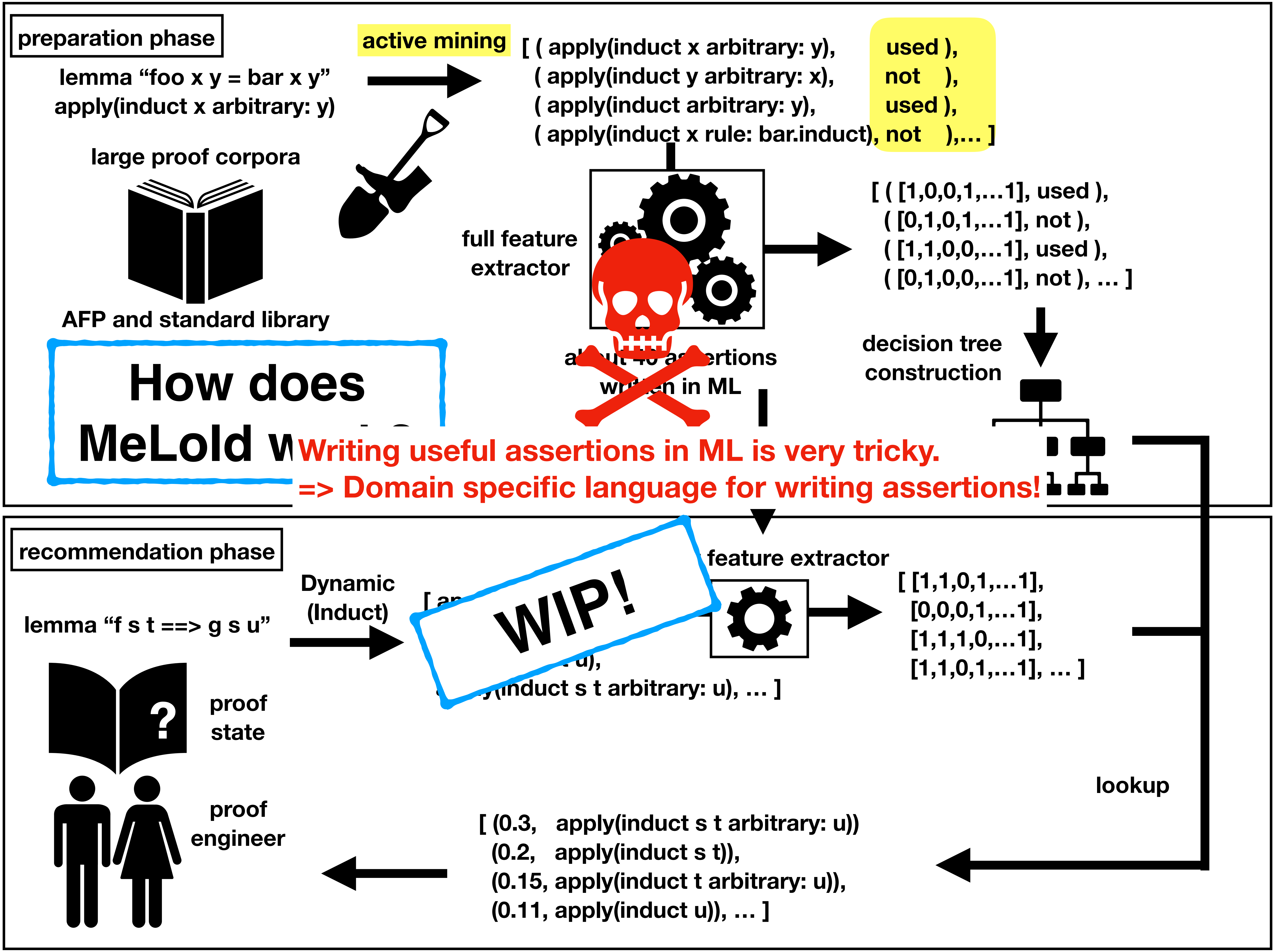
preparation phase
active mining
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[(apply(induct x arbitrary: y), used),
(apply(induct y arbitrary: x), not),
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AFP and standard library
full feature extractor
[([1,0,0,1,...1], used),
([0,1,0,1,...1], not),
([1,1,0,0,...1], used),
([0,1,0,0,...1], not), ...]
decision tree construction
in ML
How does
MeLold w
Writing useful assertions in ML is very tricky.
=> Domain specific language for writing assertions!
recommendation phase
WIP!
feature extractor
lemma “f s t ==> g s u”
Dynamic (Induct)
u),
(induct s t arbitrary: u), ...]
[[1,1,0,1,...1],
[0,0,0,1,...1],
[1,1,1,0,...1],
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Thank you!

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Thank you!

Leave a star at GitHub for PSL!

git clone https://github.com/data61/PSL

Thank you!

Leave a star at GitHub for PSL!

Let's write a review paper "AITP deserves High-Performance Computing, Too!"

Thank you!

git clone https://github.com/data61/PSL

Leave a star at GitHub for PSL!

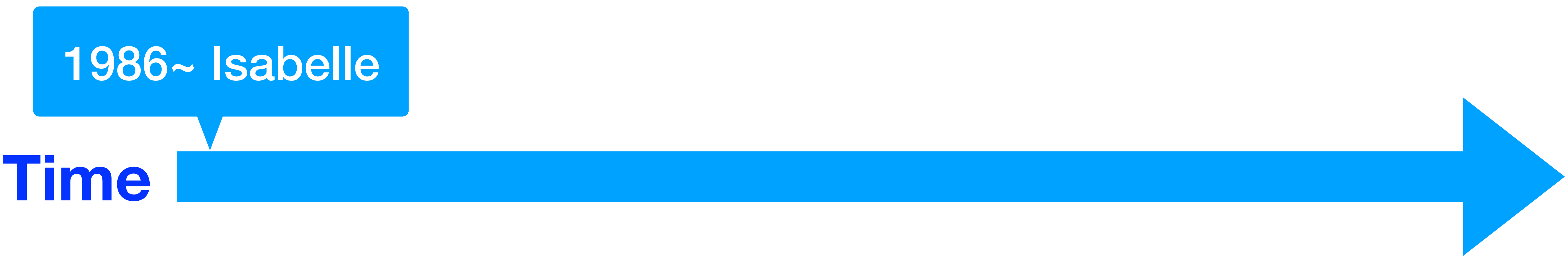
Let's write a review paper
"AITP deserves High-Performance Computing, Too!"

PaMpeR's feature extractor?

git clone https://github.com/data61/PSL

Time

git clone https://github.com/data61/PSL



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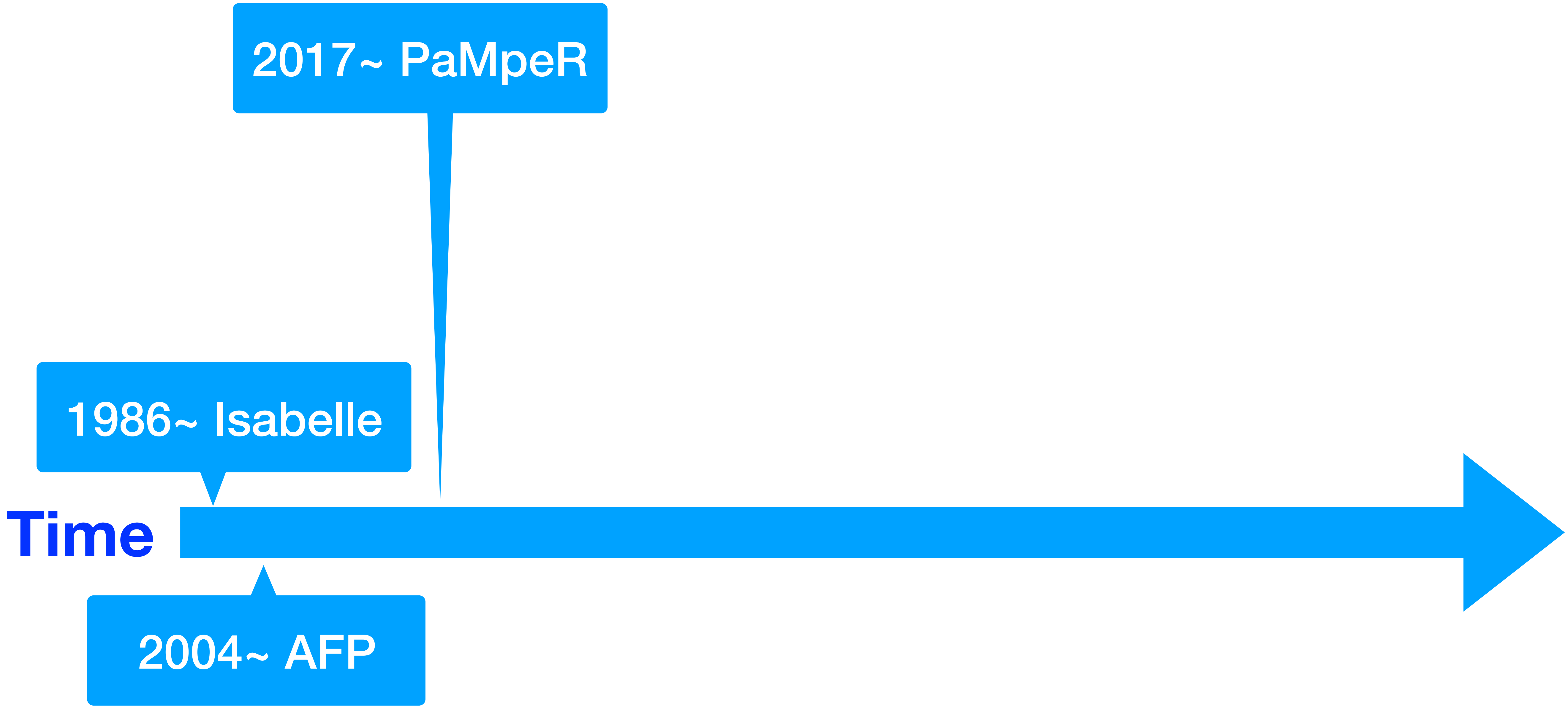

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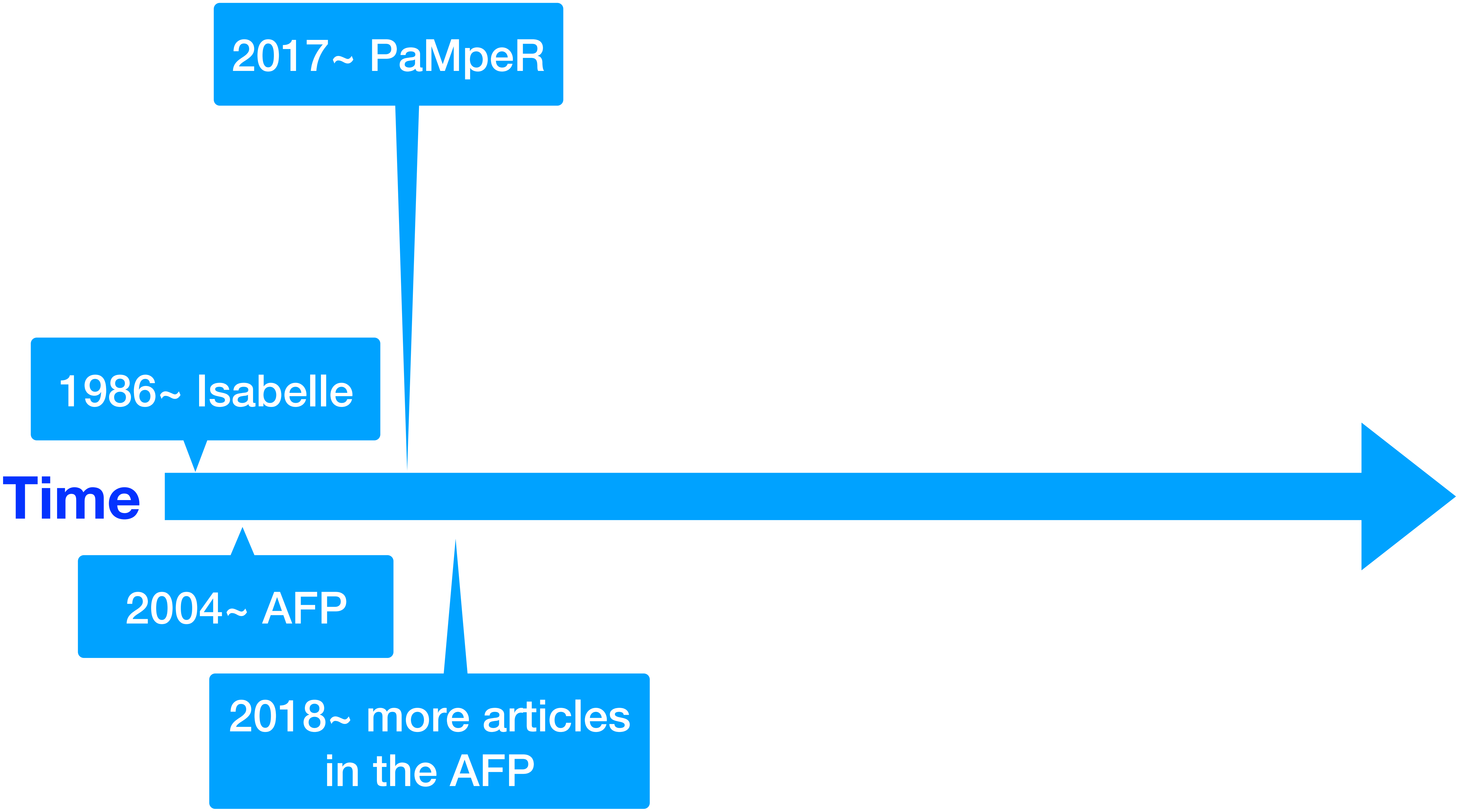

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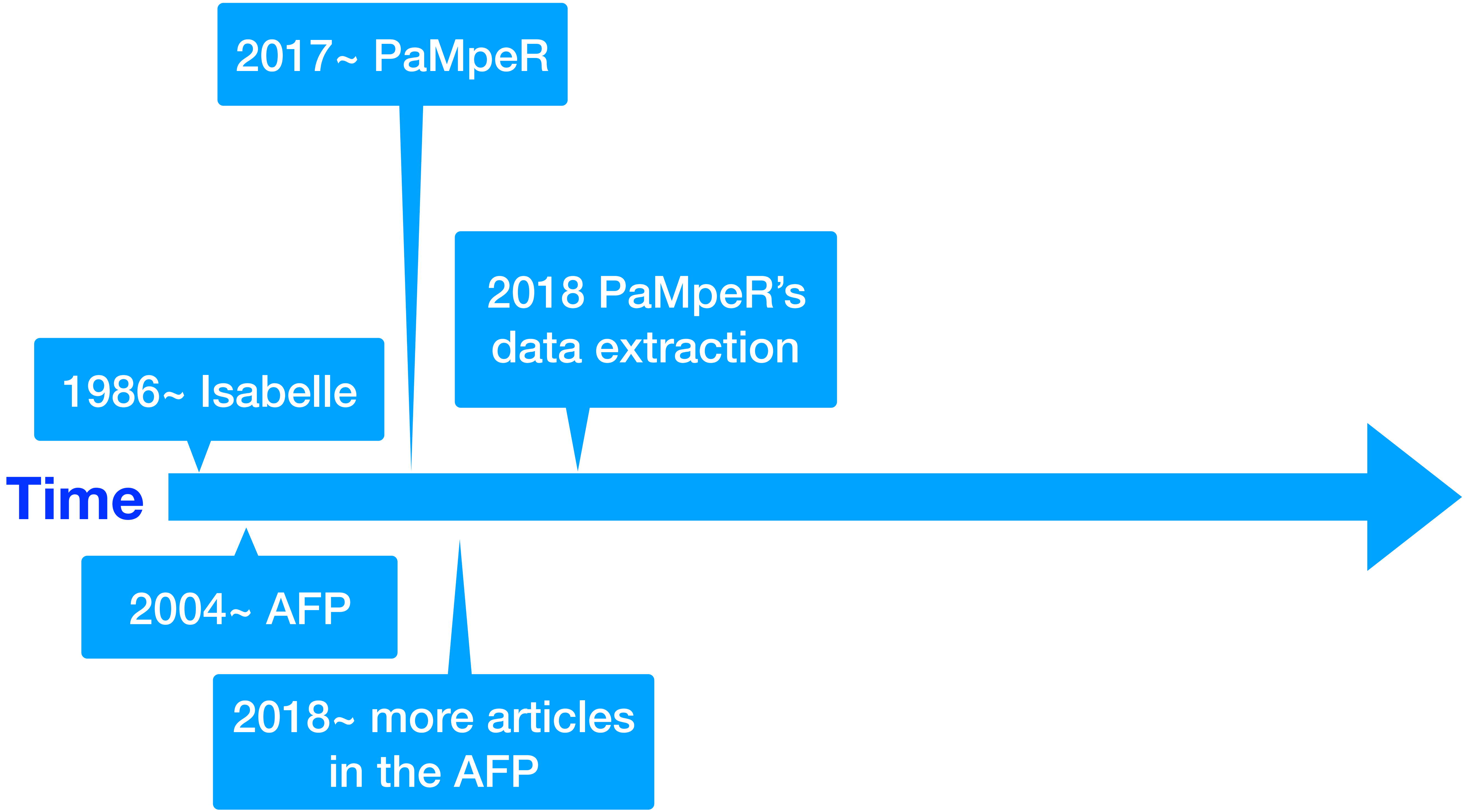

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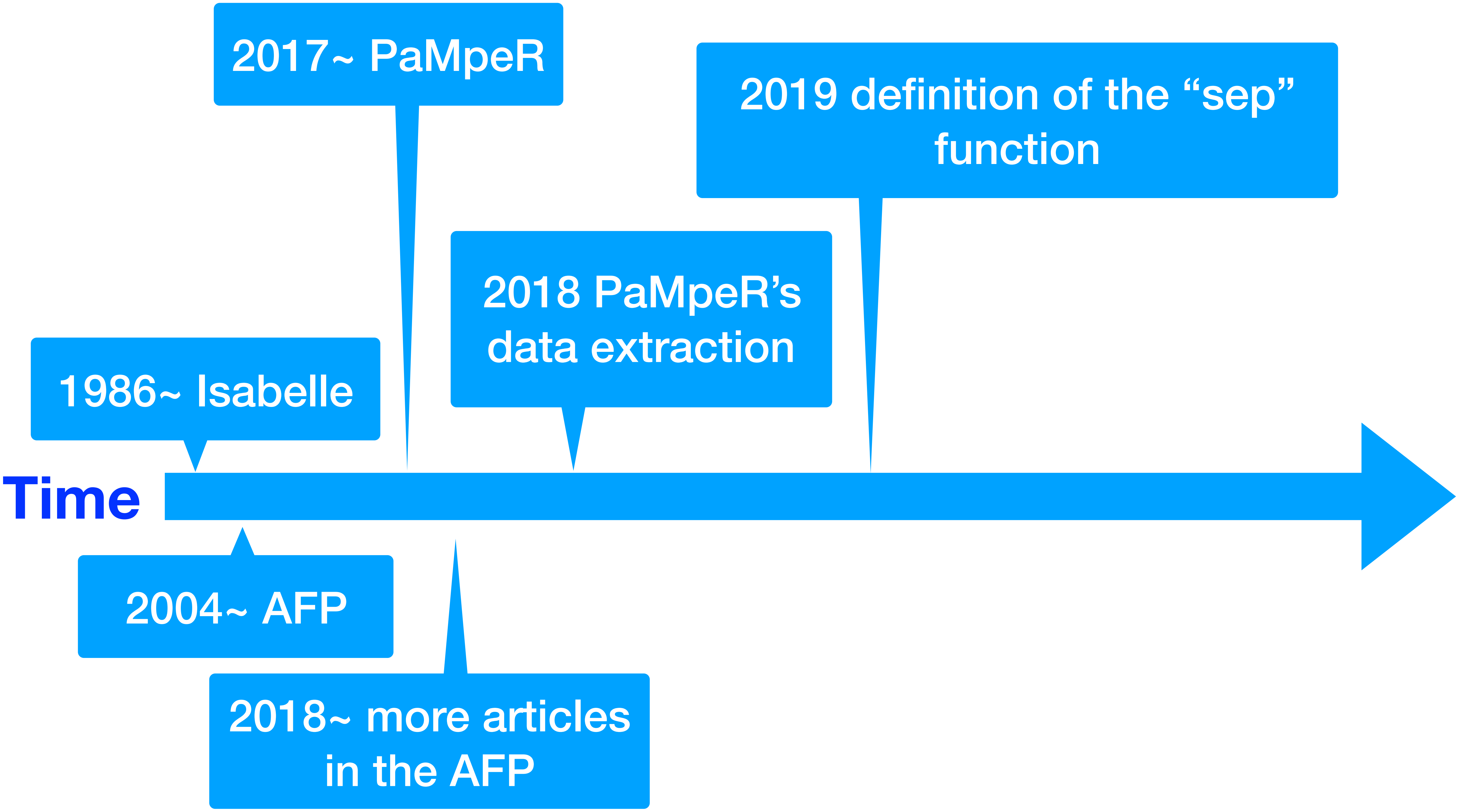

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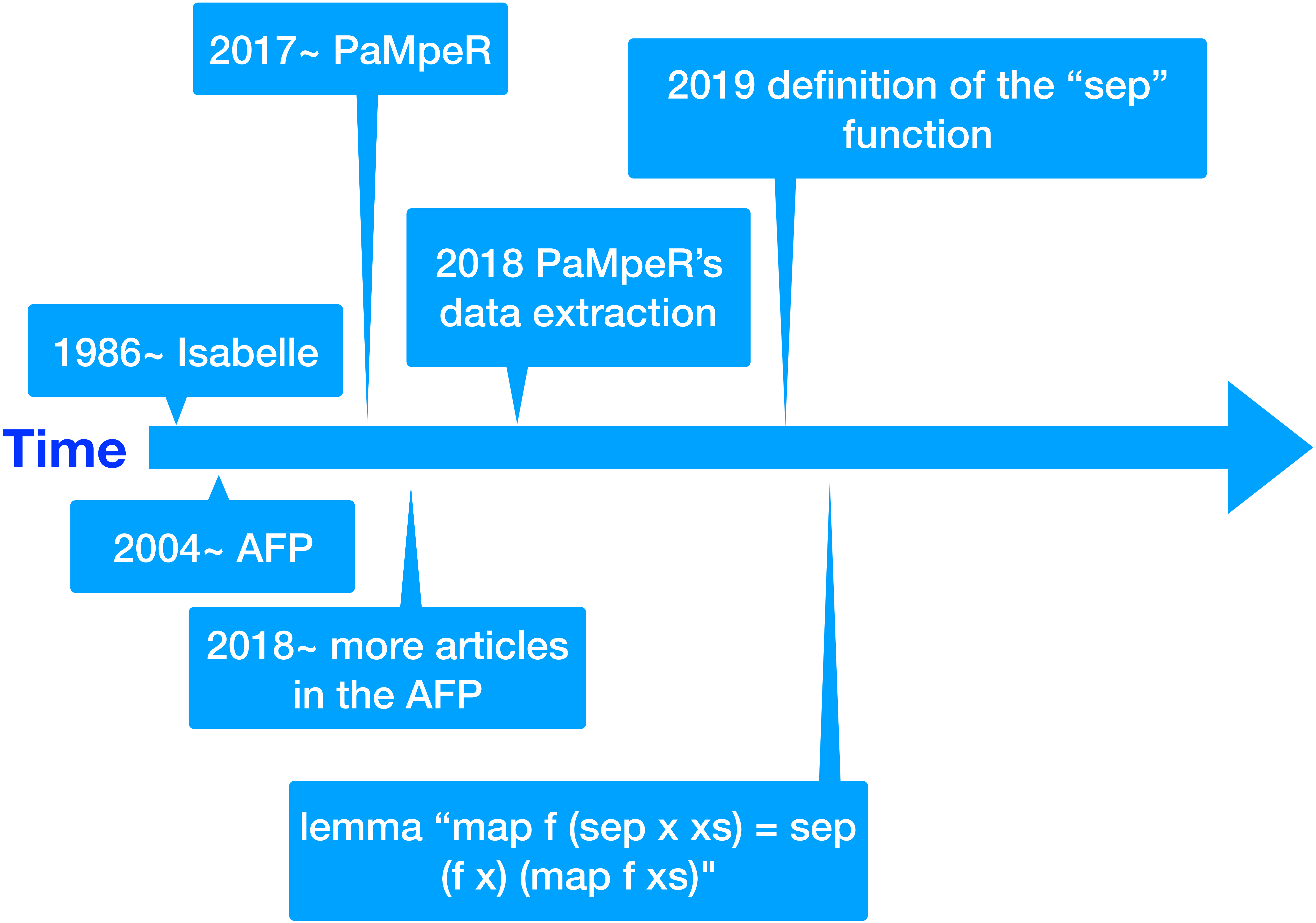

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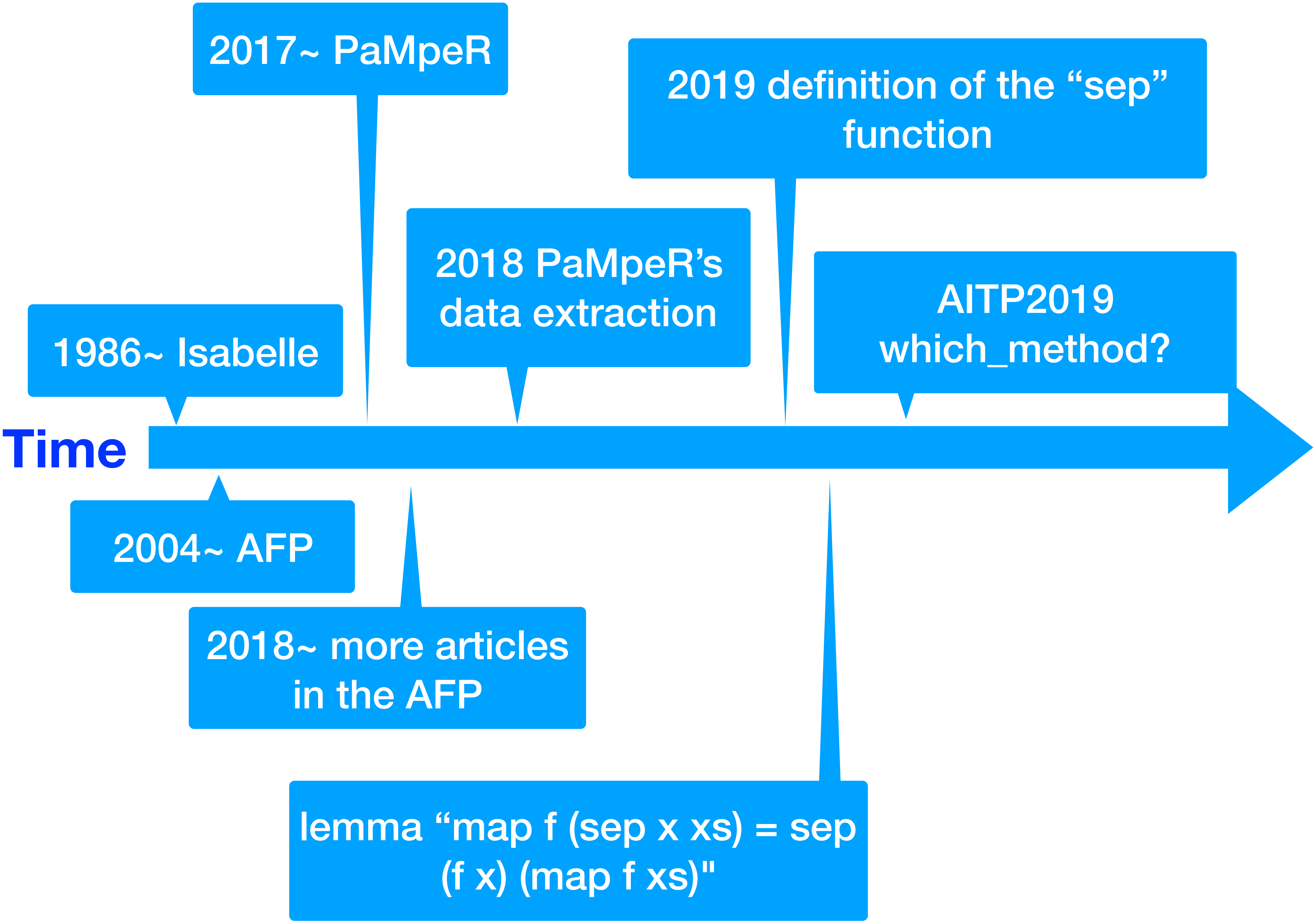

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2017~ PaMpeR

2019 definition of the “sep” function

2018 PaMpeR’s data extraction

AITP2019

19

Tim

PaMpeR’s feature extractor has to be able to analyze things (e.g. “sep”) that do not exist yet!

2018~ more articles in the AFP

lemma “map f (sep x xs) = sep (f x) (map f xs)"

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DEMO!

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resulting feature vector: [...,1,...,1,...0,...,1,...0,...]

10th 27th 32nd 58th 93rd

What assertions I wanted to write / wrote…

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Induction variables (x and xs) appear multiple times in the goal!

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lemma "(x @@ y) @@ z = x @@ (y @@ z)" apply (induct x)
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P x y ==> Q y z ==> R z w

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Time

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2017: PSL

Time

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2017: PSL

2019: define the “sep” function

Time

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2017: PSL

2019: define the “sep” function

2019: define the “DInd” strategy

2019:

```
lemma "map f (sep x xs) = sep (f x) (map f xs)"
  find_proof DInd
```

Time

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At the time of development (2017), PSL does not know about

- user defined constants (e.g. “sep”) or
- user defined proof strategies (e.g. DInd).