Incremental Maximum Satisfiability

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Maximum satisfiability (MaxSAT)

- Declarative **optimization paradigm** based on SAT
  - hard constraints as propositional clauses
  - minimize linear objective function
- Suitable **declarative modelling language** for various real-world optimization problems
  - planning, scheduling, verification, data analysis, machine learning, knowledge representation and reasoning, ...
- State-of-the-art solvers build on the success of SAT solvers
  - significant progress in MaxSAT solver technology
  - incremental API for SAT essential in practical implementations

Incremental optimization

- Various problem domains call for iterative solving procedures where **a sequence of related instances are solved**
  - adding or removing constraints
  - modifying objective function
- Solving each instance from scratch often too costly: **reuse information obtained during previous calls**
- Incremental SAT solving well-established Eén and Sörensson [2003]
  - extensively applied by MaxSAT solvers, QBF solvers, etc.
- Currently **MaxSAT solvers offer limited support** for incrementality
  - despite potentially useful information that could be preserved across solver invocations: state of SAT solver, cores

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Contributions

Niskanen, Berg, and Järvisalo [2021, 2022]

1. Detail **various forms of incrementality in MaxSAT**
   - adding hard clauses, soft literals, assumptions
2. Propose **IPAMIR: incremental API for MaxSAT**
   - generic interface for developing incremental MaxSAT solvers and applications making use of incremental MaxSAT
   - MaxSAT Evaluation 2022: incremental track
3. Develop a fully-fledged **incremental MaxSAT solver**
   - support for all functionality specified in IPAMIR
   - extends MaxHS: the state-of-the-art implicit hitting set based solver
4. Provide **empirical evidence on benefits of incrementality**
   - solving under different sets of assumptions

Implementation and benchmark data openly available:
`https://bitbucket.org/coreo-group/incremental-maxhs`

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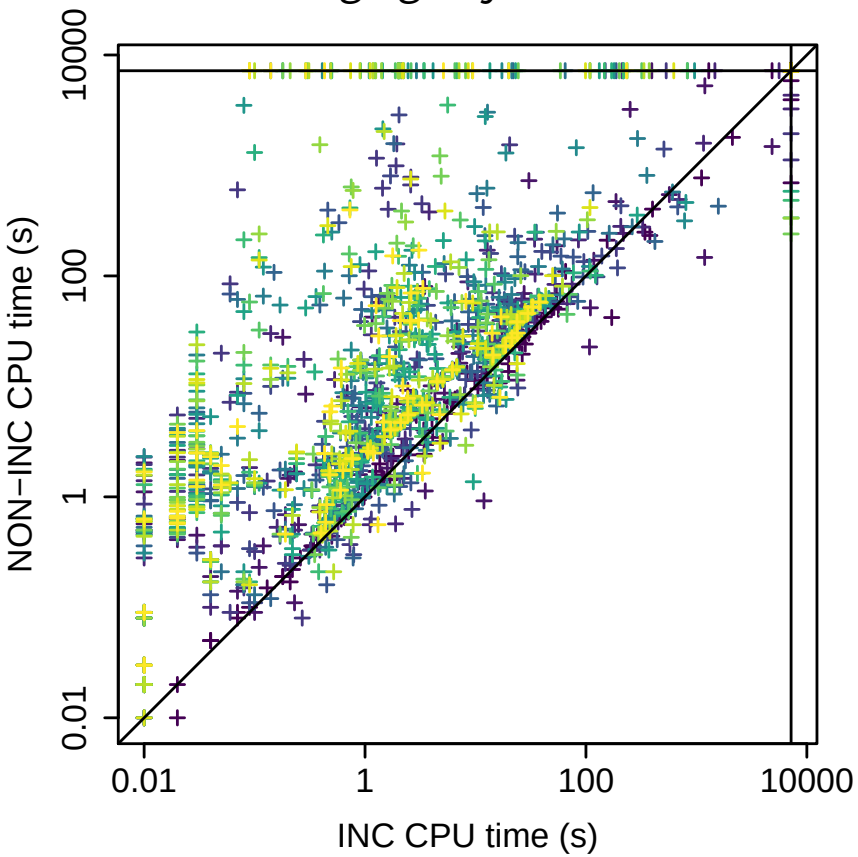
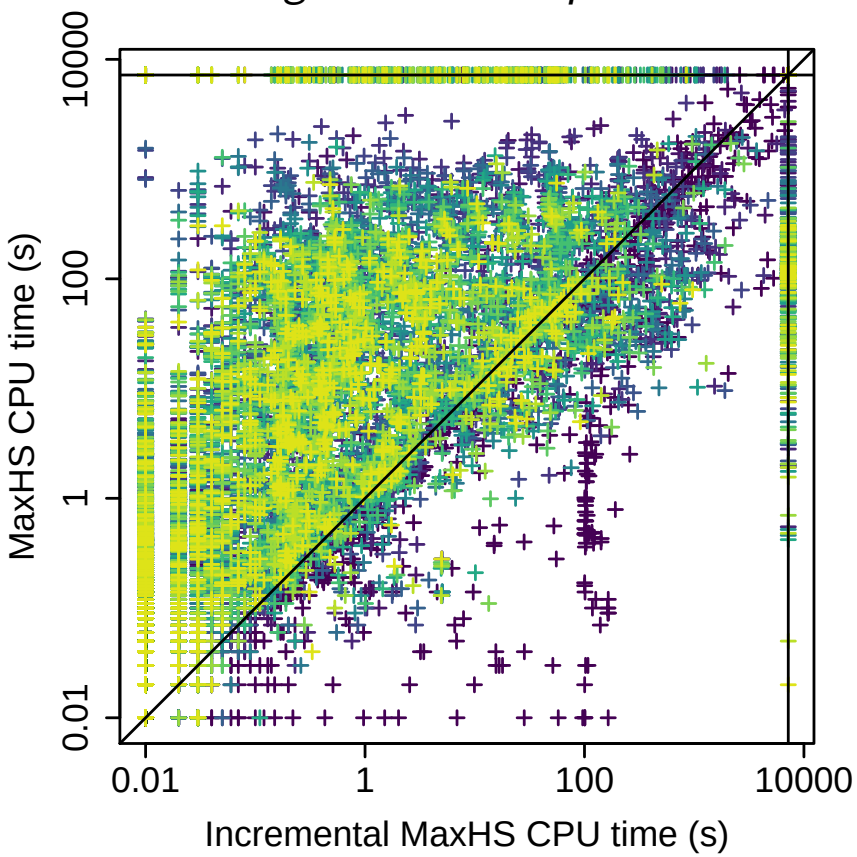
iMaxHS

An extension of the IHS solver MaxHS that supports incrementality

changing objective



solving under assumptions



- blue points → earlier iterations
- yellow points → later iterations

MaxSAT

- Optimization extension of SAT
- An instance consists of
  - a set of hard clauses $\mathcal{F}_H$,
  - a set of soft literals S,
  - a weight function w over soft literals S.
- Find τ that satisfies all hard clauses and minimizes $\sum_{b \in S} w(b) \cdot b$.

Note: definition equivalent to weighted soft clauses $\mathcal{F}_S$:

- *relax each soft clause $C \in \mathcal{F}_S$ to $C \vee \neg b_C$,*
- *add $C \vee \neg b_C$ to $\mathcal{F}_H$, and b_C to S with weight $w(b_C) = w(C)$.*

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Incremental changes in MaxSAT

- Aim for solving **a sequence of related MaxSAT instances** efficiently, avoiding computation from scratch
- Different scenarios call for different forms of **incremental changes**
  - adding hard clauses: MaxSAT-based CEGAR

    Mangal, Zhang, Nori, and Naik [2015]; Niskanen and Järvisalo [2020]
  - changing weights of soft literals: AdaBoost

    Hu, Siala, Hebrard, and Huguet [2020]
  - solving under assumptions: timetabling with disruptions

    Lemos, Monteiro, and Lynce [2020]

Note: similarly as in SAT, assumptions can be used to simulate the removal of clauses.

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IPAMIR: Incremental API for MaxSAT

- **Generic interface** for incremental MaxSAT
  - for MaxSAT solvers providing support for incrementality
  - for applications making use of incrementality
- Builds on **IPASIR**: standard interface for incremental SAT
- Specifies **incremental changes** to a MaxSAT instance
  - adding hard clauses
  - adding soft literals or changing their weights
  - assumptions on variables
- Includes other essential declarations
  - constructing and releasing a solver
  - solving, variable assignments, objective values

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```
// Construct a MaxSAT solver and return a pointer to it.
void * ipamir_init ();
// Deallocate all resources of the MaxSAT solver.
void ipamir_release (void * solver);
// Add a literal to a hard clause or finalize the clause with zero.
void ipamir_add_hard (void * solver, int32_t lit_or_zero);
// Add a weighted soft literal.
void ipamir_add_soft_lit (void * solver, int32_t lit, uint64_t weight);
// Assume a literal for the next solver call.
void ipamir_assume (void * solver, int32_t lit);
// Solve the MaxSAT instance under the current assumptions.
int ipamir_solve (void * solver);
// Compute the cost of the solution.
uint64_t ipamir_val_obj (void * solver);
// Extract the truth value of a literal in the solution.
int32_t ipamir_val_lit (void * solver, int32_t lit);
// Set a callback function for terminating the solving procedure.
void ipamir_set_terminate (void * solver, void * state,
                           int (*terminate)(void * state));
```

Functions declared in the IPAMIR header.

In contrast to IPASIR:

- `ipamir_add_soft_lit` declares a soft literal b with weight w
  - if literal b already declared soft, changes its weight
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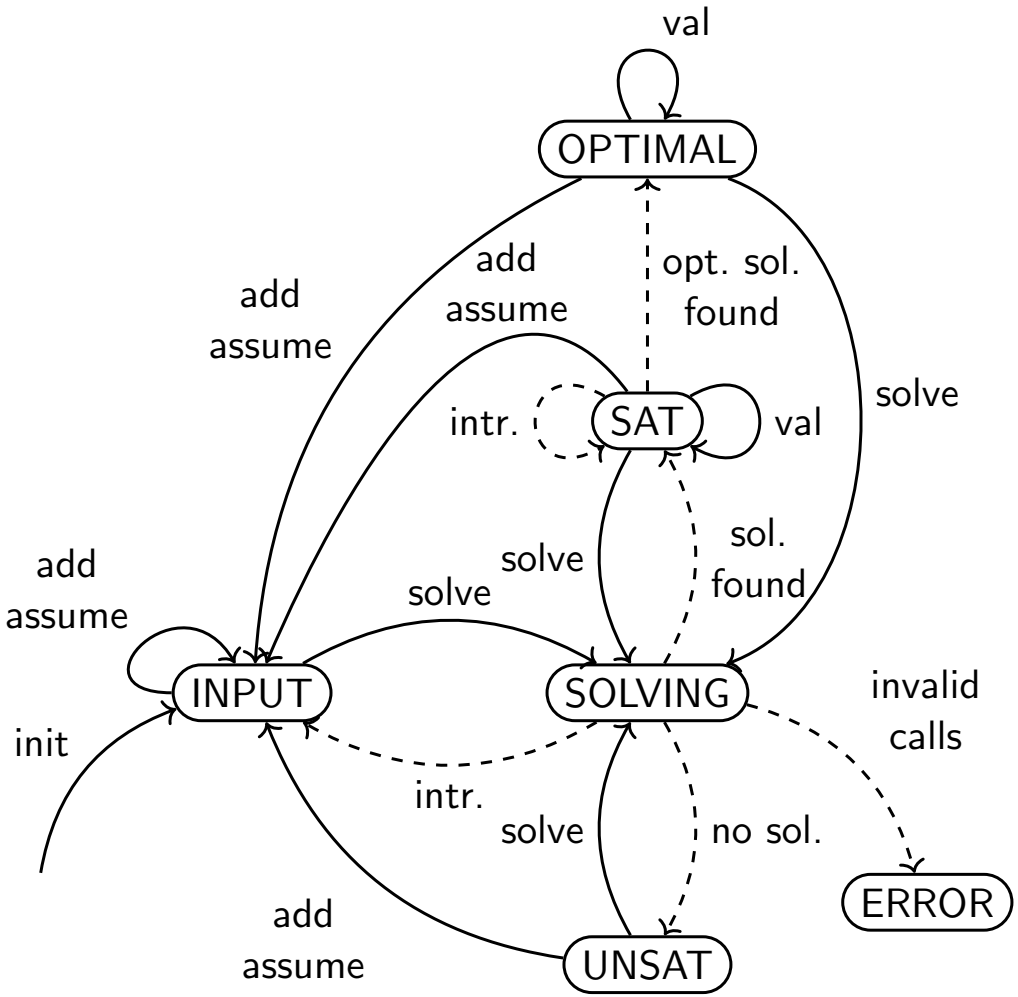
IPAMIR: an incremental interface for MaxSAT



Implicit Hitting Set (IHS) based MaxSAT solving

Davies and Bacchus [2011, 2013]

An iterative approach: identify *sources of inconsistency* and *repair the inconsistencies* in a minimal way.

- A *core* is a clause over soft literals entailed by the hard clauses.
  - SAT solver as *core extractor*
- *hs* is a *hitting set* over a set of cores $\mathcal{C}$ if *hs* intersects each $\kappa \in \mathcal{C}$
  - *cost* of a hitting set determined by weights of soft literals
  - IP solver for computing *minimum-cost* hitting sets

Reasoning and *optimization* effectively decoupled:

- *upper bounds* from assignments given by the SAT solver
- *lower bounds* from costs of optimal hitting sets

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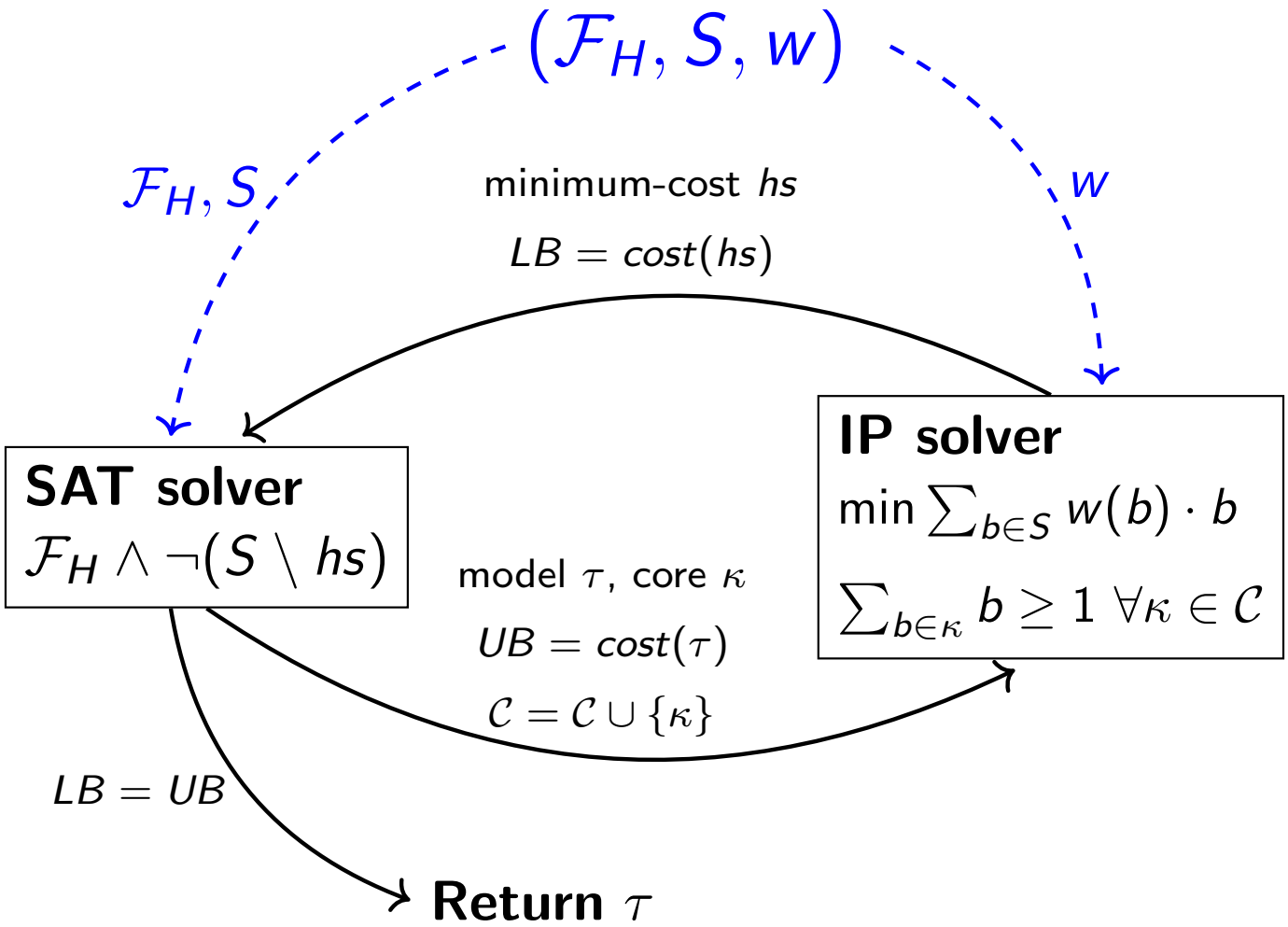

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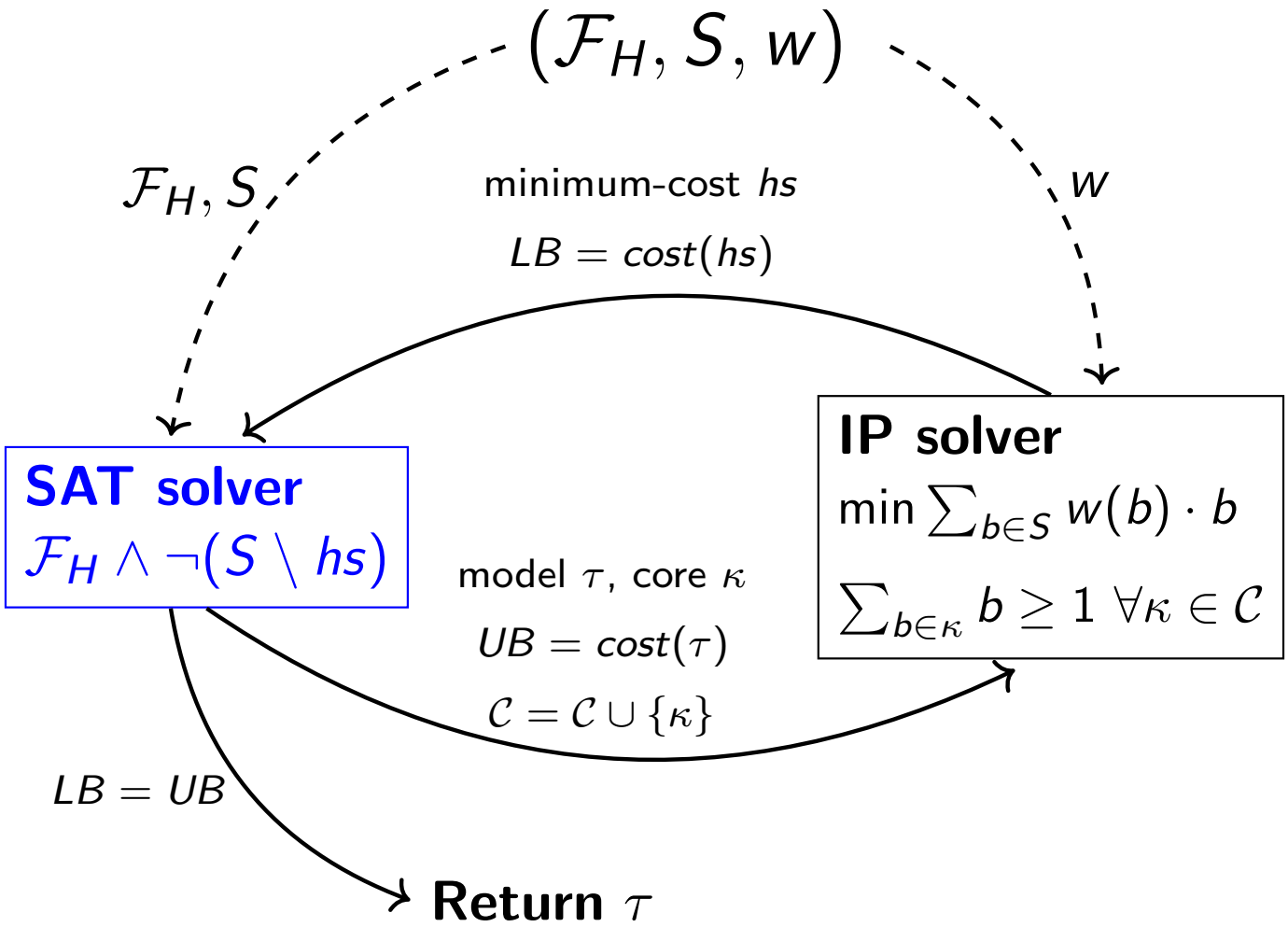

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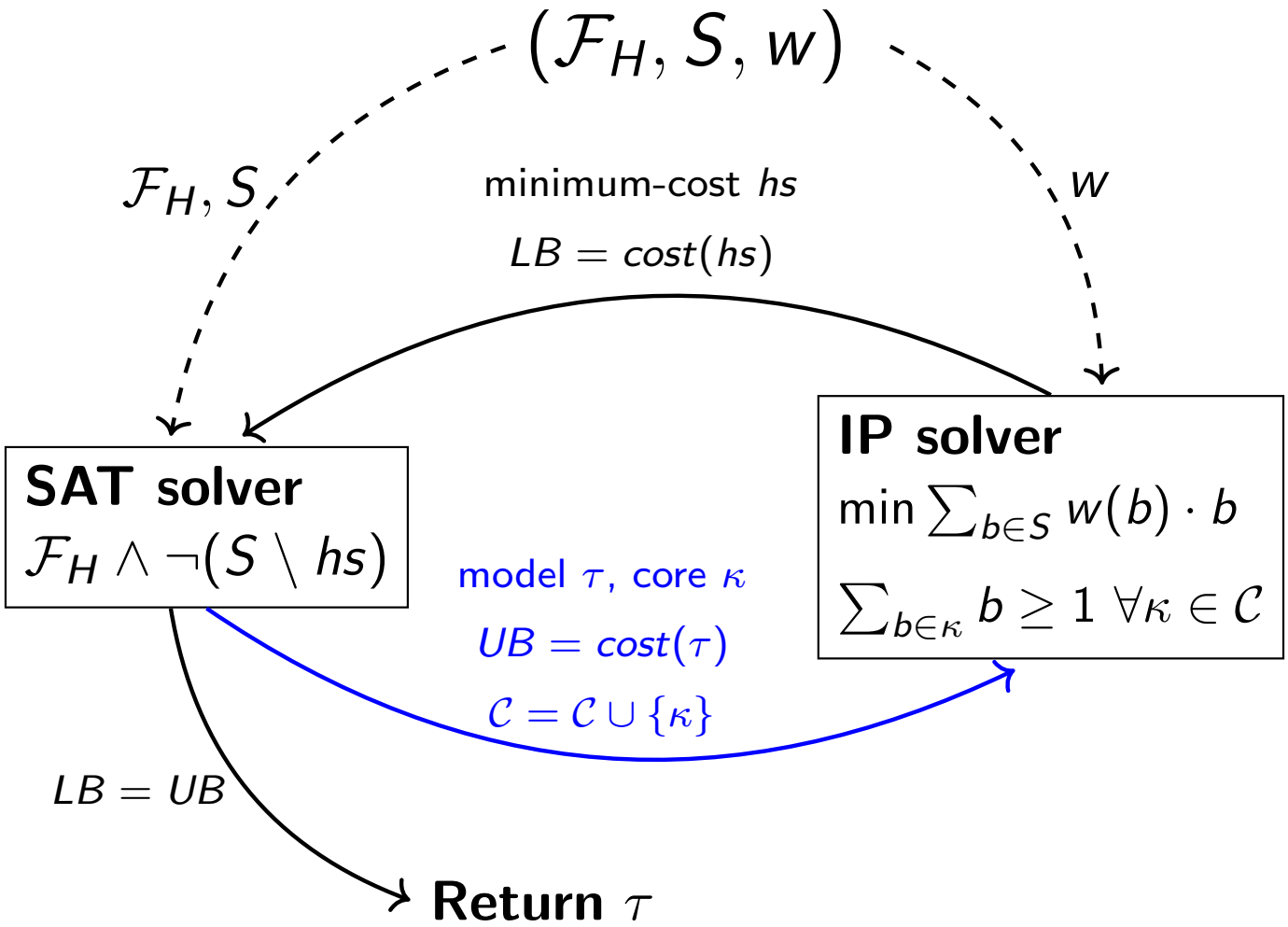

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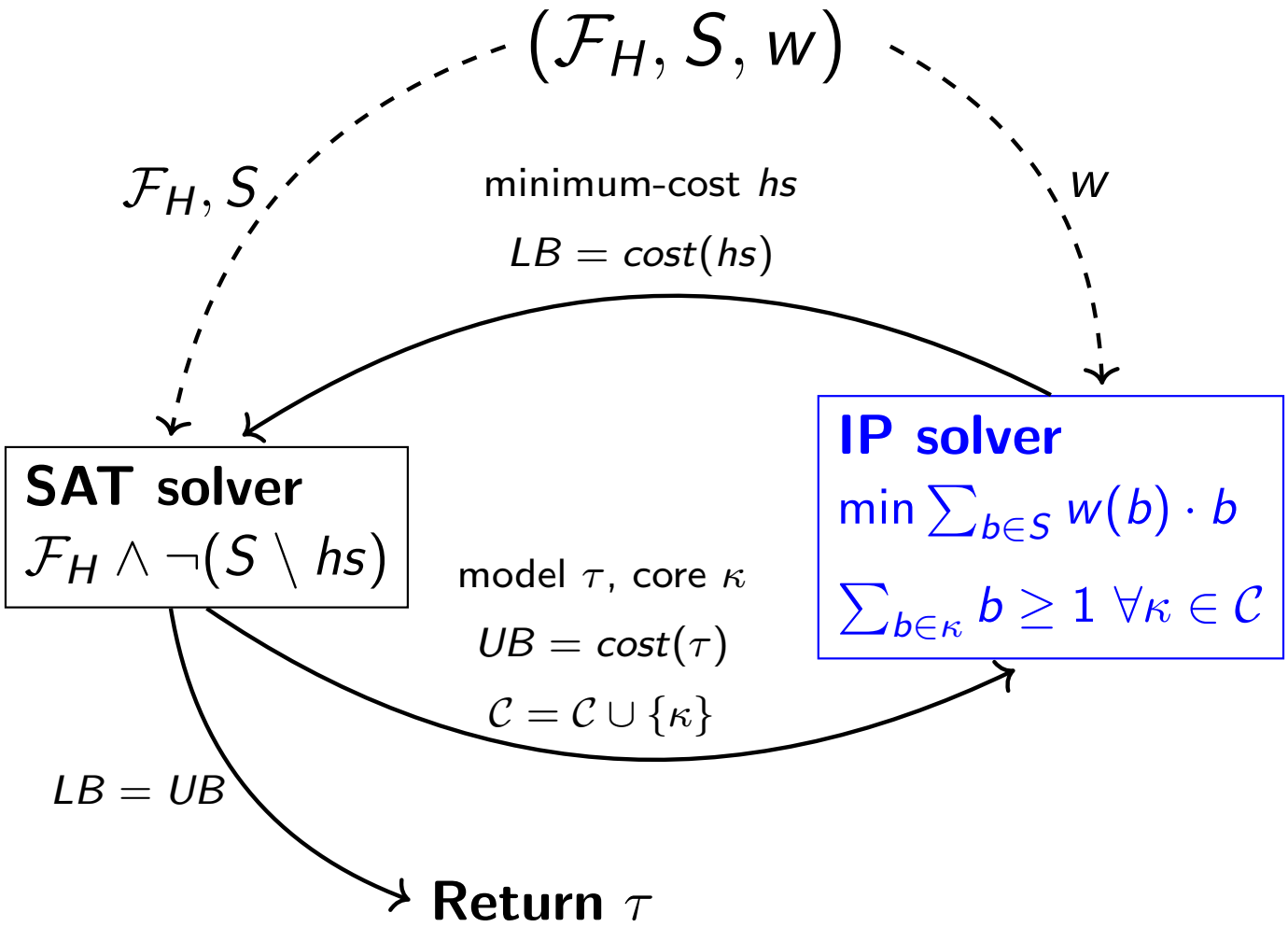

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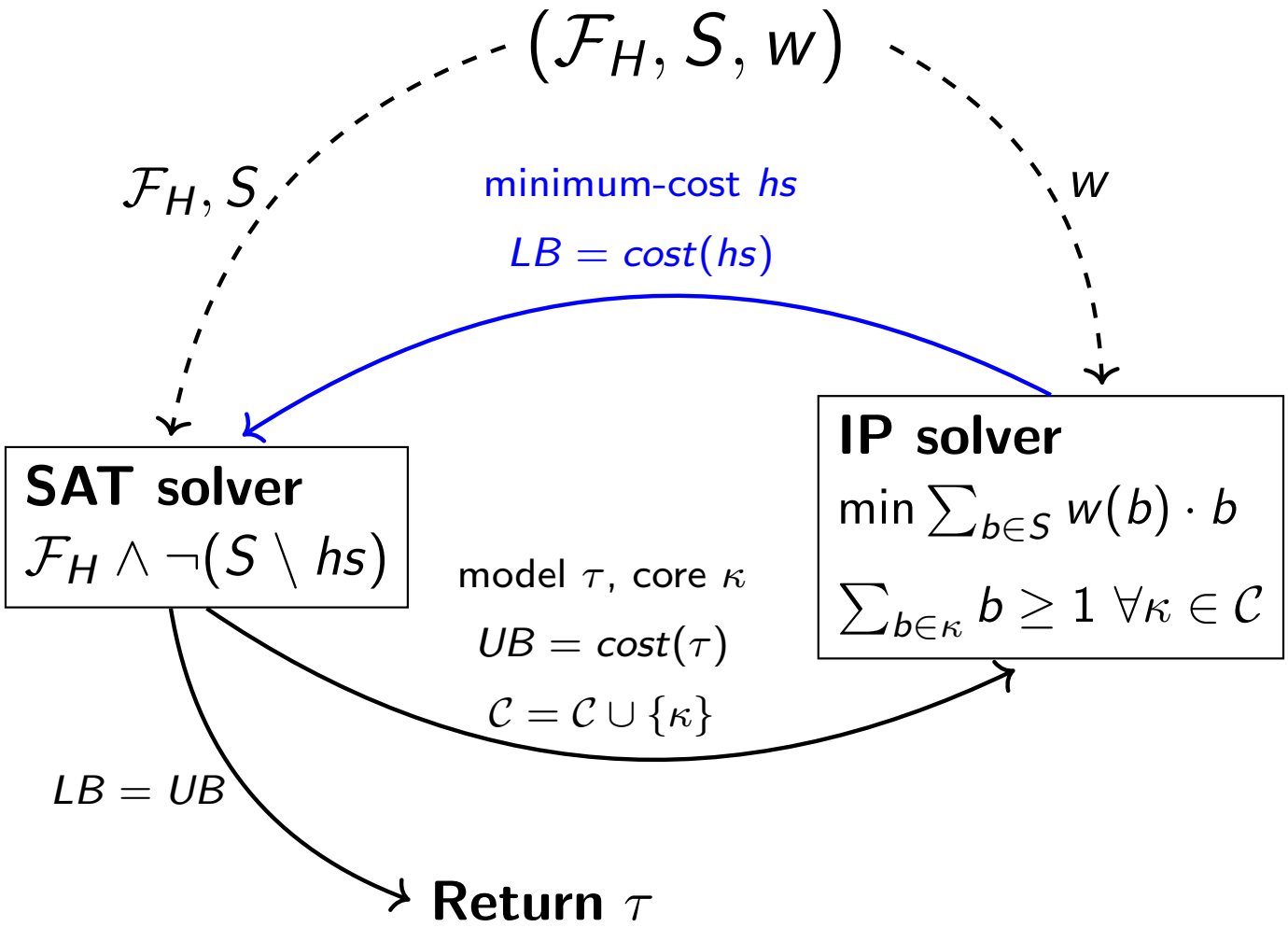

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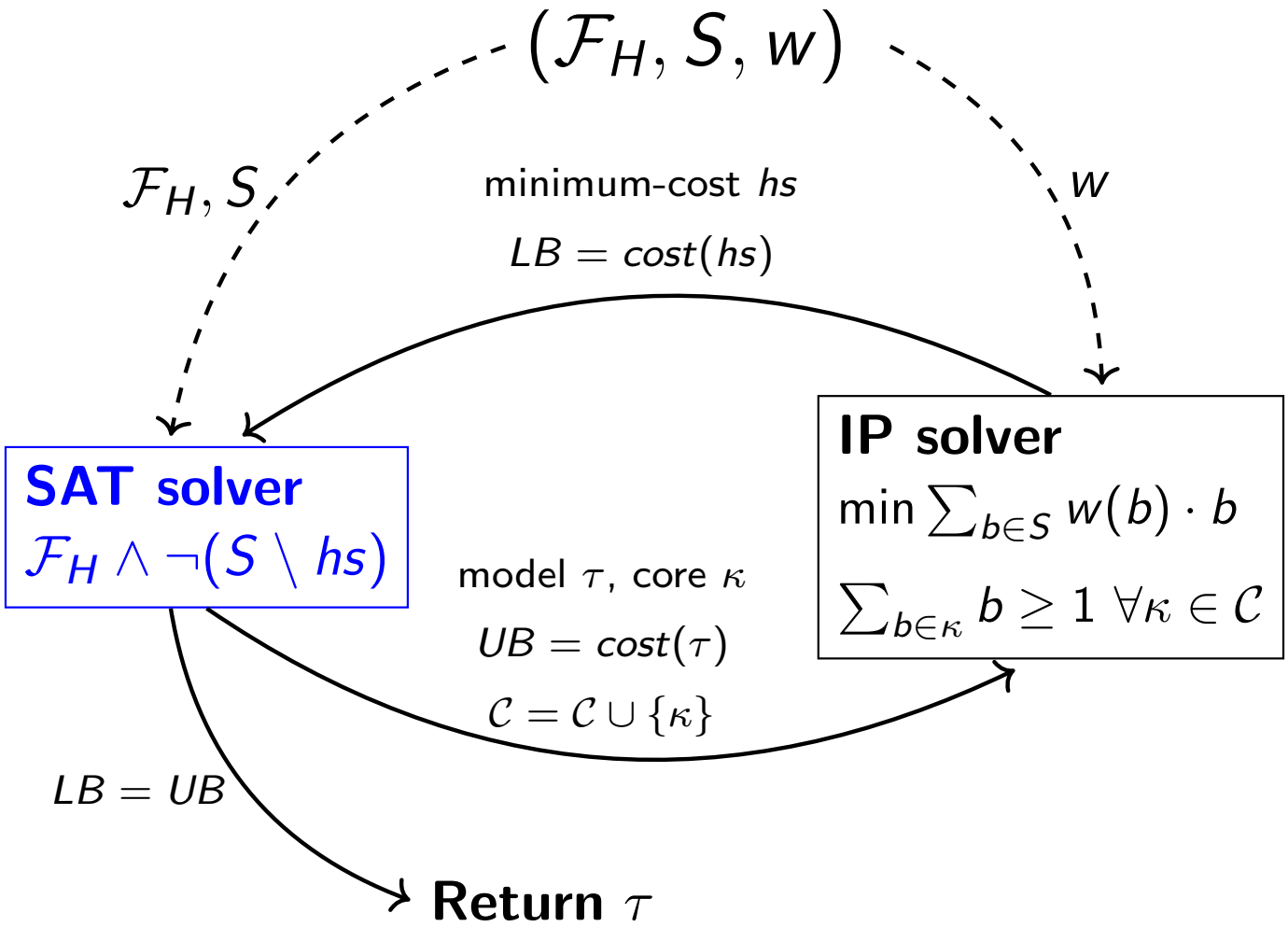

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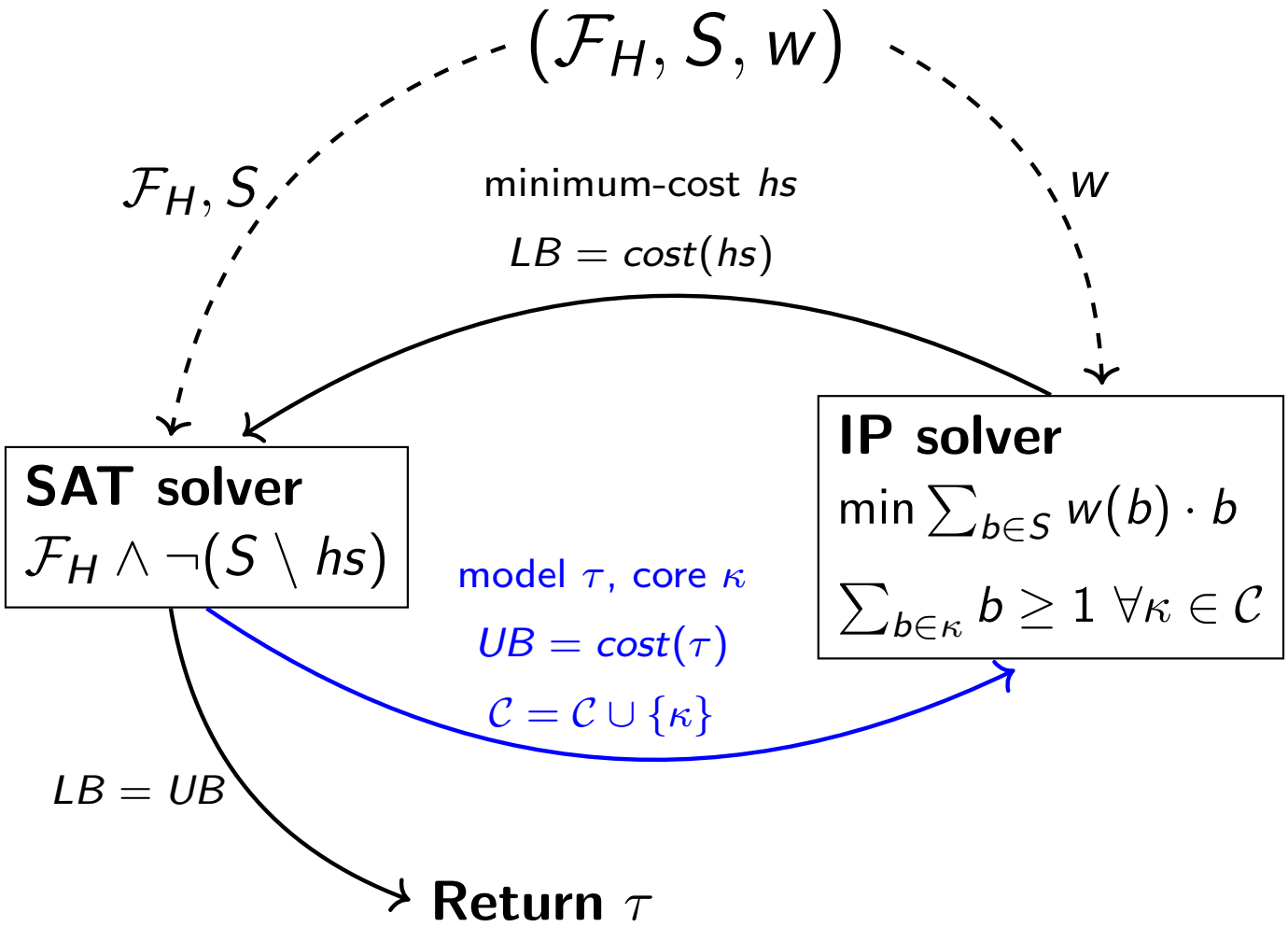

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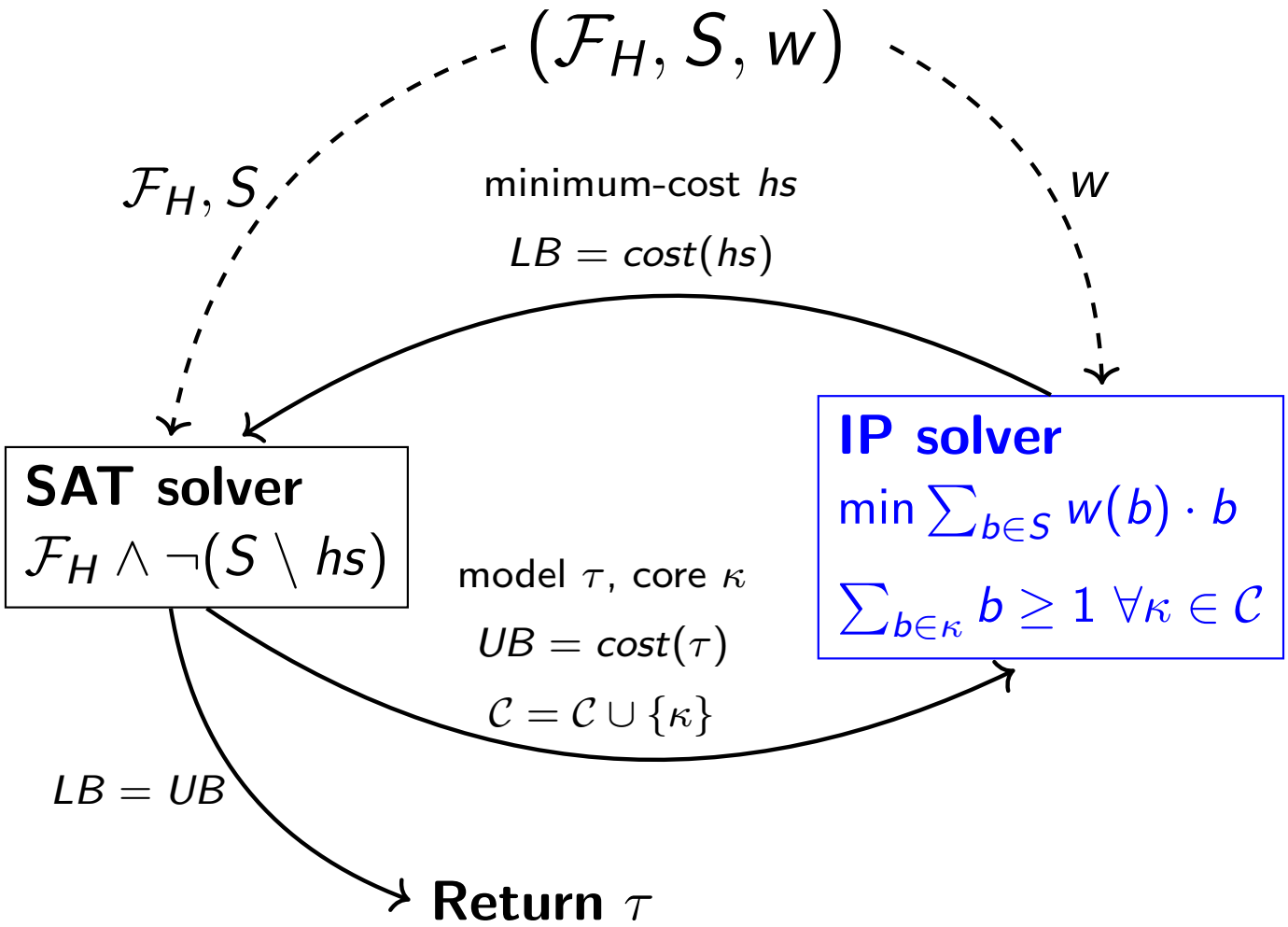

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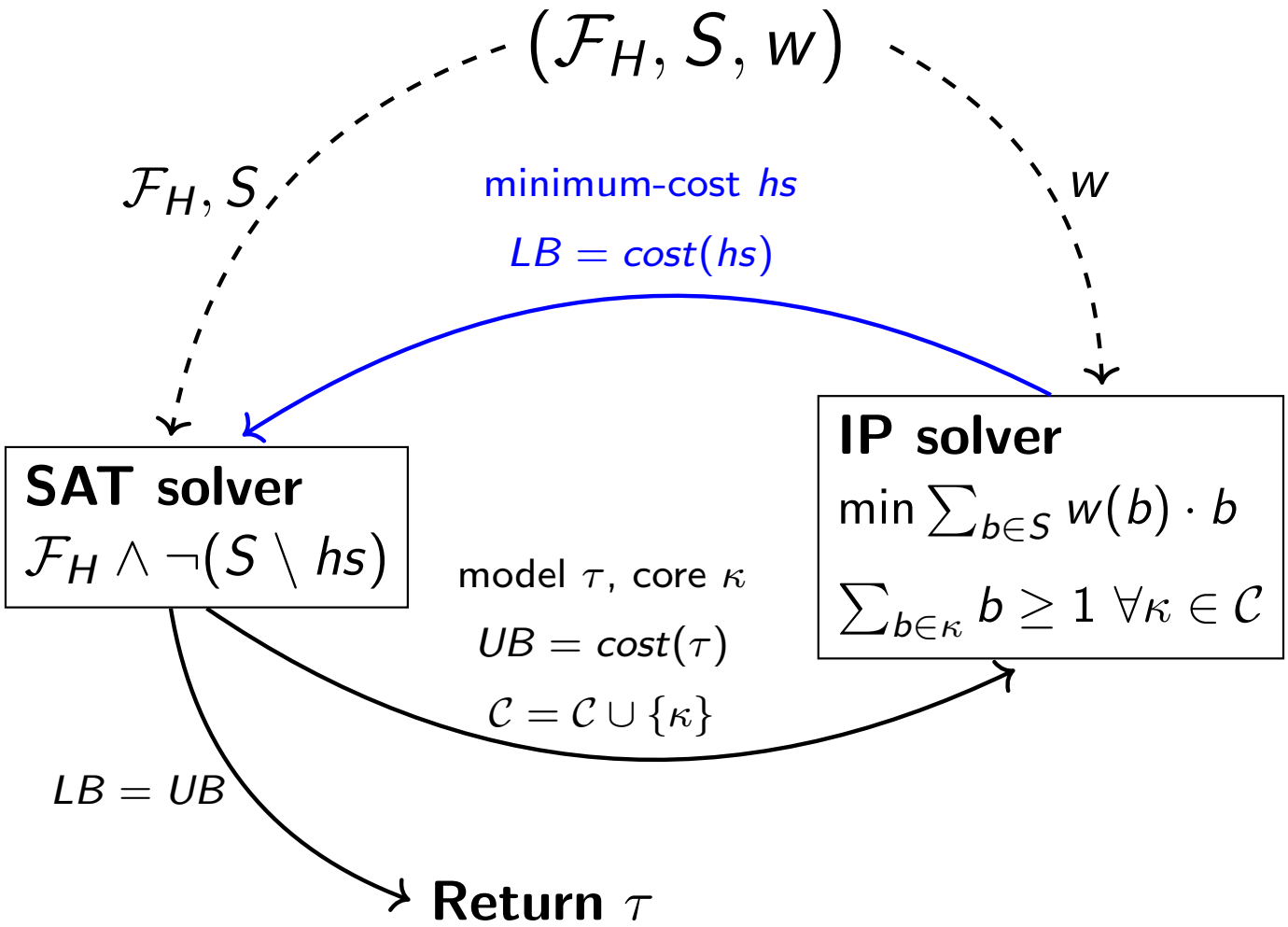

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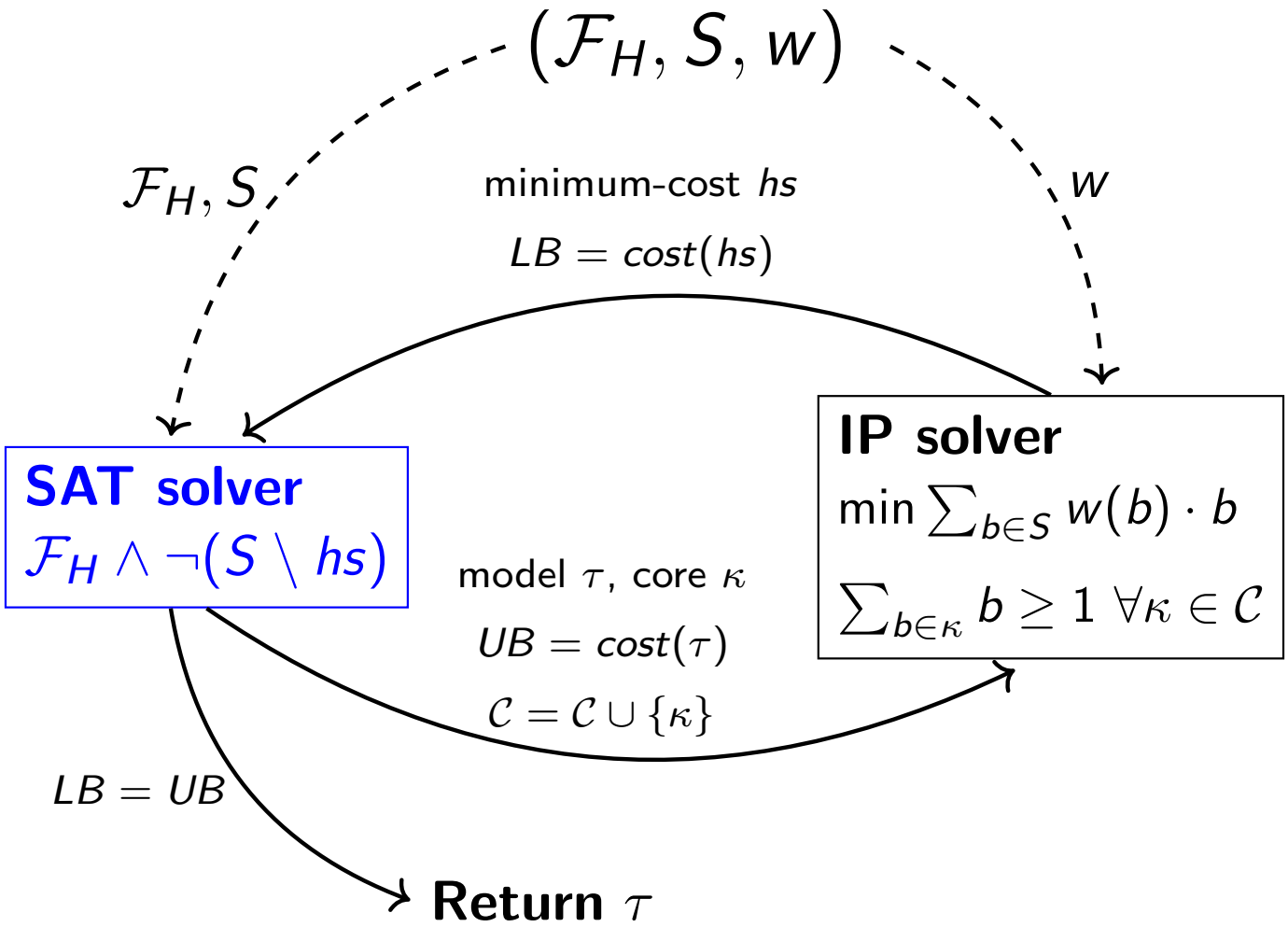

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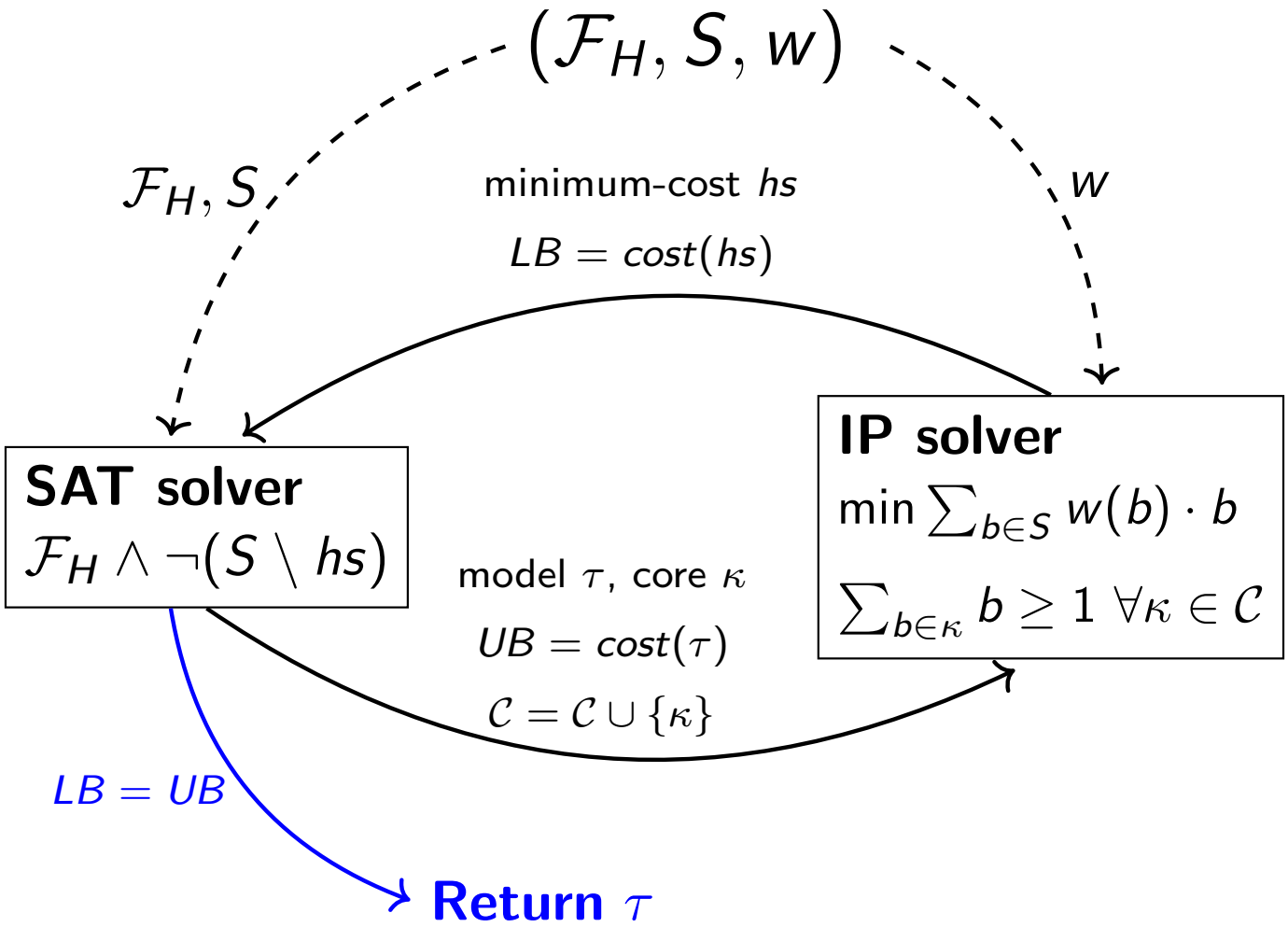

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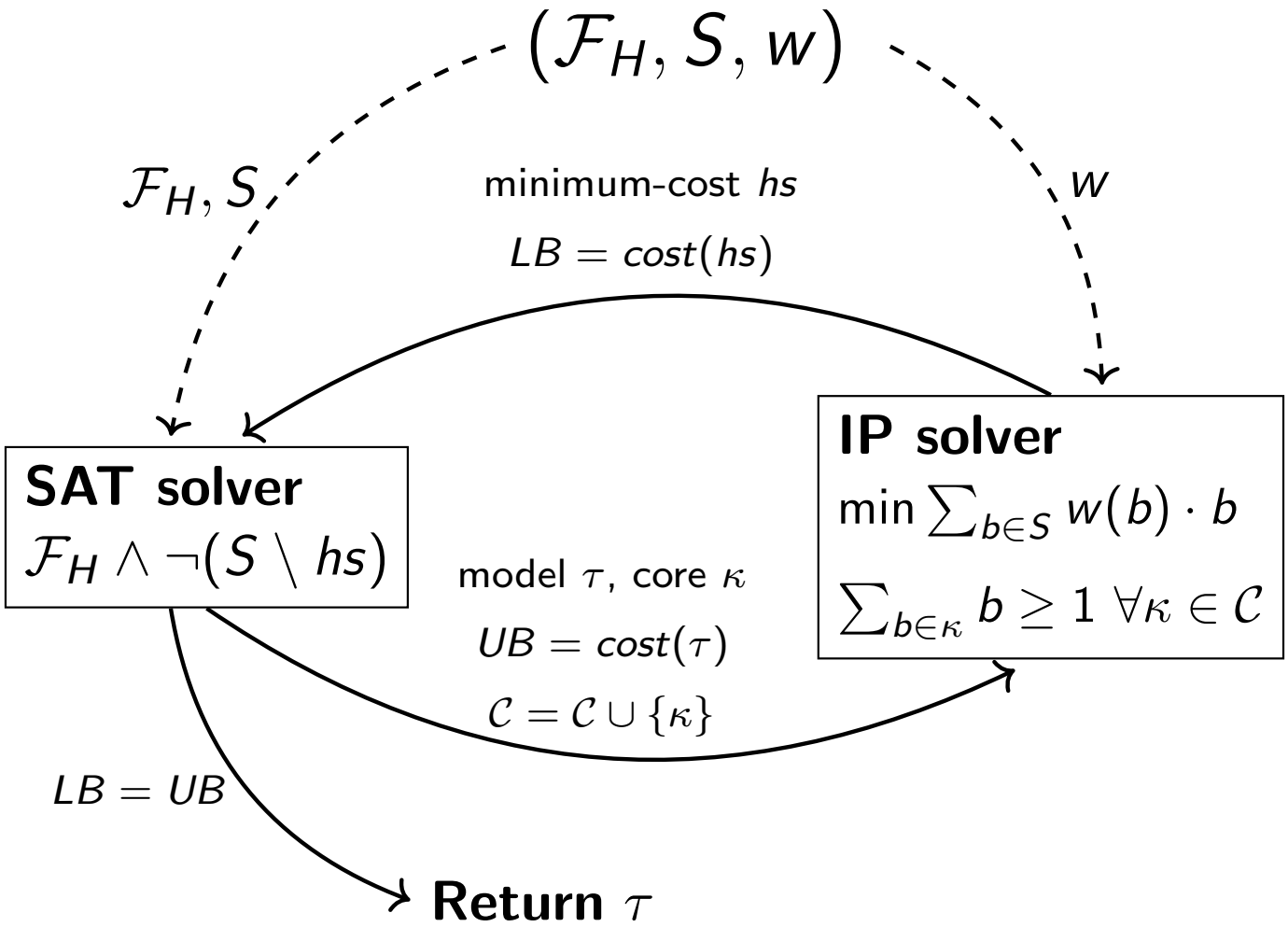

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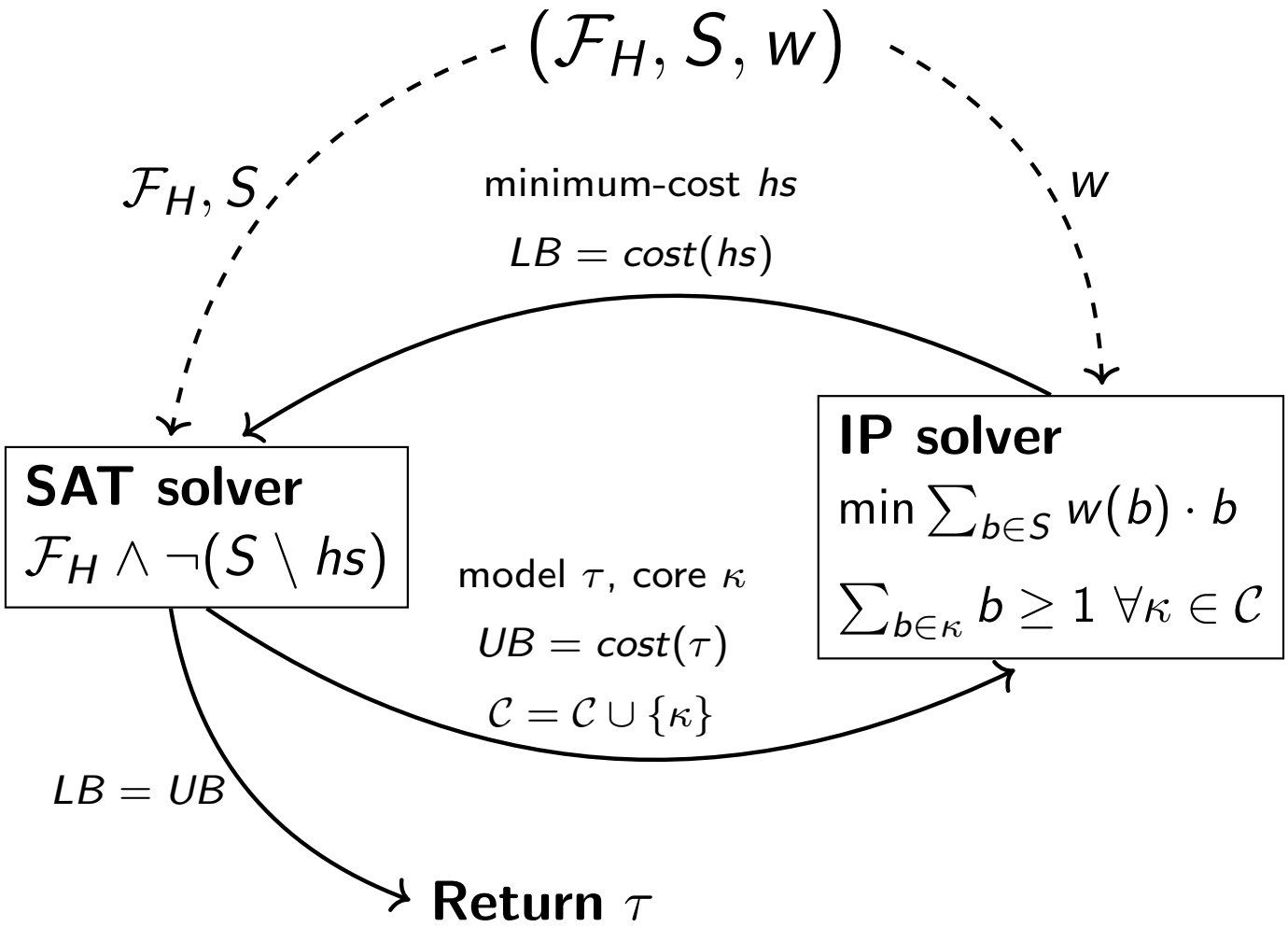

Note: $\neg(S \setminus hs)$ passed as assumptions to the SAT solver.

Incremental IHS

In theory

Observations:

- If we add a new hard clause, a new soft literal, or change the weight of a soft literal, **all extracted cores are still valid**
  - **cores can be preserved** between solver invocations
  - only objective needs to be altered in the IP solver
- The SAT solver knows nothing about the weights of soft literals
  - add hard clauses directly to the SAT solver
  - no need to reinitialize

How to deal with assumptions without restarting the SAT solver?

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Incremental IHS for solving under assumptions

In theory

Main idea: pass user-provided assumptions A along with IHS solving assumptions $\neg(S \setminus hs)$ to the internal SAT solver

- if $a \in A \cap S$, do not include $\neg a$ as assumption from $\neg(S \setminus hs)$
- cores extracted during search may also contain literals from $\neg A$
  - *How to preserve cores when solving under assumptions?*

Conditional cores

Given a MaxSAT instance $(\mathcal{F}_H, S, w)$, a *conditional core* with respect to assumptions A is a clause $\kappa^a \subset \neg A \cup S$ that is entailed by $\mathcal{F}_H$.
The *restriction* of a conditional core is $\kappa^a \setminus \neg A$.

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With current MaxSAT assumptions A:

- Include A in the assumptions of every internal SAT solver call (and remove conflicting soft literals)
  - models reported by the SAT solver will satisfy A
- SAT solver extracts conditional cores κ^a
  - add κ^a to a set of all collected conditional cores
  - add the restriction $\kappa^a \setminus \neg A$ to the IP solver

With next MaxSAT assumptions A':

- Reinitialize the IP solver
- Check all known conditional cores κ^a
  - if $\kappa^a \cap A' = \emptyset$ and the restriction $\kappa^a \setminus \neg A' \subseteq S$, add the restriction to the IP solver

No need to reinitialize the SAT solver, and cores are preserved.

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  - if $\kappa^a \cap A' = \emptyset$ and the restriction $\kappa^a \setminus \neg A' \subseteq S$, add the restriction to the IP solver

No need to reinitialize the SAT solver, and cores are preserved.

Incremental IHS for solving under assumptions

In theory

With current MaxSAT assumptions A:

- Include A in the assumptions of every internal SAT solver call (and remove conflicting soft literals)
  - models reported by the SAT solver will satisfy A
- SAT solver extracts conditional cores κ^a
  - add κ^a to a set of all collected conditional cores
  - add the restriction $\kappa^a \setminus \neg A$ to the IP solver

With next MaxSAT assumptions A':

- Reinitialize the IP solver
- Check all known conditional cores κ^a
  - if $\kappa^a \cap A' = \emptyset$ and the restriction $\kappa^a \setminus \neg A' \subseteq S$, add the restriction to the IP solver

No need to reinitialize the SAT solver, and cores are preserved.

Incremental IHS

In practice

Make use of **MaxHS: state-of-the-art IHS-based MaxSAT solver**. Realizing incrementality requires a non-trivial amount of engineering.

- **Maintaining conditional cores:** use another SAT solver as a database for storing conditional cores. To extract valid cores, perform unit propagation under current MaxSAT assumptions.
  - removes redundant cores and simplifies them
  - still need to check that the resulting cores only contain soft literals
- **IPAMIR wrapper:** When initialized, MaxHS performs several rounds of simplification to the input formula.
  - variable mappings must be maintained
  - fixed literals need to be handled correctly
  - no pure literal elimination can be performed
- **Other techniques** must be modified to preserve correctness
  - reduced cost fixing Bacchus, Hyttinen, Järvisalo, and Saikko [2017]
  - abstract cores Berg, Bacchus, and Poole [2020]

End result: **iMaxHS** (incremental MaxHS)

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Empirical evaluation

Optimizing under assumptions

Benchmark instances

- All 1184 instances from complete tracks of MaxSAT Evaluation 2021
- For each benchmark, create 20 different sets of assumptions by hardening each soft clause with probability 0.01.
  - 23680 iterations overall

Benchmark setup

- iMaxHS vs. its non-incremental version *in default settings*
  - for non-incremental, add assumptions directly as hard clauses
- Per-instance limits: 7200 seconds and 16 GB memory
  - instance: 20 MaxSAT solver calls each with different assumptions
  - exclude WCNF parsing times from consideration

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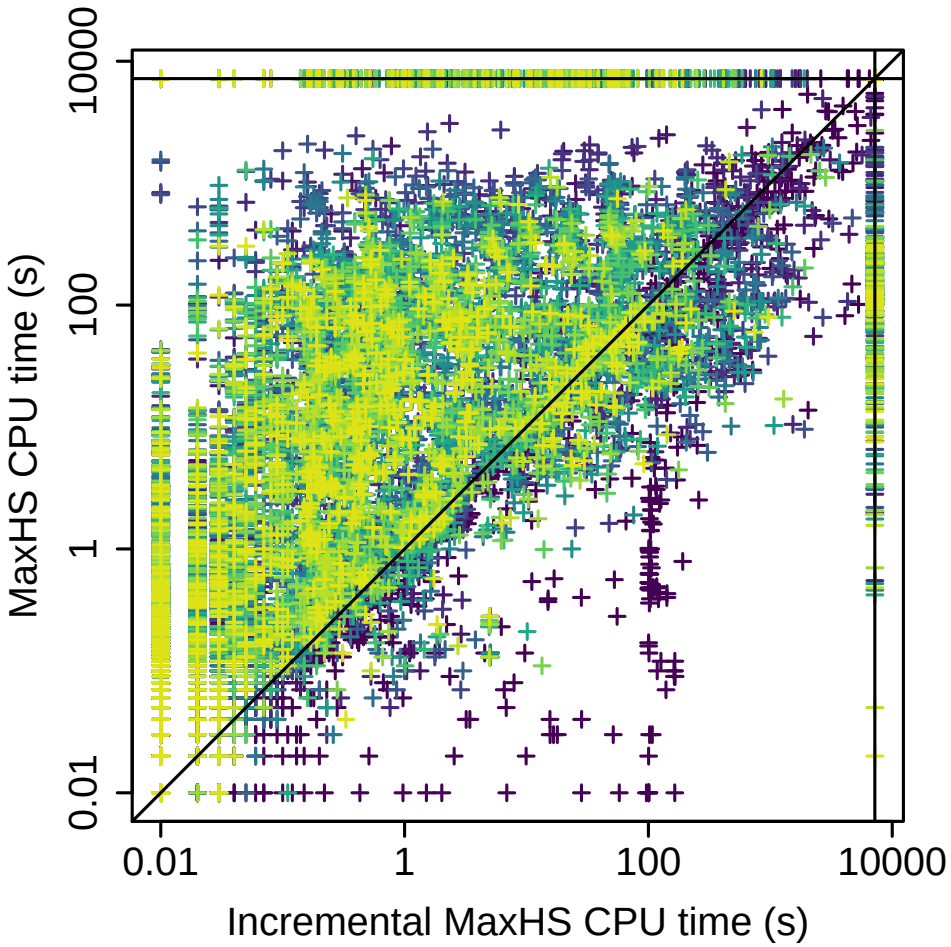
Empirical evaluation

Optimizing under assumptions

Increased performance gained by preserving cores:



Summary

Contributions

- **IPAMIR:** incremental API for MaxSAT
  - specifies various forms of incrementality in MaxSAT
  - provides a standard interface to facilitate the development of solvers and applications
- **iMaxHS:** fully-fledged incremental MaxSAT solver
  - supports all IPAMIR functionality
  - internal SAT solver used without reinitializing
  - cores preserved between solver invocations
- **Empirical evaluation:** clear benefit from incrementality

Implementation available online in open source:
`https://bitbucket.org/coreo-group/incremental-maxhs`

Thank you for your attention!

Get in touch via email:
andreas.niskanen@helsinki.fi

Or come chat in person :)

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