AXDInterpolator

A Tool for Computing Interpolants for Arrays with MaxDiff

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Motivation

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- Interpolant in $\langle =, \mathtt{wr}, \mathtt{rd} \rangle$ is $\exists j.(\mathtt{rd}(h, j) \neq \mathtt{rd}(h', j) \wedge \forall k.(k \neq j \rightarrow \mathtt{rd}(h, k) = \mathtt{rd}(h', k)))$

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- Interpolant in $\langle =, \mathtt{wr}, \mathtt{rd}, \mathtt{diff} \rangle$ is $\mathtt{let}\ j = \mathtt{diff}(h, h')$ be in $h' = \mathtt{wr}(h, j, \mathtt{rd}(h, j))$

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- The `diff` operator in this work returns 0 if the two input arrays are the same and otherwise returns the biggest index where the input arrays are different
- Endowing this semantic on `diff` allows the theory to formalize desirable specifications (in particular, the `length` function) without quantifiers of bounded arrays

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- Provided support for the quantifier-free fragment of the index theories $\mathcal{TO}$, $\mathcal{IDL}$, and $\mathcal{LIA}$.
- Designed an architecture allowing the system to use different interpolation engines as black boxes. Currently, we support iZ3, SMTInterpol, and MathSAT.

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\forall y, i, e. &\quad i \geq 0 \to \mathtt{rd}(\mathtt{wr}(y, i, e), i) = e && (1)\\
\forall y, i, j, e. &\quad i \neq j \to \mathtt{rd}(\mathtt{wr}(y, i, e), j) = \mathtt{rd}(y, j) && (2)\\
\forall x, y. &\quad x \neq y \to \mathtt{rd}(x, \mathtt{diff}(x, y)) \neq \mathtt{rd}(y, \mathtt{diff}(x, y)) && (3)\\
\forall x, y, i. &\quad i > \mathtt{diff}(x, y) \to \mathtt{rd}(x, i) = \mathtt{rd}(y, i) && (4)\\
\forall x. &\quad \mathtt{diff}(x, x) = 0 && (5)\\
\forall x.i &\quad i < 0 \to \mathtt{rd}(x, i) = \bot && (6)\\
\forall i. &\quad \mathtt{rd}(\varepsilon, i) = \bot && (7)
\end{aligned}$$

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\end{aligned}$$

- As an effect of the above axioms, we have that an array x is undefined outside the interval $[0, |x|]$, where $|x|$ is defined as $|x| := \mathtt{diff}(x, \varepsilon)$.

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Given array variables a, b, we define by mutual recursion the sequence of array terms $b_1, b_2, \ldots$ and of index terms $\mathtt{diff}_1(a, b), \mathtt{diff}_2(a, b), \ldots$:

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$$\begin{aligned} b_1 &:= b; & \mathtt{diff}_1(a,b) &:= \mathtt{diff}(a,b_1); \\ b_{k+1} &:= \mathtt{wr}(b_k, \mathtt{diff}_k(a,b), \mathtt{rd}(a, \mathtt{diff}_k(a,b))); & \mathtt{diff}_{k+1}(a,b) &:= \mathtt{diff}(a,b_{k+1}) \end{aligned}$$

Theory Arrays with MaxDiff - Lemma

The conjunctive formula

$$\texttt{diff}_1(a, b) = k_1 \wedge \cdots\cdots \wedge \texttt{diff}_l(a, b) = k_l \tag{8}$$

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is equivalent modulo $\mathcal{ARD}$ to the conjunction of the following five formulæ:

$$k_1 \geq k_2 \wedge \cdots \wedge k_{l-1} \geq k_l \wedge k_l \geq 0 \tag{9}$$

$$\textstyle\bigwedge_{j<l}(k_j > k_{j+1} \to \mathtt{rd}(a, k_j) \neq \mathtt{rd}(b, k_j)) \tag{10}$$

$$\textstyle\bigwedge_{j<l}(k_j = k_{j+1} \to k_j = 0) \tag{11}$$

$$\textstyle\bigwedge_{j\leq l}(\mathtt{rd}(a, k_j) = \mathtt{rd}(b, k_j) \to k_j = 0) \tag{12}$$

$$\forall h\ (h > k_l \to \mathtt{rd}(a, h) = \mathtt{rd}(b, h) \vee h = k_1 \vee \cdots \vee h = k_{l-1}) \tag{13}$$

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(1) Φ_1 contains equalities of the form $\texttt{diff}_k(a, b) = i$ and $a = \texttt{wr}(b, i, e)$; moreover if it contains the equality $\texttt{diff}_k(a, b) = i$, it must also contain an equality of the form $\texttt{diff}_l(a, b) = j$ for every $l < k$;

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(2) Φ_2 contains Boolean combinations of T_I-atoms and of atoms of the forms: $\{\mathtt{rd}(a, i) = \mathtt{rd}(b, j), \ \ \mathtt{rd}(a, i) = e, \ \ e_1 = e_2\}$, where a, b, i, j, e, e_1, e_2 are variables or constants of the appropriate sorts.

M-Instantiations

If $\mathcal{I}$ is a set of $\mathcal{T}_{\mathcal{I}}$-terms, an $\mathcal{I}$-*instance* of a universal formula of the kind $\forall i\, \phi$ is a formula of the kind $\phi(t/i)$ for some $t \in \mathcal{I}$.

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Let $\mathcal{I}$ be a set of $\mathcal{T}_{\mathcal{I}}$-terms and let $\Phi = (\Phi_1, \Phi_2)$ be a separated pair; we let $\Phi(\mathcal{I}) = (\Phi_1(\mathcal{I}), \Phi_2(\mathcal{I}))$ be the smallest separated pair satisfying the following conditions:

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- if Φ_1 contains $a = \mathtt{wr}(b, i, e)$, then $\Phi_2(\mathcal{I})$ contains *all the* $\mathcal{I}$*-instances of the equivalent formula* $(i \geq 0 \to \mathtt{rd}(a, i) = e) \wedge \forall h\, (h \neq i \to \mathtt{rd}(a, h) = \mathtt{rd}(b, h))$;

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- if Φ_1 contains the conjunction $\bigwedge_{i=1}^{l} \mathtt{diff}_i(a, b) = k_i$, then $\Phi_2(\mathcal{I})$ contains the formulae (9), (10), (11), (12) as well as *all $\mathcal{I}$-instances of the formula* (13).

M-Instantiations (Cont'd)

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For $M \in \mathbb{N} \cup \{\infty\}$, the *M-instantiation* of $\Phi = (\Phi_1, \Phi_2)$ is the separated pair $\Phi(\mathcal{I}_\Phi^M) = (\Phi_1(\mathcal{I}_\Phi^M), \Phi_2(\mathcal{I}_\Phi^M))$, where $\mathcal{I}_\Phi^M$ is the set of T_I-terms of complexity at most M built up from the index variables occurring in Φ_1, Φ_2.

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The *full instantiation* of $\Phi = (\Phi_1, \Phi_2)$ is the separated pair $\Phi(\mathcal{I}_\Phi^\infty) = (\Phi_1(\mathcal{I}_\Phi^\infty), \Phi_2(\mathcal{I}_\Phi^\infty))$ (which is usually not finite). A separated pair $\Phi = (\Phi_1, \Phi_2)$ is *M-instantiated* iff $\Phi = \Phi(\mathcal{I}_\Phi^M)$

M-Instantiations - Pseudo Code for quantifier-free $\mathcal{IDL}$

Algorithm 1 M-Instantiation

```
procedure StandardInput::InstantiatedTerms::M-Instantiate
    for term ∈ terms do
        new-term ← (term + 1).simplify()
        if ¬ inSet(new-term, terms) then
            terms.push-back(new-term)
        end if
        new-term ← (term - 1).simplify()
        if ¬ inSet(new-term, terms) then
            terms.push-back(new-term)
        end if
    end for
end procedure
```

Interpolation Algorithm

Algorithm 2 Main Loop

```
procedure AXDInterpolator::MainLoop(StandardPair part-a, StandardPair part-b)
    if ¬(common-array-vars.areCommonPairsAvailable()) then
        SmtSolverSetup(solver, part-a)
        SmtSolverSetup(solver, part-b)
        if solver.check() = z3::unsat then
            is-unsat ← true
        end if
        return
    end if
    CircularPairIterator search-common-pairs(common-array-vars)
    while (num-attemps++ < remaining-fuel) do
        solver.push()
        SmtSolverSetup(solver, part-a)
        SmtSolverSetup(solver, part-b)
        if solver.check() = z3::unsat then
            is-unsat ← true
            return
        end if
        solver.pop()
        common-pair ← *search-common-pair
        part-a-dim ← part-a.diff-map.size-of-entry(common-pair)
        part-b-dim ← part-b.diff-map.size-of-entry(common-pair)
        dim ← min(part-a-dim, part-b-dim)
        new-index = fresh-index-constant()
        part-a.updateSaturation(common-pair, new-index, dim)
        part-b.updateSaturation(common-pair, new-index, dim)
        search-common-pair.next()
    end while
end procedure
```

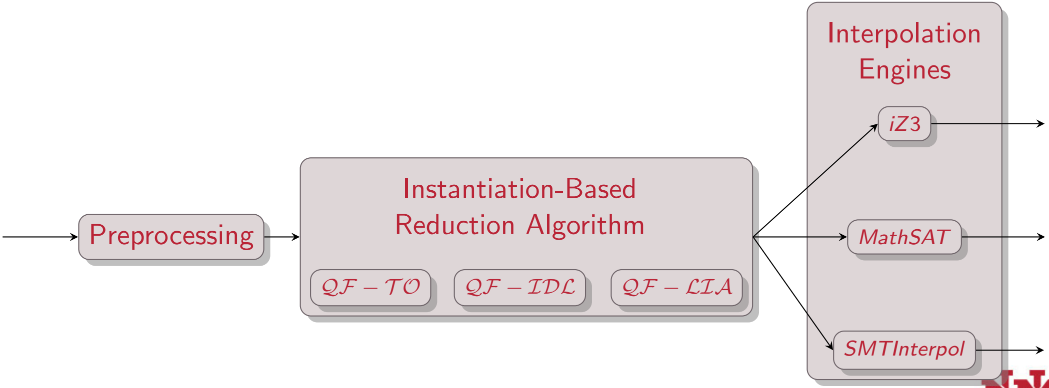
Algorithm 3 SmtSolverSetup

```
procedure AXDInterpolator::SmtSolverSetup(z3::solver solver, StandardPair side-part)
    for assertion ∈ side-part.part-2 do
        solver.add(assertion)
    end for
    side-part.instantiate(solver, ∀x, i.i < 0 → rd(x, i) = ⊥)
    side-part.instantiate(solver, ∀i.rd(ε, i) = ⊥)
    for a = wr(b, i, e) ∈ side-part.write-vector do
        side-part.instantiate(solver, ∀h.h ≠ i → rd(a, h) = rd(b, h))
    end for
    for diff(a, b) = i ∈ side-part.diff-map do
        side-part.instantiate(solver, ∀h.h > i → rd(a, h) = rd(b, h))
    end for
end procedure
```

Algorithm 4 UpdateSaturation

```
procedure StandardPair::updateSaturation(z3Pair entry, z3::expr new-index, unsigned min-dim)
    a ← entry.first
    b ← entry.second
    map-element ← diff-map.find(entry)
    instantiated-terms.addVar(new-index)
    if Heuristic then
        instantiated-terms.M-instante()
    end if
    if min-dim < old-dim then
        part-2.push-back(new-index = (map-element.second)[min-dim]
    else
        prev-index ← (map-element.second)[old-min - 1]
        part-2.push-back(prev-index ≥ new-index)
        part-2.push-back(new-index ≥ 0)
        part-2.push-back(prev-index > new-index → rd(a, prev-index) ≠ rd(b, prev-index))
        part-2.push-back(prev-index = new-index → prev-index = 0)
    end if
    part-2.push-back(rd(a, new-index) = rd(b, new-index) → new-index = 0)
end procedure
```

Architecture Overview



Input Files and Extended Signature

Our extended language is parameterized by the array sorts in the input formula as well as by an *index theory*. The domain sort of every array is currently implemented using the `Int` sort.

```
(declare-sort A)
(declare-fun diff'A' ((Array Int A) (Array Int A)) Int)
(declare-fun length'A' ((Array Int A)) Int)
(declare-fun empty_array'A' () (Array Int A))
(declare-fun undefined'A' () A)
```

Figure: Our extended language parameterized with a sort A.

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Demo

Benchmarks using SV-COMP and UAutomizer - Setup

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- We used the model checker UAutomizer [4] to extract their SMT Scripts from the previous C-programs
- We let the machine produce SMT Scripts for 15 minutes. We used these SMT Scripts files to compare the number of interpolants computed from unsatisfiable formulas. For the latter we assigned each process up to 360 seconds and 6 GB of memory

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Benchmarks using SV-COMP and UAutomizer - Memsafety-track Results

Subtracks	AXD Interpolator *iZ3*		AXD Interpolator *MathSAT*		AXD Interpolator *SMTInterpol*	
	Success	Timeout	Success	Timeout	Success	Timeout
array-examples	584	1	584	1	584	1
array-memsafety	118	0	118	0	118	0
termination-crafted	52	3	52	3	52	3

Table: Memsafety-track results - Our implementation

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Table: Memsafety-track results - Other solvers

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Benchmarks using SV-COMP and UAutomizer - Reachsafety-track Results

Subtracks	AXD Interpolator *iZ3*		AXD Interpolator *MathSAT*		AXD Interpolator *SMTInterpol*	
	Success	Timeout	Success	Timeout	Success	Timeout
array-cav19	31	0	31	0	31	0
array-examples	50	0	50	0	50	0
array-fpi	774	21	774	21	774	21
array-industry-pattern	8	0	8	0	8	0
array-lopstr16	54	0	54	0	54	0
array-patterns	11	0	11	0	11	0
array-tiling	6	0	6	0	6	0
reducercommutativity	53	0	53	0	53	0

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Future Work

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- The current design does not perform incremental satisfiability checks. Incremental checks are possible to implement due to the incremental nature of the proposed interpolation algorithm by including a hash consed data structure on the terms/predicates produced in the main loop of the algorithm and because the data structure `z3::solver` can keep track of previously proven assertions.

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- We were able to show the feasibility of AXDInterpolator by validating it on two benchmarks taken from the SV-COMP.
- We also compared our implementation with state-of-the-art solvers: apart from very few timeout outcomes, our tool managed to handle all the examples the other solvers did.

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- In this paper we described AXDInterpolator, the implementation of the interpolation algorithm presented in [2].
- We were able to show the feasibility of AXDInterpolator by validating it on two benchmarks taken from the SV-COMP.
- We also compared our implementation with state-of-the-art solvers: apart from very few timeout outcomes, our tool managed to handle all the examples the other solvers did.
- We also found interesting examples that are not handled by other state-of-the-art solvers, which makes the option of our language extension and tool an appealing consideration.

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Thanks for your attention!

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