Karlsruhe Institute of Technology

A Theory of Arrays with `set` and `copy` Operations

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```
struct list_node {
    int data;
    struct list_node *tail;
};
typedef struct list_node list;

list *reverse(list *l) {
  list *r = l, *p = NULL;
  while (r != NULL) {
    list *q = r;
    r = r->tail;
    q->tail = p;
    p = q;
  }
  return p;
}
```

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  - Bounded model checking
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  - ...
- Prominent theory: $\mathcal{T}_{\mathcal{A}}$ (theory of arrays)
  - Model arrays/structures/objects in the program
  - Model main memory

Motivation

What to do with standard library functions such as `memset` and `memcpy`/`memmove`?

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void *memset(void *s, int c, size_t n);

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$\Longrightarrow$ Extend $\mathcal{T}_{\mathcal{A}}$ to allow for dynamically-sized read/writes!

Contributions

1. $\mathcal{T}_{\mathcal{ASC}}$: an extension of $\mathcal{T}_{\mathcal{A}}$ with `set` and `copy` operations
   - `set`: sets ranges in an array at once
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   - `set`: sets ranges in an array at once
   - `copy`: copies ranges between arrays
2. Satisfiability checking for $\mathcal{T}_{\mathcal{ASC}}$ by reducing to $\mathcal{T}_{\mathcal{A}}$ + index arithmetic

Applications of $\mathcal{T}_{\mathcal{ASC}}$

- Precisely model `memset` and `memcpy`/`memmove`

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- "Havoc" memory regions (volatile variables)
- Model memory mapped I/O
- Attaching metadata to memory regions (allocated, de-allocated, . . .)

$\mathcal{T}_{\mathcal{A}}$: The Theory of Arrays

Sorts	E : elements I : indices A : arrays
Functions	$\texttt{read} : \mathsf{A} \times \mathsf{I} \to \mathsf{E}$ $\texttt{write} : \mathsf{A} \times \mathsf{I} \times \mathsf{E} \to \mathsf{A}$

$$p = r \implies \texttt{read}(\texttt{write}(a, p, v), r) = v$$

$$\neg(p = r) \implies \texttt{read}(\texttt{write}(a, p, v), r) = \texttt{read}(a, r)$$

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replace read (write (a, p, v), r) by ITE (p = r, v, read (a, r))
treat remaining arrays as uninterpreted functions

The Theory of Arrays with `set` and `copy`

Sorts	$S = I$
Functions	$\texttt{set} : A \times I \times E \times S \to A$ $\texttt{copy} : A \times I \times A \times I \times S \to A$

$$p \leq r < p + s \implies \texttt{read}(\texttt{set}(a, p, v, s), r) = v$$

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$$p \leq r < p + s \implies \texttt{read}(\texttt{copy}(a, p, b, q, s), r) = \texttt{read}(b, q + r - p)$$

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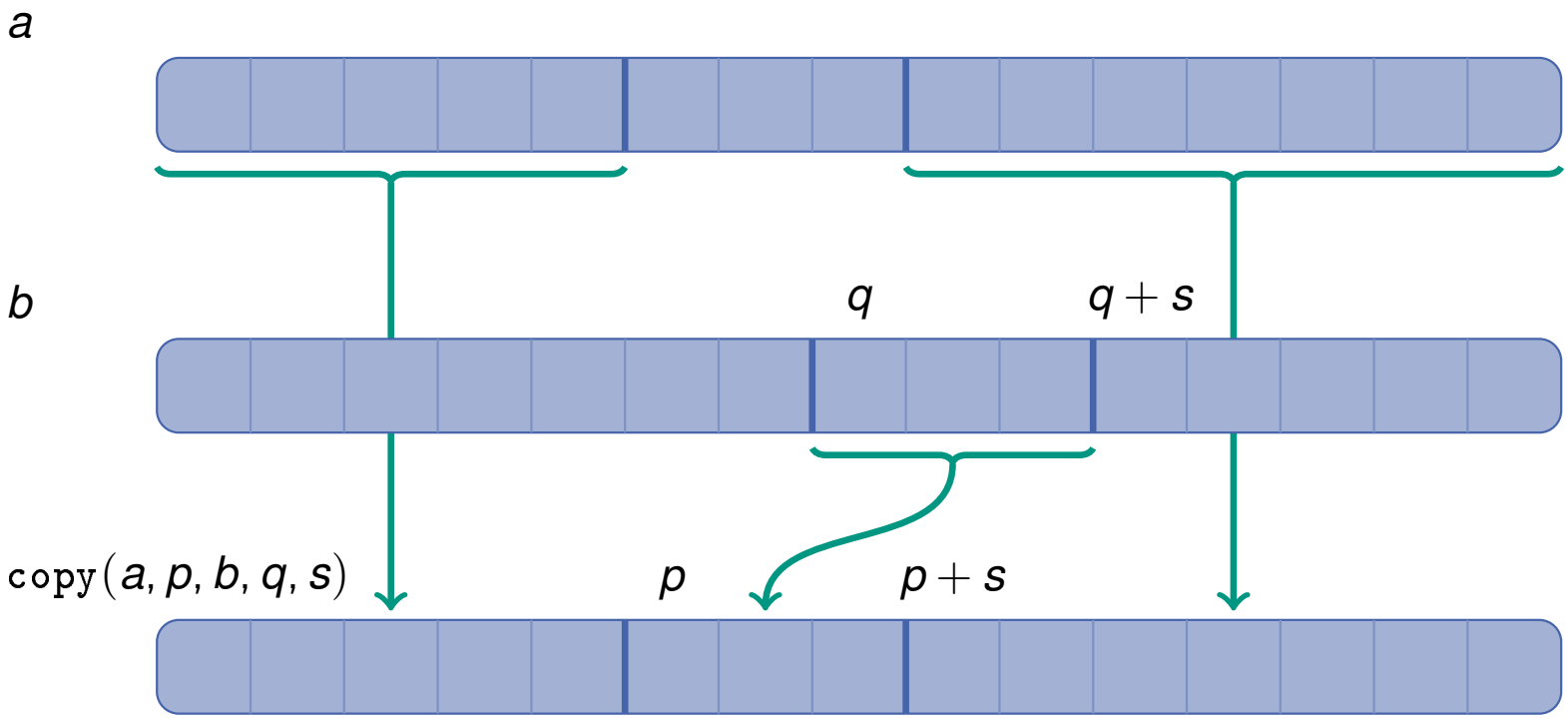
The `copy` Operation: Illustration



The Theory of Arrays with $\mathtt{set}_\infty$ and $\mathtt{copy}_\infty$

Sorts	S = I
Functions	$\mathtt{set}_\infty : A \times I \times E \to A$ $\mathtt{copy}_\infty : A \times I \times A \times I \to A$ $\mathtt{set} : A \times I \times E \times S \to A$ $\mathtt{copy} : A \times I \times A \times I \times S \to A$

$$p \leq r \implies \mathtt{read}(\mathtt{set}_\infty(a, p, v), r) = v$$

$$\neg(p \leq r) \implies \mathtt{read}(\mathtt{set}_\infty(a, p, v), r) = \mathtt{read}(a, r)$$

$$p \leq r \implies \mathtt{read}(\mathtt{copy}_\infty(a, p, b, q), r) = \mathtt{read}(b, q + r - p)$$

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$\mathcal{T}_{\mathcal{ASC}}$ with Bitvectors (`set`)

$$\mathsf{bvule}(p, r) \wedge \mathsf{bvult}(r, \mathsf{bvadd}(p, s)) \implies \mathtt{read}(\mathtt{set}(a, p, v, s), r) = v$$

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- Based on reductions to $\mathcal{T}_{\mathcal{A}}$ + index arithmetic

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- 2 quantifier-free approaches
  - Eager encoding
  - Instantiation-based approach

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- Fully Quantified Axioms

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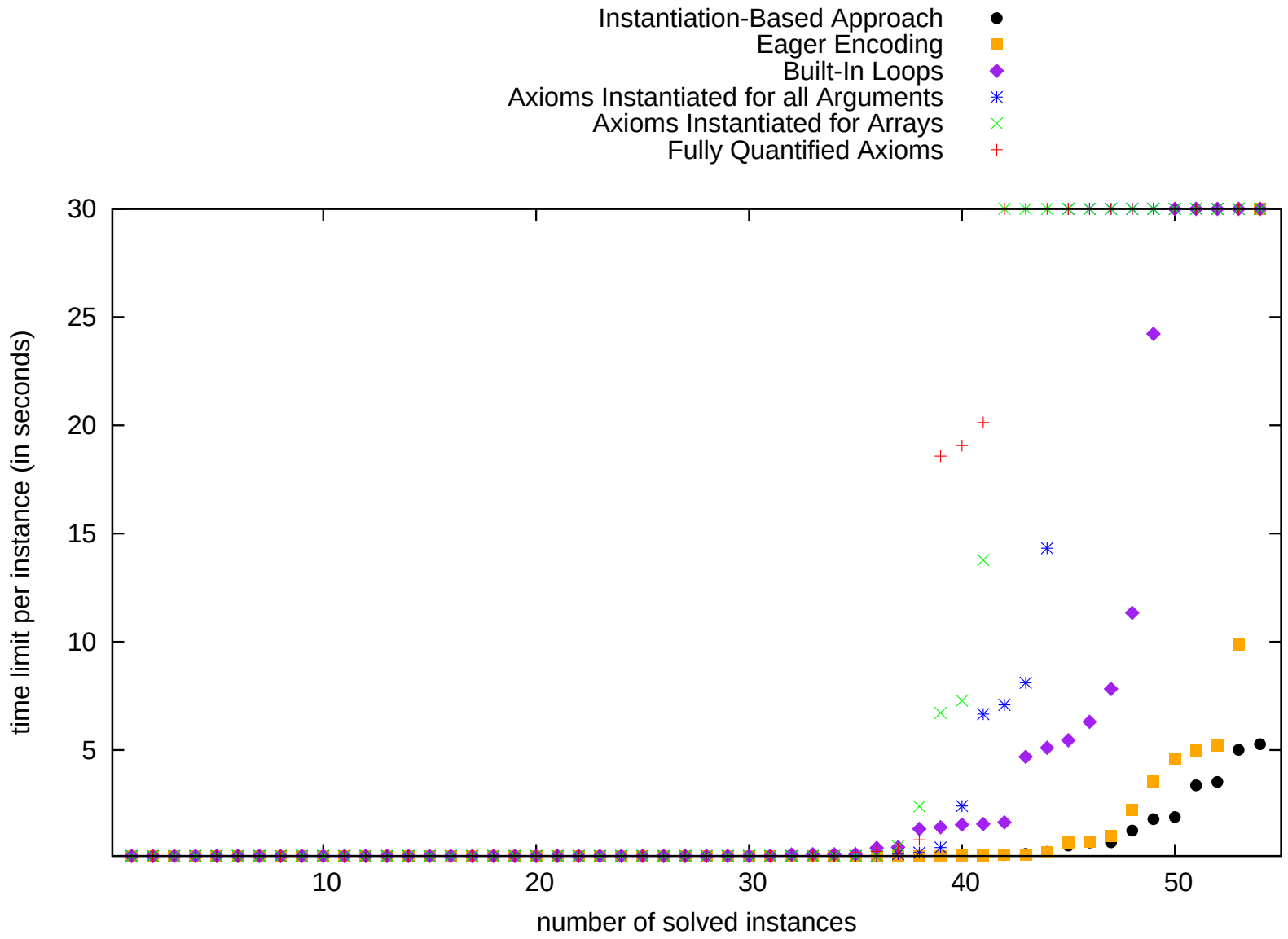
- Evaluated all 5 encodings + built-in loops
  - Quantifier-based approaches used `Z3`
  - Eager- and instantiation-based approaches used `STP`
  - Built-in loops approach used `STP`

Results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time limit per instance (in seconds)
number of solved instances
30
25
20
15
10
5
10
20
30
40
50

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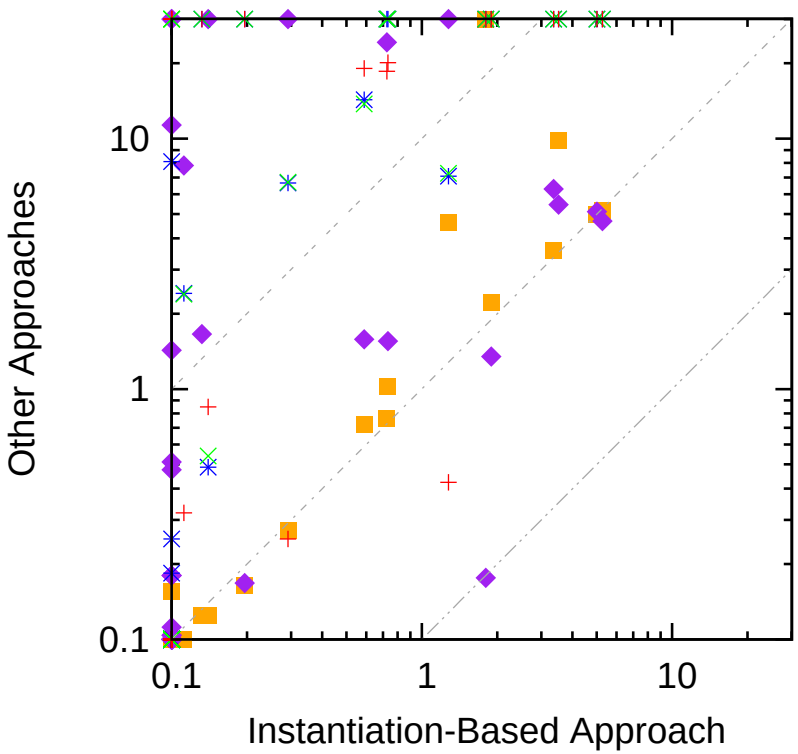

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- We can do better than Z3's reasoning involving quantifiers
- "Lemmas-on-demand"/"layz instantiation" is the next step

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