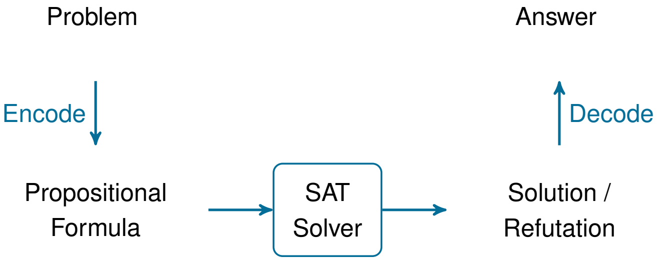
IPASIR-UP: User Propagators for CDCL

SAT Conference, July 7, 2023
Alghero, Italy

Katalin Fazekas[1], Aina Niemetz[2], Mathias Preiner[2],
Markus Kirchweger[1], Stefan Szeider[1], Armin Biere[3]

[1]TU Wien, Vienna, Austria
[2]Stanford University, Stanford, USA
[3]University of Freiburg, Freiburg, Germany

Usual Use of SAT Solvers



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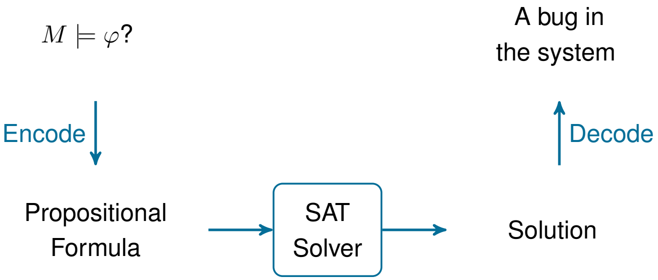

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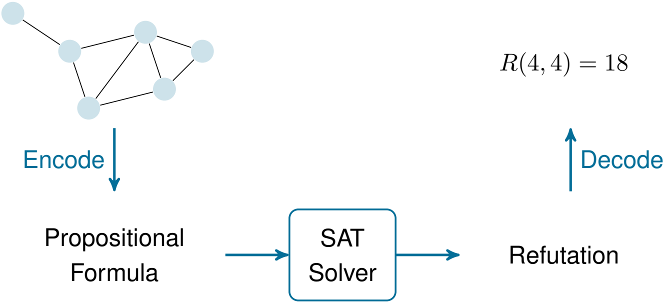
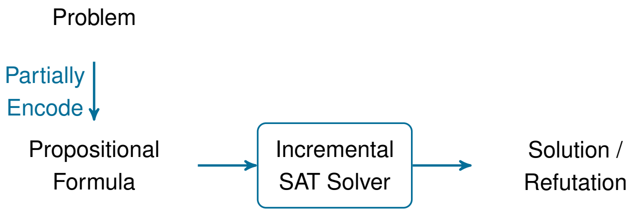


Usual Use of Incremental SAT Solvers



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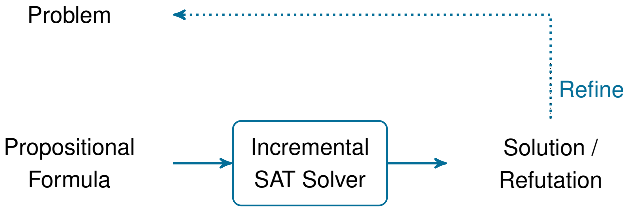

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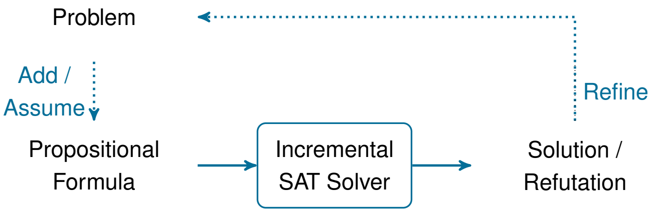

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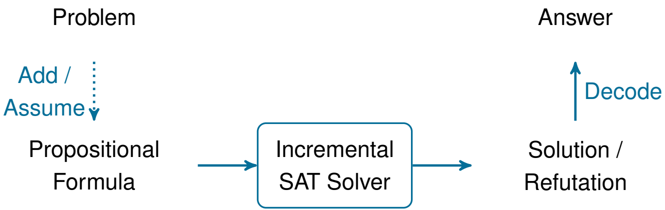

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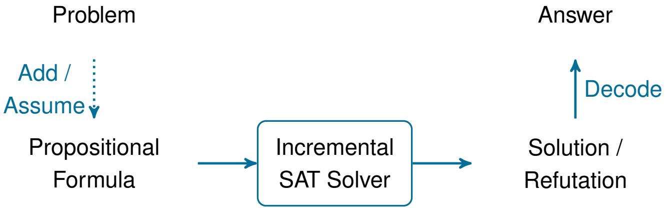
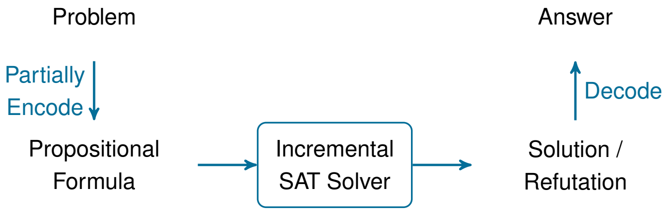


- Model enumeration, model checking, CEGAR, symbolic execution, . . .

Use of Incremental SAT Solvers via User Propagators



- Combinatorial problems, SMT, symmetry breaking, model enumeration, MaxSAT, . . .

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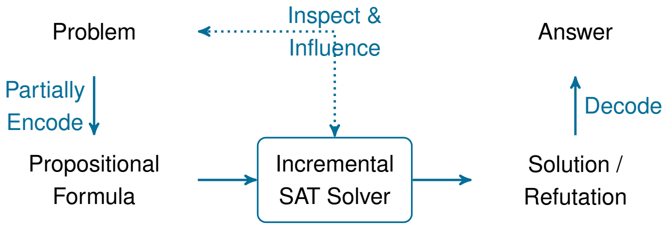

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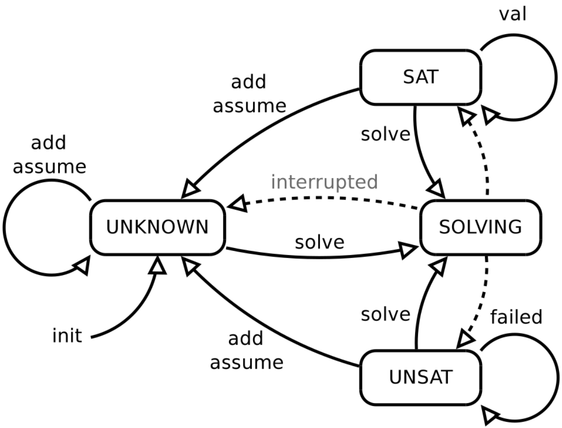
IPASIR-UP: A New Interface for Interactive CDCL

- Interface to support standardized interactions with the solver during solving
  - – Needs to be implemented in SAT solvers (only once)
  - + Easy to implement and use
  - + Solver independent application development
  - + No more black-box SAT solving $\rightarrow$ new potentials
  - + Standardized and clean interactions

IPASIR Model of Incremental SAT Solvers [BalyoBiereIserSinz'16]



- IPASIR: *"Re-entrant Incremental Satisfiability Application Program Interface"*
- Supports interactions **between** solve calls

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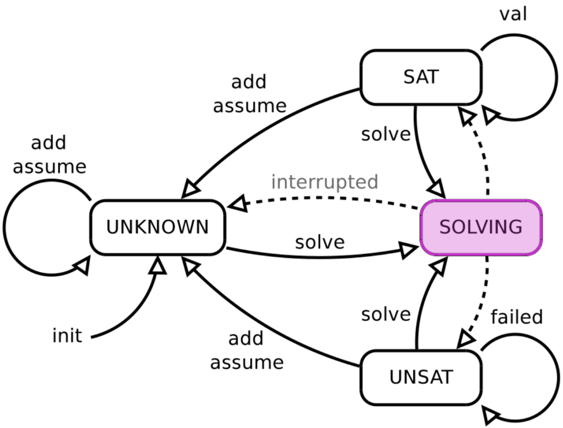

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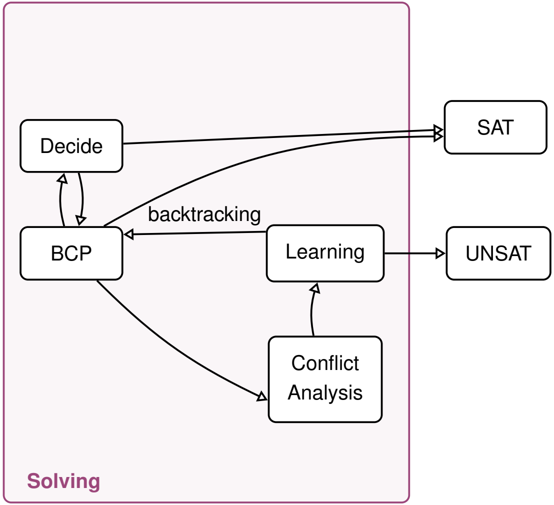
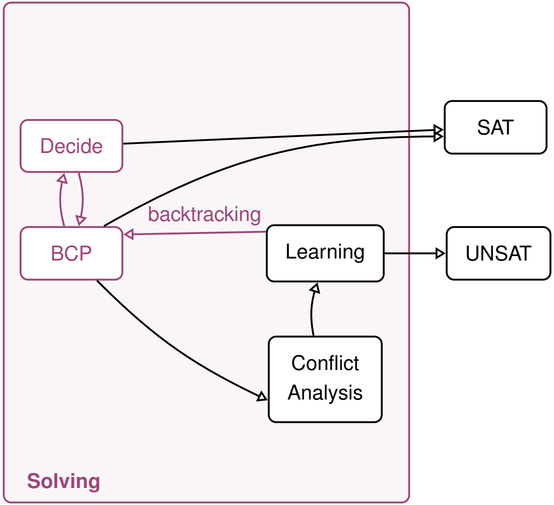
IPASIR-UP: IPASIR with User Propagators

- Supports interactions **during** the solve () calls



IPASIR-UP: IPASIR with User Propagators

- Supports interactions **during** the solve () calls
- Inspect search
  - Notify all changes to the trail



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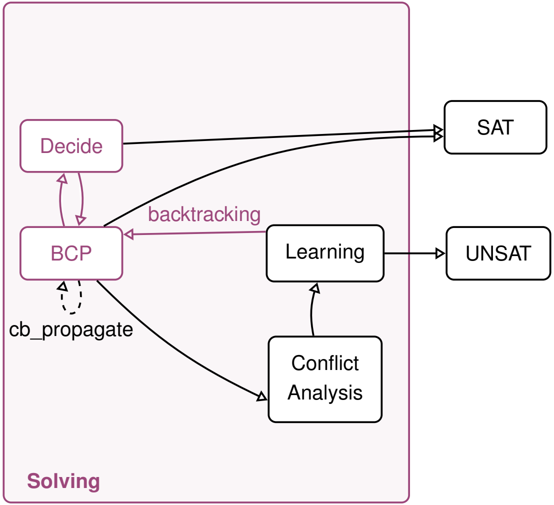
  1. Add propagations (without adding reason clauses)



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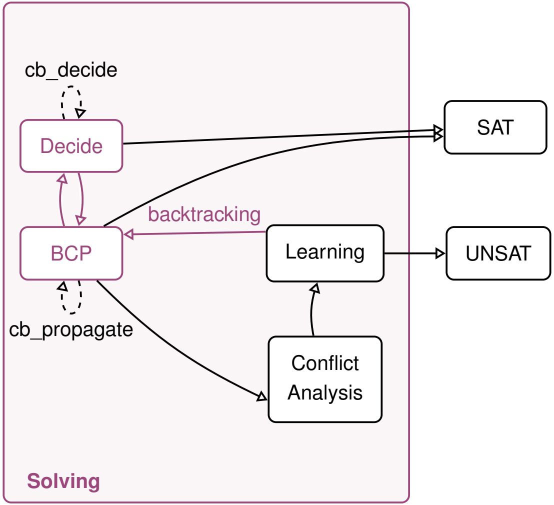
  2. Dictate decisions & phases



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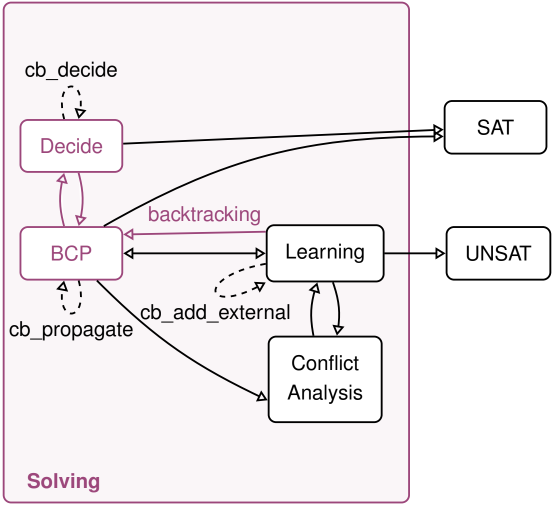

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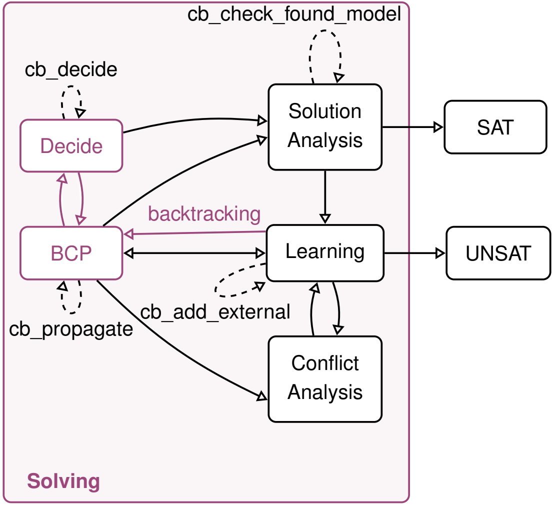
  4. Overrule found solutions



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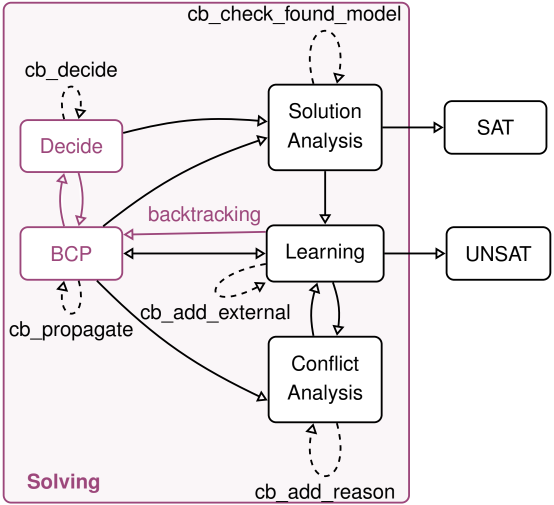
  5. Explain relevant propagations



Related Work

- clingo [GebserKaminskiKaufmannOstrowskiSchaubWanko'16]
  - A state-of-the-art ASP solver
  - Supports *theory propagators*
- IntelSAT [Nadel'22]
  - Add clauses during search while maintaining propagation levels
- CP solvers [GentMiguelMoore'10]
  - Lazy explanation, lazy clause generation
- SAT solvers of SMT solvers [NieuwenhuisOliverasTinelli'06]
  - SAT worker interface [CimattiGriggioSchaafsmaSebastiani'13]
  - User propagators of z3 [BjørnerEisenhoferKovács'22]

Propagators are widely used, but there is no standard about how to do it.

IPASIR-UP Experiments

- Extended CaDiCaL with IPASIR-UP
  - A state-of-the-art incremental, inprocessing, proof producing SAT solver
  - $\sim$800 lines of additional code (plus another $\sim$700 for testing)

- Evaluated on two representative use cases
  - Combinatorial problem solving: SAT modulo Symmetries (SMS)
  - Satisfiability modulo Theories: cvc5

IPASIR-UP for SAT modulo Symmetries – Example

- Goal: Find complete set of non-isomorphic graphs over n vertices
  - Enumerate graphs with lexicographically minimal adjacency matrix
  - Would require exponential number of additional clauses
- `cb_add_clause`:
  - Enforce minimality
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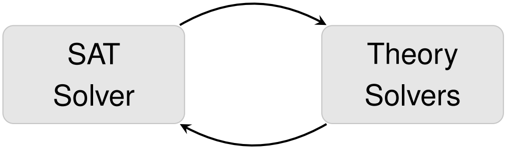
			CaDiCaL+IPASIR-UP [s]			Clingo [s]	
	#vertices	#graphs	*default*	*enum-IPASIR*	*no-prop*	*red*	*irred*
All graphs	6	156	0.01	0.02	0.01	0.02	0.01
	7	1044	0.09	0.13	0.09	0.10	0.09
	8	12346	0.95	1.59	1.00	1.15	1.07
	9	274668	34.24	64.27	34.31	81.67	94.65
	10	12005168	50815.60	109443.72	57616.47	213959.23	196576.58

IPASIR-UP for Satisfiability Modulo Theories – cvc5

Satisfiability Modulo Theories (SMT):

- Satisfiability of a first-order formula w.r.t. some background theories
- Example theories: Arrays, bit-vectors, Arithmetic, . . .
- Back-end solvers in verification, synthesis, planning, optimization, etc.
- Lazy CDCL($\mathcal{T}$) approach:



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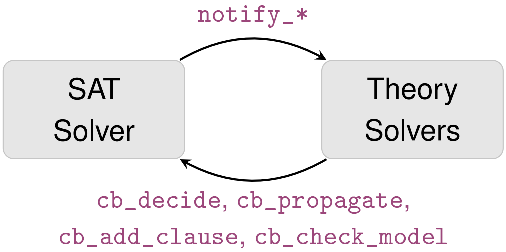

IPASIR-UP in cvc5

- **cvc5:** State-of-the-art SMT solver
  - Best ranking in several tracks of SMT'22 competition
- Supports all standard background theories
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cvc5 with CaDiCaL through IPASIR-UP:

- Additional $\sim$700 LOC to work with IPASIR-UP
- Encouraging performance without much tuning or optimizations
  - $+$1080 solved instances
  - $\sim 2\times$ faster in several logics
  - 13 out of 19 divisions are improved
- Any IPASIR-UP supporting SAT solver can be plugged in

  $\rightarrow$ solid baseline to tune and improve cvc5's internals for the IPASIR-UP interface

Summary

- Generic interface to inspect and influence CDCL search
  - Simple & Flexible → relatively easy to implement
  - Sufficient to simplify several use cases
- Implemented in a complex, modern SAT solver
  - Allows inprocessing of non-changing parts
- Evaluated in representative use cases (SMS, SMT)
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Future Work

- Consider further extensions
  - Propagate assumptions, guide backtrack, query/change variable scores, ...
- Proofs
  - Incremental (inprocessing) proofs
  - External proofs of external clauses
- More inprocessing

Thank you for your attention!

IPASIR Interface

```c
// Get solver name and version
const char* ipasir_signature();
// Initialize a solver instance and return a pointer to it
void* ipasir_init();
// Destroy the solver instance
void ipasir_release(void* solver);
// Set a callback function for aborting solving
void ipasir_set_terminate(void* solver, void* state,
                          int (*terminate)(void* state));
// Add a literal or finalize clause
void ipasir_add(void* solver, int lit_or_zero);
// Assume a literal for the next solve call
void ipasir_assume(void* solver, int lit);
// Solve the formula
int  ipasir_solve(void* solver);
// Retrieve a variables truth value (SAT case)
int  ipasir_val(void* solver, int lit);
// Check for a failed assumption (UNSAT case)
int  ipasir_failed(void* solver, int lit);
```

Functions to Manage and Configure

```
// VALID = UNKNOWN | SATISFIED | UNSATISFIED
//
// require (VALID) -> ensure (VALID)
//
void connect_external_propagator (ExternalPropagator * propagator);

// require (VALID) -> ensure (VALID)
//
void disconnect_external_propagator ();

// require (VALID_OR_SOLVING) /\ CLEAN(var) -> ensure (VALID_OR_SOLVING)
//
void add_observed_var (int var);

// require (VALID) -> ensure (VALID)
//
void remove_observed_var (int var);

// require (VALID_OR_SOLVING) -> ensure (VALID_OR_SOLVING)
//
bool is_decision (int observed_var);

// require (VALID_OR_SOLVING) -> ensure (VALID_OR_SOLVING)
//
void phase (int lit);

// require (VALID_OR_SOLVING) -> ensure (VALID_OR_SOLVING)
//
void unphase (int lit);
```

Example C++ implementation

```
class ExternalPropagator {
public:
  virtual ~ExternalPropagator () { }

  virtual void notify_assignment (int lit, bool is_fixed) {}
  virtual void notify_new_decision_level () {}
  virtual void notify_backtrack (size_t new_level) {}

  virtual int cb_decide () { return 0; }
  virtual int cb_propagate () { return 0; }
  virtual int cb_add_reason_clause_lit (int propagated_lit) {
      return 0;
  }
  virtual bool cb_check_found_model (const std::vector<int> & model) {
      return true;
  }

  virtual bool cb_has_external_clause () { return false; }
  virtual int cb_add_external_clause_lit () { return 0; }
};
```

Complete SMS Results

	#vertices	#graphs	CaDiCaL+IPASIR-UP [s]			Clingo [s]	
			default	*enum-IPASIR*	*no-prop*	*red*	*irred*
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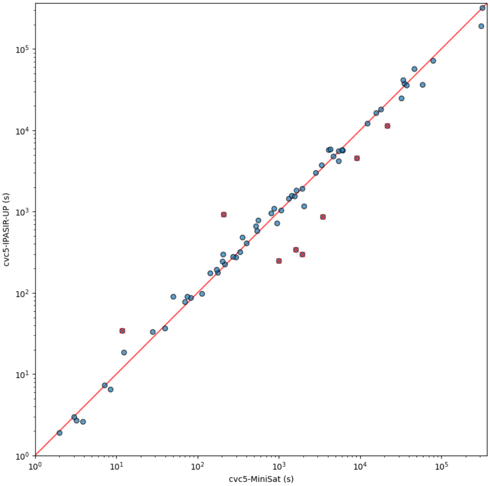
	#vertices	#graphs	*default*	*no-inpro*	*no-prop*	*red*	*irred*
KS candidates	16	0	10.58	9.14	13.58	25.07	18.56
	17	1	39.82	31.48	44.58	122.28	87.92
	18	0	190.16	59.37	187.29	872.98	493.17
	19	8	1220.51	1253.96	1341.80	10542.41	3348.14
	20	147	13647.66	16449.50	13493.86	67728.42	82871.65

- Task 2: Generate up to isomorphism all non-010-colorable graphs with a minimum degree of at least three not containing a cycle of length 4 (used for Kochen-Specker Theorem)

cvc5 Results (Divisions)

	cvc5		cvc5-ipasirup	
Division	solved	time [s]	solved	time [s]
Arith (6,865)	**6,303**	173,628	6,299	176,278
BitVec (6,045)	**5,552**	153,899	5,529	161,482
Equality (12,159)	5,320	2,062,804	**5,322**	2,061,758
Equality+LinearArith (53,453)	45,902	2,288,230	**45,906**	2,288,352
Equality+MachineArith (6,071)	983	1,533,646	**987**	1,532,782
Equality+NonLinearArith (21,104)	**13,314**	2,419,535	13,053	2,486,588
FPArith (3,965)	3,145	268,628	**3,155**	266,245
QF_Bitvec (42,472)	**40,321**	984,880	40,320	985,946
QF_Datatypes (8,403)	8,077	110,704	**8,168**	82,878
QF_Equality (8,054)	8,044	9,394	**8,047**	7,169
QF_Equality+Bitvec (16,585)	15,817	307,558	**16,015**	234,369
QF_Equality+LinearArith (3,442)	**3,388**	23,041	3,381	23,465
QF_Equality+NonLinearArith (709)	627	27,428	**629**	27,598
QF_FPArith (76,238)	76,054	94,487	**76,081**	76,700
QF_LinearIntArith (16,387)	11,670	1,575,635	**12,004**	1,512,696
QF_LinearRealArith (2,008)	1,721	130,408	**1,766**	113,919
QF_NonLinearIntArith (25,361)	13,037	4,094,712	**13,682**	3,840,933
QF_NonLinearRealArith (12,134)	11,166	333,933	**11,238**	316,728
QF_Strings (69,908)	**69,357**	203,677	69,296	230,918
Total (391,363)	339,798	16,796,234	**340,878**	16,426,813

cvc5 Results (Logics)



- Considered only the commonly solved instances