Recent Improvements of Theory Reasoning in Vampire

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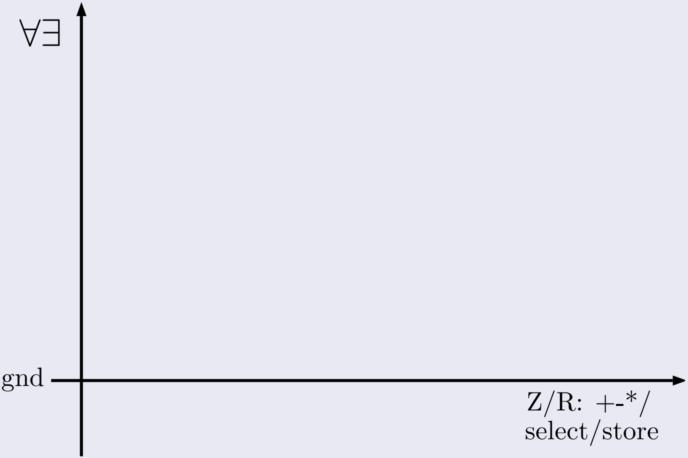
Reasoning with quantifiers and theories

Two Dimensions of Complexity



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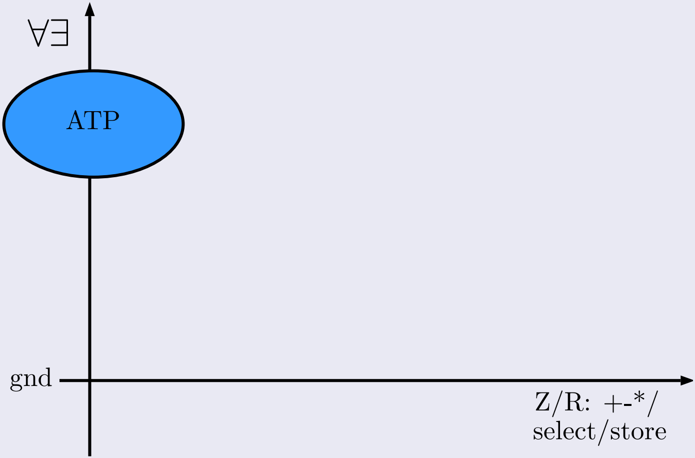

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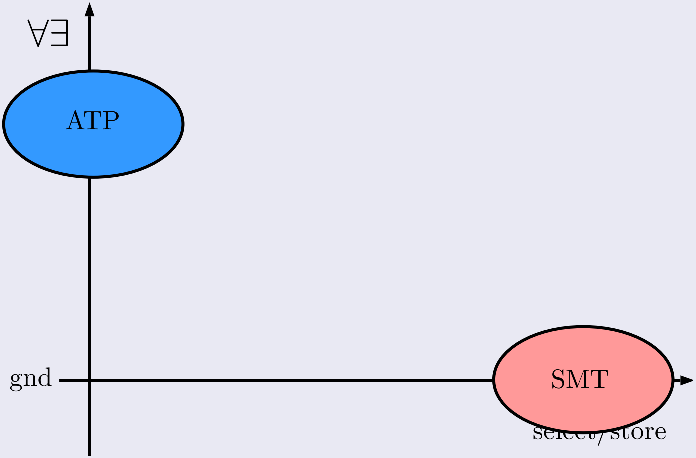

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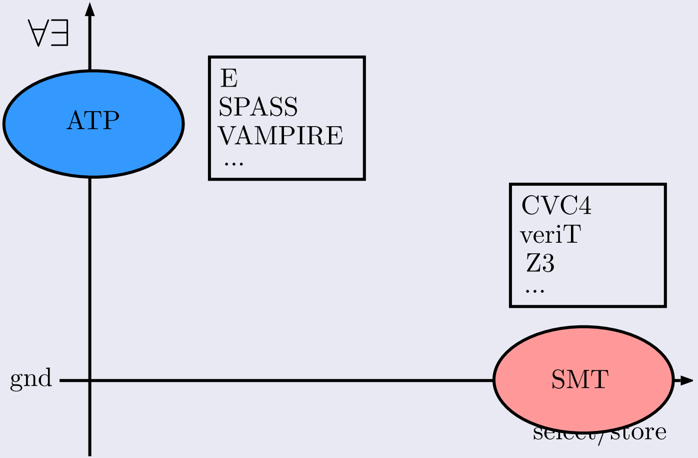

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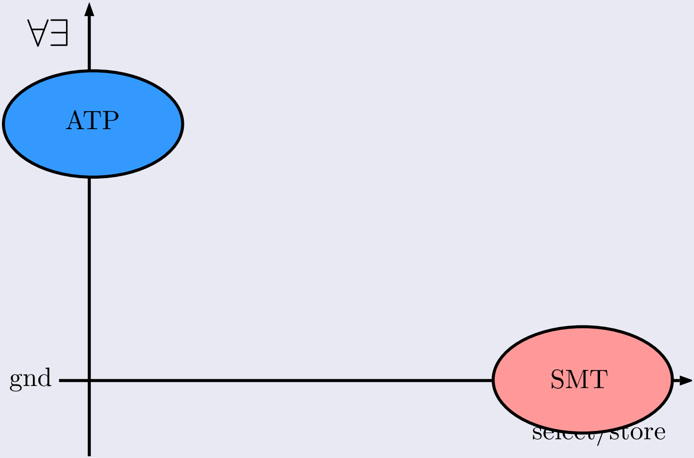

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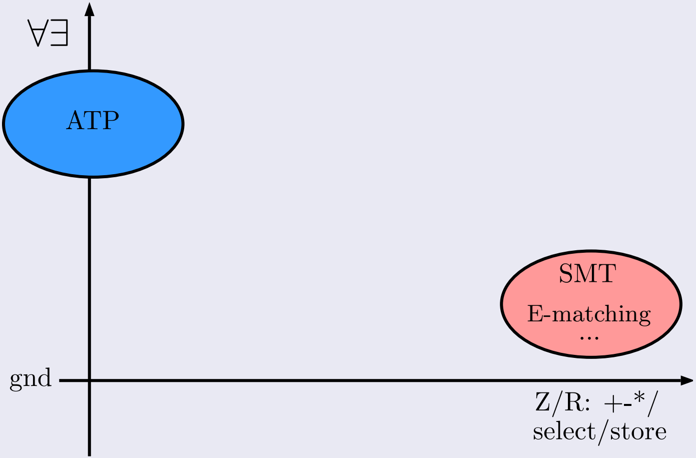

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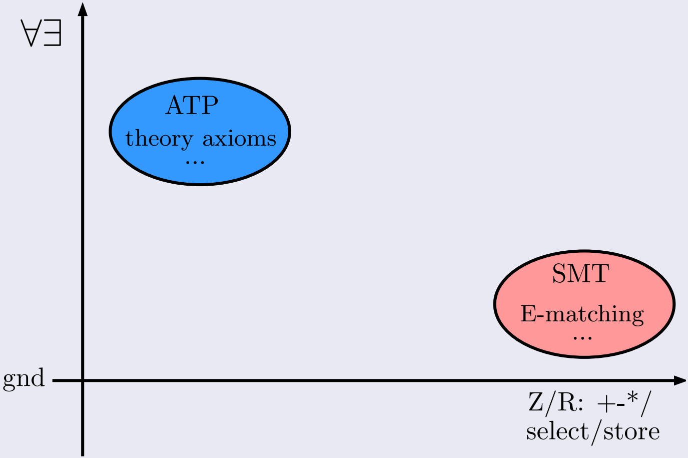

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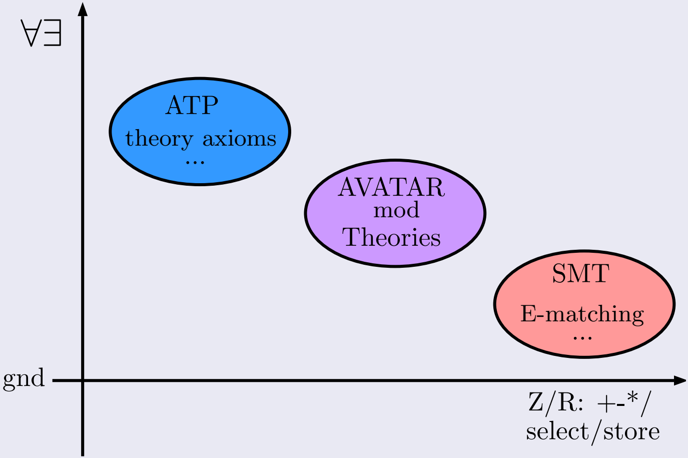

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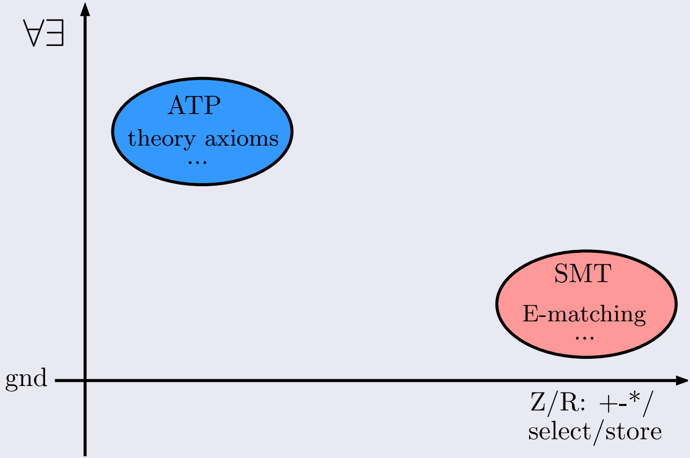

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- extension of unification that introduces theory constraints

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- a lazy approach to abstraction
- new constrains can be often "discharged" by 1.

Outline

Short preliminaries

Main Arsenal for Theory reasoning in Vampire

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$$L[t] \vee C \implies x \not\simeq t \vee L[x] \vee C,$$

where L is a theory literal, t a non-theory term, and x fresh.

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Example

$5 < f(y) \vee p(y) \implies x \not\simeq f(y) \vee 5 < x \vee p(y)$

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NB: abstraction can be “undone” by the equality factoring rule

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Theory instantiation by examples

Example

Consider the conjecture $(\exists x)(x + x \simeq 2)$ negated and clausified to

$$x + x \not\simeq 2.$$

It takes Vampire 15 seconds to solve using theory axioms deriving lemmas such as

$$x + 1 \simeq y + 1 \vee y + 1 \leq x \vee x + 1 \leq y.$$

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Example (`ARI120=1`)

Initial clauses:

$$x * x \not\simeq 4 \vee x \simeq y \vee \neg p(y) \qquad p(2)$$

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$$x * x \not\simeq 4 \vee x \simeq y \vee \neg p(y) \qquad p(2)$$

immediately resolve to $$x * x \not\simeq 4 \vee 2 \simeq x,$$

but this cannot be solved with axioms only in reasonable time.

Theory instantiation more formally

As an inference rule

$$\frac{C}{(D[\mathsf{x}])\theta}\ \mathit{TheoryInst}$$

where $\mathcal{A}_{(P)}(C) = T[\mathsf{x}] \to D[\mathsf{x}]$ is a (partial) abstraction of C, and θ a subst. such that $T[\mathsf{x}]\theta$ is valid in the underlying theory.

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Implementation:

- Abstract relevant literals
- Collect relevant pure theory literals $L_1, \ldots, L_n$
- Run an SMT solver on $T[\mathbf{x}] = \neg L_1 \wedge \ldots \wedge \neg L_n$
- If the SMT solver returns a model, transform it into a substitution θ and produce an instance
- If the SMT solver returns <u>unsatisfiable</u> then C is a theory tautology and can be removed

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When (not) to abstract

Example

Consider a unit clause $p(1,5)$ abstracted as

$$(x \simeq 1 \wedge y \simeq 5) \rightarrow p(x,y).$$

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Example

Consider a theory instantiation step

$$x \not\simeq 1 + y \lor p(x,y) \implies p(1,0).$$

But we can obtain a "more general" instance

$$p(y+1,y)$$

using equality resolution.

Selecting Pure Theory Literals

Example (some literals constrain less/more than others)

$$(x \not\simeq 0) \to p(x)$$

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Three options for `thi`:

- `strong`: Only select <u>strong</u> literals where a literal is strong if it is a negative equality or an interpreted literal
- `overlap`: Select all strong literals and additionally those theory literals whose variables overlap with a strong literal
- `all`: Select all non-trivial pure theory literals

Interacting with the SMT solver

Recall that we collect relevant pure theory literals $L_1, \ldots, L_n$ to run an SMT solver on $T[\mathsf{x}] = \neg L_1 \wedge \ldots \wedge \neg L_n$

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Example (The Division by zero catch!)

The following two clauses are satisfiable:

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Evaluation may fail:

- result out of Vampire's internal range
- result is a proper algebraic number

A new redundancy rule

Theory Tautology Deletion

Recall we abstract C as $T[\mathsf{x}] \rightarrow D[\mathsf{x}]$. If the SMT solver shows that $T[\mathsf{x}]$ is unsatisfiable, we can remove C from the search space.

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then resolve to get

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Finally, Theory Instantiation could produce

$$p(7).$$

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Why one might not like full abstraction

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2. The AVATAR modulo theories approach cannot help
   (full abstraction destroys ground literals)
3. incompatible with theory axiom reasoning
   (theory part requires special treatment)
4. inferences need to be protected from undoing abstraction
   (recall equality resolution)

Unification with constraints

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Example (strive for generality)

Unifying $a + b$ with $c + d$ should produce $(\{\}, a + b = c + d)$ and not $(\{\}, a = c \wedge b = d)$.

Unification with constraints Algorithm part I

function $\text{mgu}_{\text{Abs}}(s, t)$

    if t is a variable and not $\texttt{occurs}(t, s)$ **then**

        return $(\{t \mapsto s\}, \mathit{true})$

    if s is a variable and not $\texttt{occurs}(s, t)$ **then**

        return $(\{s \mapsto t\}, \mathit{true})$

    if s and t have different top-level symbols **then**

        if $\texttt{canAbstract}(s, t)$ **then**

            return $(\{\}, s = t)$

        return $(\perp, \perp)$

    if s and t are constants **then**

        return $(\{\}, \mathit{true})$

    ...

...

let $s = f(s_1, \ldots, s_n)$ **and** $t = f(t_1, \ldots, t_n)$ **in**

$\theta = \{\}$ **and** $\Gamma = \mathit{true}$

for $i = 1$ **to** n **do**

$\quad (\theta_i, \Gamma_i) = \mathrm{mgu}_{\mathrm{Abs}}((s_i\theta), (t_i\theta))$

$\quad$ **if** $(\theta_i, \Gamma_i) = (\bot, \bot)$ **or** $\mathtt{canAbstract}(s, t)$ **and** $\Gamma_i \neq \mathit{true}$

then

$\qquad$ **if** $\mathtt{canAbstract}(s, t)$ **then**

$\qquad\quad$ **return** $(\{\}, s = t)$

$\qquad$ **return** $(\bot, \bot)$

$\quad \theta = \theta \circ \theta_i$ **and** $\Gamma = \Gamma \wedge \Gamma_i$

return (θ, Γ)

When do we abstract?

Example (do not produce unsatisfiable constraints)

Allowing $p(1)$ and $p(2)$ to unify under the constraint that $1 \simeq 2$ is not useful in any context.

`canAbstract` will always be false if the two terms are always non-equal in the underlying theory.

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For option to choose from:

- `interpreted_only`: only produce a constraint if the top-level symbol of both terms is a theory-symbol,
- `one_side_interpreted`: only produce a constraint if the top-level symbol of at least one term is a theory symbol,
- `one_side_constant`: as `one_side_interpreted` but if the other side is uninterpreted it must be a constant,
- `all`: allow all terms of theory sort to unify and produce constraints.

Updated calculus

New inference rule: Resolution-wA

$$\frac{\underline{A} \vee C_1 \quad \underline{\neg A'} \vee C_2}{(\Gamma \rightarrow (C_1 \vee C_2))\theta}\ ,$$

where $(\theta, \Gamma) = \mathrm{mgu}_{\mathsf{Abs}}(A, A')$ and A is not an equality literal.

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When starting from an obvious conflict:

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But **Resolution-wA** allows us to still derive

$$4 \not\simeq x + 3$$

and Theory Instantiation could derive the empty clause.

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Experiments

The setup:

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For this experiment:

- 24 reasonable combinations of option values: `fta`, `uwa`, `thi`
- approx. 100 000 runs in total

Comparison of Three Options

fta	uwa	thi	solutions
on	off	all	252
on	off	overlap	265
on	off	strong	266
on	off	off	276
off	all	all	333
off	all	overlap	351
off	all	strong	354
off	one_side_interpreted	all	364
off	all	off	364
off	one_side_constant	all	374
off	interpreted_only	all	379
off	one_side_interpreted	overlap	385
off	one_side_interpreted	strong	387
off	off	all	392
off	one_side_constant	strong	397
off	one_side_constant	overlap	401
off	interpreted_only	overlap	407
off	one_side_interpreted	off	407
off	interpreted_only	strong	409
off	one_side_constant	off	417
off	off	overlap	428
off	interpreted_only	off	430
off	off	strong	431
off	off	off	450

Contribution of New Options to Strategy Building

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The latter dominates in FO reasoning since . . .

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Contribution of New Options to Strategy Building

A new technique in the context of a portfolio approach:

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2. solves previously unsolved problems

The latter dominates in FO reasoning since ...

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Problems newly solved thanks to `thi` and `uwa`:

- ALIA (arrays and linear integer arithmetic): 2
- AUFNIRA: **3**
- LIA : 10
- LRA : 1
- UFLIA : **1**
- UFNIA : 1

Conclusion

Two new techniques for reasoning with theories and quantifiers

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Thank you for your attention!