Structuring an Abstract Interpreter through Value and State Abstractions:

EVA, an Evolved Value Analysis for Frama–C

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VALUE Analysis

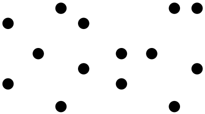
- An historic plugin of Frama-C.
- *Abstract interpretation* based analysis.
- Handles the subset of C99 used in embedded softwares.
- Emits alarms at potentially unsafe program points.

Abstract Interpretation [CC77]

- A general theory for the approximation of program semantics.
- A practical framework for automatic analyzes.
- Links a very precise but generally non computable semantics to relaxed *abstract* semantics through *abstract domains*.

Abstract Domains

- Abstract domains $\mathbb{D}$ over-approximate the behaviors of a program.



- A set of discrete concrete states in $\mathcal{S}$ represents the possible behaviors at a program point.

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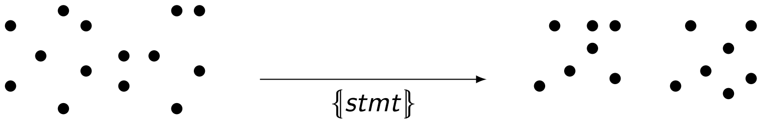

- A concrete semantics characterizes the effects of a statement as a function over states.

$$[\![\texttt{stmt}]\!] : \boldsymbol{\mathcal{S}} \rightarrow \boldsymbol{\mathcal{S}}$$

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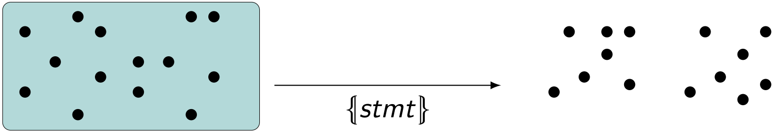

- An abstract domain $\mathbb{D}$ represents sets of concrete states.

$$\gamma : \mathbb{D} \to \mathcal{P}(\boldsymbol{\mathcal{S}})$$

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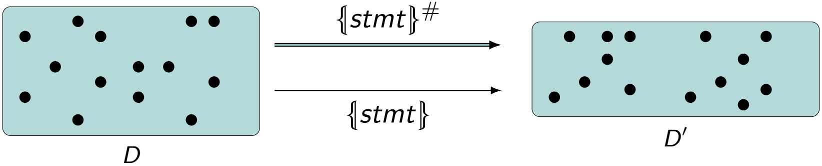

- Sound abstract semantics through transfer functions $\{\!| \cdot |\!\}^{\#} : \mathbb{D} \to \mathbb{D}$.

$$\{\!|\texttt{stmt}|\!\}(\gamma(D)) \subseteq \gamma(\{\!|\texttt{stmt}|\!\}^{\#}(D))$$

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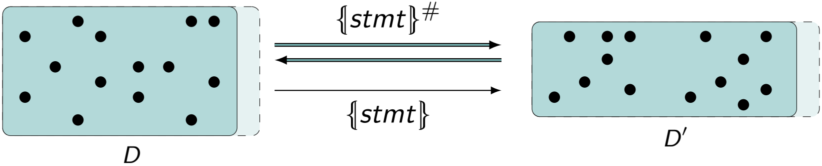

- Sound backward semantics $\overleftarrow{\llbracket \cdot \rrbracket}^{\#} : \mathbb{D} \rightarrow \mathbb{D}$.

$$\{S \mid \llbracket \texttt{stmt} \rrbracket(S) \in \gamma(D')\} \subseteq \gamma(\overleftarrow{\llbracket \texttt{stmt} \rrbracket}^{\#}(D'))$$

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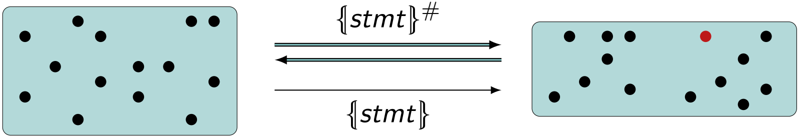

- Report illegal operations
  (divisions by zero, integer overflows, invalid accesses to memory. . .)
- All incorrect programs are detected.

Abstract Domains

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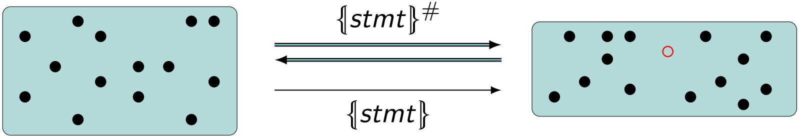
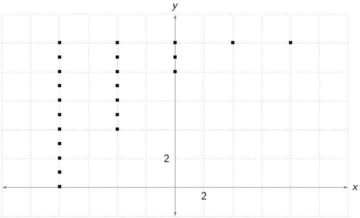


- But over-approximations may lead to false alarms.
- May fail to verify correct programs.

Known Abstract Domains

Numerous abstractions are already well-known in the literature:

- Intervals: $x \in [-10..10]$ $y \in [0..10]$
- Congruences: $x \equiv 0[4]$
- Octagons: $x - y \leq 0$ $-8 \leq x \leq 8$ $0 \leq y \leq 10$
- And many more. . .



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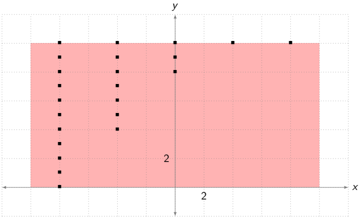

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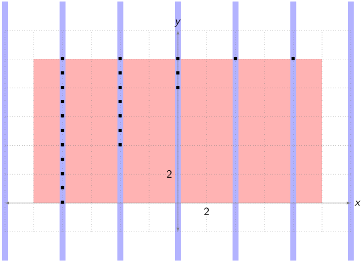

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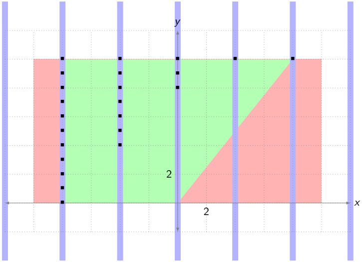

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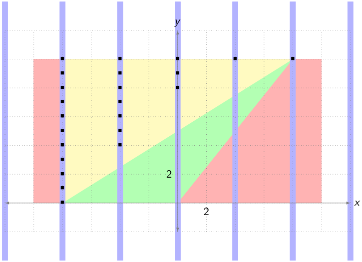

In the VALUE Analysis plugin

- One rich abstract domain based on intervals and congruences.
- Strongly optimized to achieve scalability.
- However:
  - Not extensible.
  - Lack of relational properties.
- Limitations overcomed in EVA, the Evolved Value Analysis.

Combination of Abstract Domains

How to combine abstract domains?

How to let them interact?

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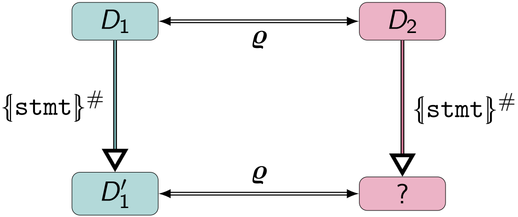
Combination of Abstract Domains

How to combine abstract domains?

How to let them interact ***in a modular way****?*

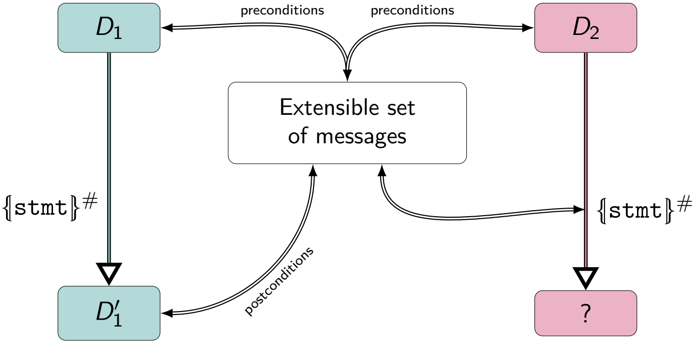
Reduced Product [CC79]

- Direct inter-reduction between two domains: $\varrho : \mathbb{D}_1 \times \mathbb{D}_2 \to \mathbb{D}_1 \times \mathbb{D}_2$



- Highly non-modular.
- No interaction during the interpretation of statements.

Communication by Messages [Cou+06]

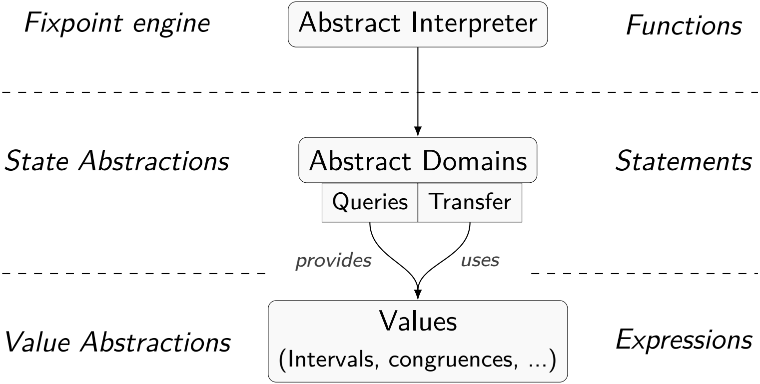


- Domains can send or request information.
- Communication system in parallel of the abstract semantics.

Our Proposal

Structuring the abstract semantics following the distinction between expressions and statements.

Core Concepts



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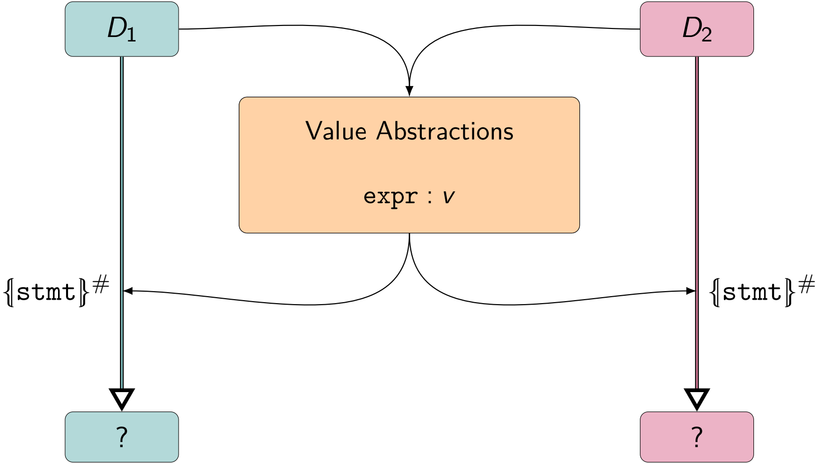

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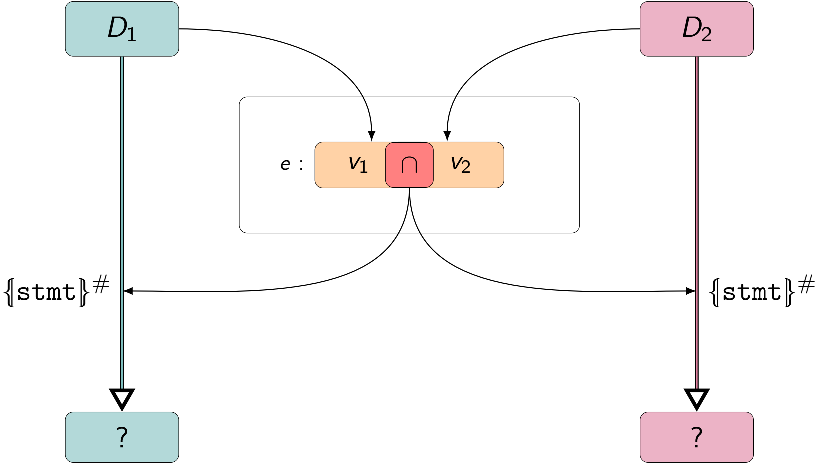

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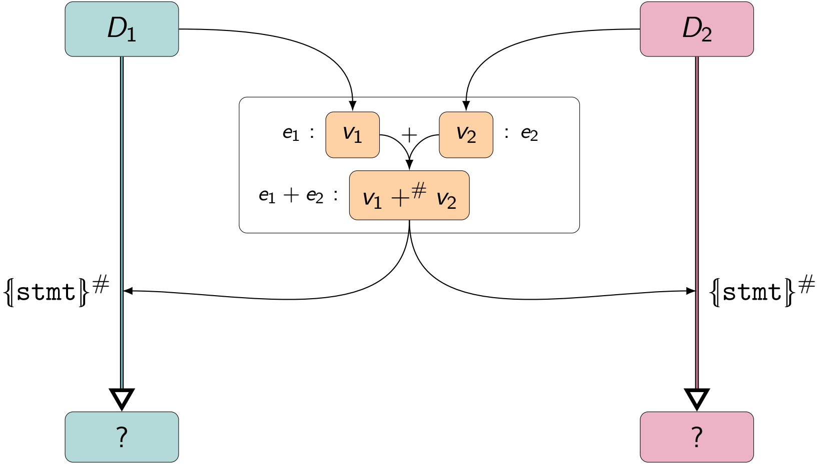

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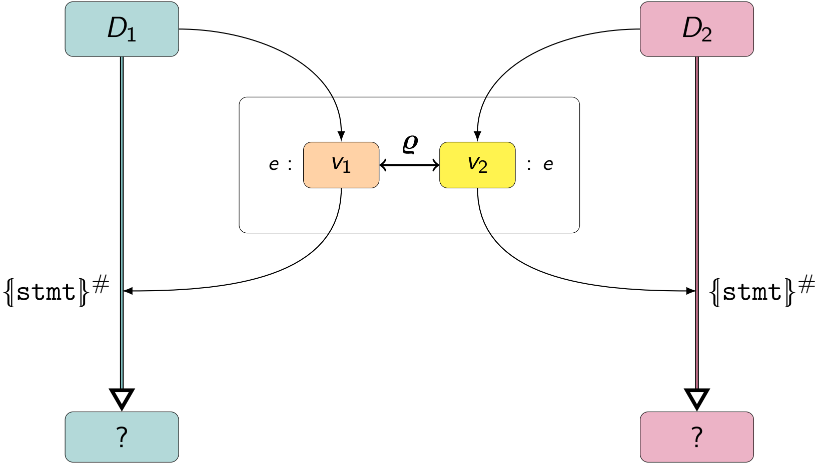

Value Abstractions $\mathbb{V}^\#$

- Represent sets of scalar values:

$$\gamma_{\mathbb{V}} : \mathbb{V}^\# \to \mathcal{P}(\mathbb{V})$$

$\mathbb{V}$ is the set of the scalar values in C, including integer and pointers.

- Used in this talk:
  - For integers: intervals

$$[x..y]$$

  - For pointers: maps from variables to intervals

$$\{\{\&x \mapsto [i..j]\}\}$$

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Operations of the Value Abstractions $\mathbb{V}^{\#}$

- Meet $\sqcap_{\mathbb{V}}$ operation, over-approximating the intersection of sets:

$$\gamma_{\mathbb{V}}(v_1) \cap \gamma_{\mathbb{V}}(v_2) \subseteq \gamma_{\mathbb{V}}(v_1 \sqcap_{\mathbb{V}} v_2)$$

- For each C operator $\diamondsuit$ on expressions, a *sound* abstract operator $\diamondsuit^{\#}$ on value abstractions:

$$\forall v_1 \in \gamma_{\mathbb{V}}(v_1^{\#}),\ \forall v_2 \in \gamma_{\mathbb{V}}(v_2^{\#}), \quad v_1 \diamondsuit v_2 \in \gamma_{\mathbb{V}}(v_1^{\#} \diamondsuit^{\#} v_2^{\#})$$

$$\diamondsuit \in \{+, -, \leq, \dots\}$$

- Injection of scalar values: $v \in \gamma_{\mathbb{V}}(v^{\#})$

State Abstractions $\mathbb{D}$

- Represent sets of concrete states:

$$\gamma_{\mathbb{D}} : \mathbb{D} \to \mathcal{P}(\boldsymbol{\mathcal{S}})$$

$\boldsymbol{\mathcal{S}}$ represents all possible behaviors when executing a program.

- Provide a *sound* abstract semantics $*^{\#}$ of dereferences:

$$*^{\#} : \mathbb{D} \to \mathbb{V}^{\#} \to \mathbb{V}^{\#}$$

- Product of semantics:

$$*^{\#}(D_1 \times D_2, v) = *^{\#}(D_1, v) \sqcap_{\mathbb{V}} *^{\#}(D_2, v)$$

Cooperative Evaluation: First Example

```
int t[5] = {1,2,3,4,5};
if (0 <= i && i < 3)
  x = t[i+1];
```

Array domain D_A

$t : \{1, 2, 3, 4, 5\}$

Interval domain D_I

$\begin{cases} i \in [0..2] \\ x \in \top \end{cases}$

- Evaluation of $t[i+1]$:

$$
\begin{aligned}
i &\rightharpoonup *^{\#}(D_A \times D_I, \{\{\&i \mapsto [0]\}\}) = \top_{\mathbb{V}} \sqcap_{\mathbb{V}} [0..2] = [0..2] \\
i+1 &\rightharpoonup [0..2] +^{\#} [1] = [1..3] \\
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Requesting Evaluations

- A domain may need further information to compute a precise value.
- A domain $\mathbb{D}$ can request the evaluation of an expression
  - The evaluation involves all available domains.
  - The result is then returned to $\mathbb{D}$.
- Information flows between domains through value abstractions.
- No direct interaction between domains.

Cooperative Evaluation: Second Example

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int t[5] = {1,2,3,4,5};
int tmp = t[i+1];
if (0 <= i && i < 3)
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Equalities D_E	Intervals D_I	Array D_A
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Backward Propagation

- Value and state abstractions also implement backward counterparts to the forward abstract operators.
- Domains can trigger new backward propagations.

Cooperative Evaluation: Third Example

```
int t[5] = {1,2,3,4,5};
int tmp = t[i+1];
if (tmp < 3) ...
```

Equality domain D_E	*Interval domain D_I*	*Array domain D_A*
$tmp = t[i+1]$	$\begin{cases} i \in [-1..3] \\ tmp \in [1..5] \end{cases}$	$t : \{1, 2, 3, 4, 5\}$

- Backward propagation on $tmp < 3$:

tmp	is reduced to	$[1..2]$	by the value semantics
$t[i+1]$	is reduced to	$[1..2]$	by the equality domain
$i+1$	is reduced to	$[0..1]$	by the array domain
i	is reduced to	$[-1..0]$	by the value semantics

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$t[i+1]$	is reduced to	$[1..2]$	by the equality domain
$i+1$	is reduced to	$[0..1]$	by the array domain
i	is reduced to	$[-1..0]$	by the value semantics

Cooperative Evaluation: Third Example

```
int t[5] = {1,2,3,4,5};
int tmp = t[i+1];
if (tmp < 3) ...
```

Equality domain D_E	*Interval domain* D_I	*Array domain* D_A
$tmp = t[i+1]$	$\begin{cases} i \in [-1..3] \\ tmp \in [1..5] \end{cases}$	$t : \{1, 2, 3, 4, 5\}$

- Backward propagation on $tmp < 3$:

tmp	is reduced to	$[1..2]$	by the value semantics
$t[i+1]$	is reduced to	$[1..2]$	by the equality domain
$i+1$	is reduced to	$[0..1]$	by the array domain
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Alarms

- In the abstractions, alarms in $\mathbb{A}$ report illegal operations.
- Each forward abstract semantics also produces alarms to over-approximate the error cases.
- The alarms produced by different abstractions are intersected.

$$\sqcap_{\mathbb{A}} : \mathbb{A} \rightarrow \mathbb{A} \rightarrow \mathbb{A}$$

- Collaboration for the emission of the alarms.

Abstract Semantics of Statements

- To interpret a statement (an assignment $*p = e$ or a test $\text{if}(c)$):

  1. All expressions are cooperatively evaluated;
  2. The resulting alarms are emitted by the analyzer;
  3. The transfer functions approximate the effect of the statement.
     They can use all value abstractions produced by the evaluations.

Frama-C/EVA

- Implemented within EVA, a major evolution of the former Value Analysis plugin.
- Same scope and functionalities for the end-user.
- Similar analysis time but slightly more precise results.

Abstract Values in EVA

- Numerical values:
  - small set of integers: `{0; 3; 8}`
  - integer intervals with congruence information: `[15..51], 3%4`
  - floating point intervals: `[3.59999990463 .. 5.60000038147]`
- Pointer values:
  - map from memory bases to numerical offsets (in bytes):
    `{{ NULL+{0} ; &t+[2..159] ; &u+{6} }}`
- Extensible.

Abstract Domains in EVA

- Main domain: low-level memory model for C [Kir+15]
  - map from (variables $\times$ bits-expressed intervals) to values.
- Symbolic equalities.
- Symbolic locations domain.
- Simple binding to the APRON domains. [JM09]
- Gauges domain. [Ven12]
- Bitwise domain.
- Also extensible.

Future Domains?

- New abstract domains dedicated to:
  - arrays
  - strings
  - dynamically allocated memories
- Make the plugins derived from the Value Analysis (inout, from) abstract domains of EVA.

Conclusion

Structuring an abstract interpreter through value and state abstractions:

- Communication embedded in the abstract semantics.
- Allows new interactions with a domain without modifying it.
- Cooperative emission of the alarms.
- Implemented within EVA, the abstract interpreter of Frama-C.

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