Code Verification using Abstract Interpretation

(Week 9)

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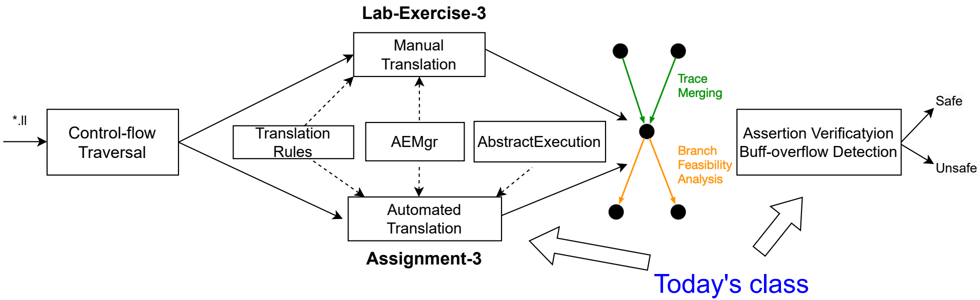
Today's class



Topological Order

Analysis Order of Nodes on Control-Flow Graph

? How to analyze a program **free of loop**?

✔ Analyze each node **once** adhering to the **topological order** on the acyclic control-flow graph of the program.

Topological Order

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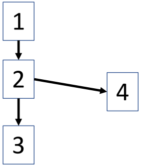
✓ Analyze each node **once** adhering to the **topological order** on the acyclic control-flow graph of the program.

A **topological order** of a graph $G(V, E)$ is a linear ordering of its nodes such that for every directed edge $a \rightarrow b$, node a always precedes node b in the ordering.

- Must be a **direct acyclic graph** (DAG) and has at least one topo ordering.
- The ordering respects the **direction of edges.**

Example of topological order:



acyclic graph G

1 2 3 4 ✓

1 2 4 3 ✓

1 3 2 4 ✗

Valid/invalid topological order

Weak Topological Order

Analysis Order of Nodes on Control-Flow Graph

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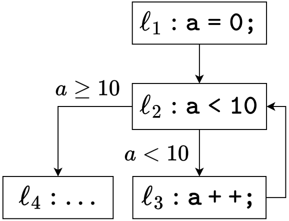
✔ We can analyze a program containing loops adhering to the **weak topological order** (WTO) on its control flow graph.

What is the weak topological order?



Control Flow Graph

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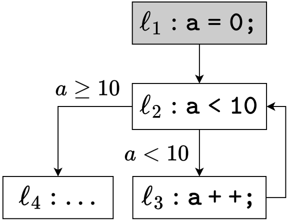
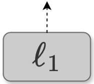


Control Flow Graph

1^{st} WTO component: a sigle node



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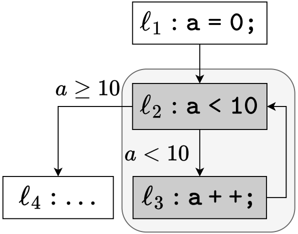
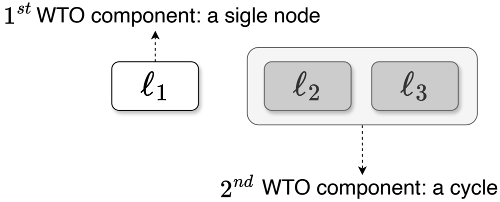


Control Flow Graph



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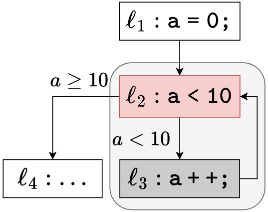
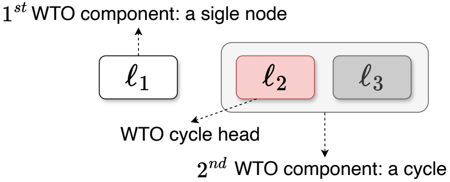


Control Flow Graph



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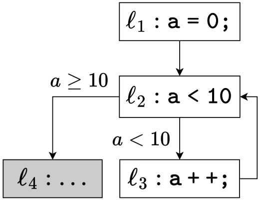

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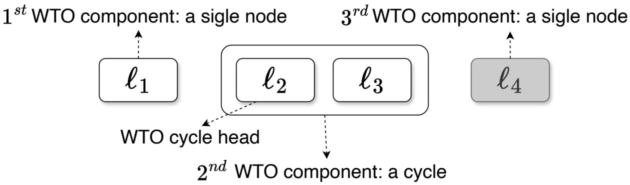

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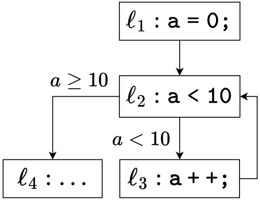
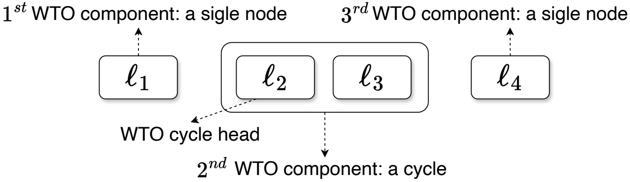


Control Flow Graph



Analyze each node following the WTO

Analyze ℓ_1 ⇨ Repeat: analyze ℓ_2 and ℓ_3 ⇨ Analyze ℓ_4

Weak Topological Order

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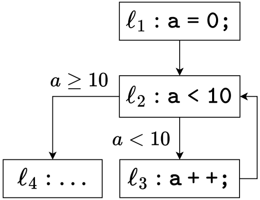
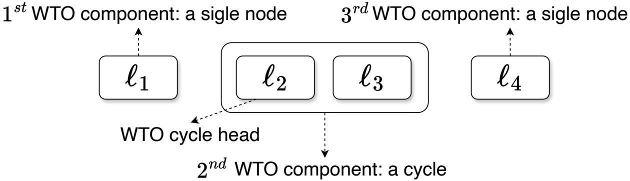


Control Flow Graph



Analyze each node following the WTO

Analyze ℓ_1 ⇨ Repeat: analyze ℓ_2 and ℓ_3 ⇨ Analyze ℓ_4

Perform widening when analyzing the cycle heads (i.e., ℓ_2)

WTO, Widening and Narrowing

Why Weak Topological Order?

- Handling cyclic dependencies
- Efficient fixed-point computation

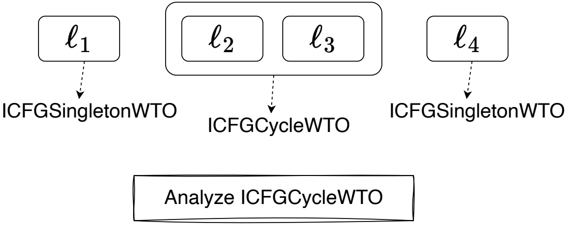
Why Widening?

- Over-approximation
- Prevent non-termination

Why Narrowing?

- Refine precision after widening converges
- The specific conditions or constraints used for narrowing:
  - Loop exit conditions (this course)
  - Type constraints (8-bit integer ranging from [-128, 127])
  - Bounds from arithmetic operations If `x = y + z`, and $y \in [1, 5]$ and $z \in [2, 3]$, then $x \in [3, 8]$. If widening gives [1, 10], narrowing can refine this to [3, 8].
  - User-specification (assertions and guard conditions)

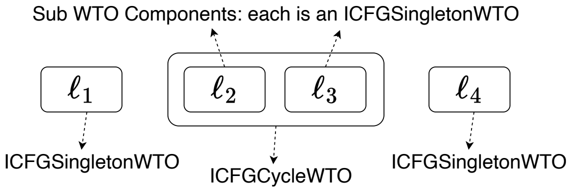
Widening and Narrowing



Algorithm 1: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleSingletonWTO(cycle→head());
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleSingletonWTO(cycle→head());
        handleWTOComponents(cycle→getWTOComponents());
```

Widening and Narrowing



Analyze ICFGCycleWTO

Algorithm 2: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++;
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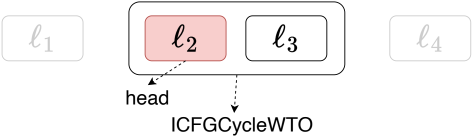
Weak Topological Order



Get ICFGCycleWTO head ℓ_2

Algorithm 3: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
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    while true do
        cur_iter++;
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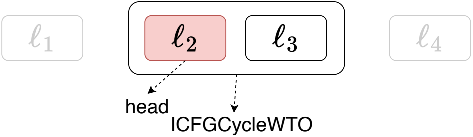
Weak Topological Order



Handle ICFGCycleWTO head ℓ_2

Algorithm 4: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++;
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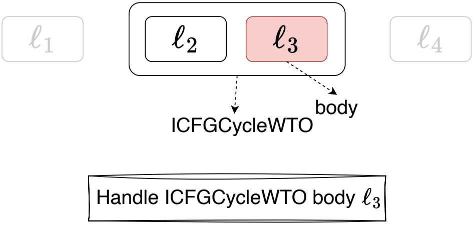
Widening and Narrowing



Algorithm 5: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
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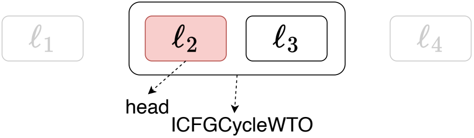
```

Note: getIWTOcomponents returns Cycle WTO body, i.e., ℓ_3

Widening and Narrowing



When $cur\_iter \geq Options :: WidenDelay()$

perform widening on ℓ_2

Algorithm 6: Abstract execution guided by WTO (part 2)

```
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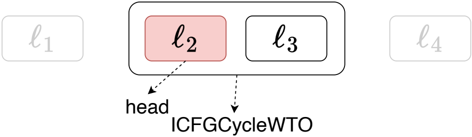
Widening and Narrowing



Widening reaches a fixpoint

Algorithm 7: Abstract execution guided by WTO (part 2)

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Function handleCycleWTO(cycle):
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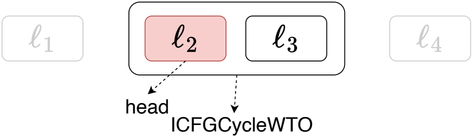
Widening and Narrowing



Perform narrowing on ℓ_2

Algorithm 8: Abstract execution guided by WTO (part 2)

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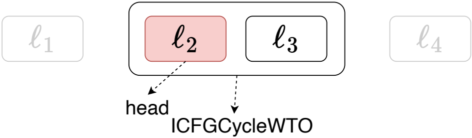
Widening and Narrowing



Narrowing reaches a fixpoint, Finish!

Algorithm 9: Abstract execution guided by WTO (part 2)

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Abstract Interpretation on SVFIR

Week 9

Yulei Sui

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University of New South Wales, Australia

Abstract Interpretation on Pointer-Free SVFIR

Interval Domain

- For simplicity, let's first consider abstract execution on a pointer-free language.
- This means there are no operations for memory allocation (like $\mathtt{p} = \mathtt{alloc_o}$) or for indirect memory accesses (such as `p = *q` or `*p = q`).
- Here are the pointer-free SVFSTMTs and their C-like forms:

SVFSTMT	C-Like form
CONSSTMT	$\ell : \mathtt{p} = \mathtt{c}$
COPYSTMT	$\ell : \mathtt{p} = \mathtt{q}$
BINARYSTMT	$\ell : \mathtt{r} = \mathtt{p} \otimes \mathtt{q}$
PHISTMT	$\ell : \mathtt{r} = \mathtt{phi}(\mathtt{p_1}, \mathtt{p_2}, \ldots, \mathtt{p_n})$
SEQUENCE	$\ell_1 ; \ell_2$
BRANCHSTMT	ℓ_1 : if$(x < c)$ then ℓ_2 else ℓ_3

Abstract Interpretation on Pointer-Free SVFIR

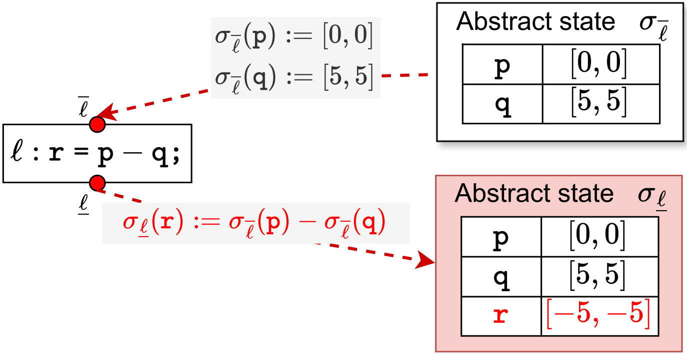
Interval Domain

Let's use the *Interval* abstract domain to update σ based on the following rules for different SVFSTMT:

SVFSTMT	**C-Like form**	**Abstract Execution Rule**
CONSSTMT	$\ell : \mathtt{p} = \mathtt{c}$	$\sigma_{\underline{\ell}}(\mathtt{p}) := [\mathtt{c}, \mathtt{c}]$
COPYSTMT	$\ell : \mathtt{p} = \mathtt{q}$	$\sigma_{\underline{\ell}}(\mathtt{p}) := \sigma_{\overline{\ell}}(\mathtt{q})$
BINARYSTMT	$\ell : \mathtt{r} = \mathtt{p} \otimes \mathtt{q}$	$\sigma_{\underline{\ell}}(r) := \sigma_{\overline{\ell}}(p) \hat{\otimes} \sigma_{\overline{\ell}}(q)$
PHISTMT	$\ell : \mathtt{r} = \mathtt{phi}(\mathtt{p}_1, \mathtt{p}_2, \ldots, \mathtt{p}_n)$	$\sigma_{\underline{\ell}}(r) := \bigsqcup_{i=1}^{n} \sigma_{\overline{\ell}}(p_i)$
SEQUENCE	$\ell_1 ; \ell_2$	$\forall v \in \mathbb{V}, \sigma_{\overline{\ell_2}}(v) \sqsupseteq \sigma_{\underline{\ell_1}}(v)$
BRANCHSTMT	ℓ_1 : if($x < c$) then ℓ_2 else ℓ_3	$\sigma_{\overline{\ell_2}}(x) := \sigma_{\underline{\ell_1}}(x) \sqcap [-\infty, c-1],$ if $\sigma_{\underline{\ell_1}}(x) \sqcap [-\infty, c-1] \neq \perp$ $\sigma_{\overline{\ell_3}}(x) := \sigma_{\underline{\ell_1}}(x) \sqcap [c, +\infty],$ if $\sigma_{\underline{\ell_1}}(x) \sqcap [c, +\infty] \neq \perp$

Abstract Interpretation on BinaryStmt

SVFStmt	C-Like form	Abstract Execution Rule
BinaryStmt	$\ell : \texttt{r} = \texttt{p} \otimes \texttt{q}$	$\sigma_{\underline{\ell}}(r) := \sigma_{\overline{\ell}}(p) \hat{\otimes} \sigma_{\overline{\ell}}(q)$

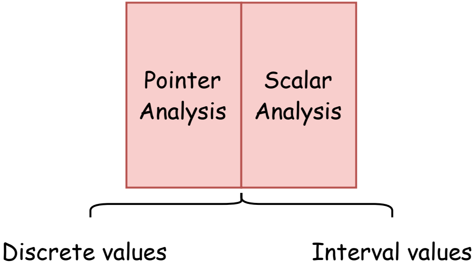


Abstract Interpretation in the Presence of Pointers

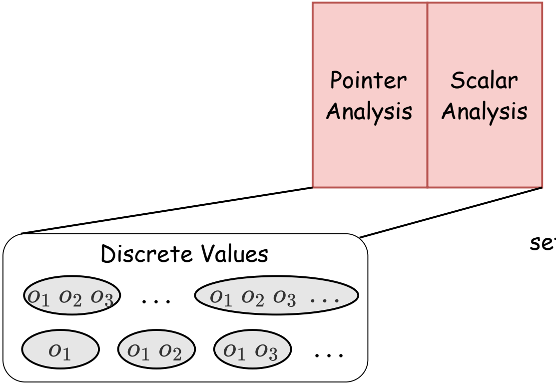
- SVFIR in the presence of pointers contain pointer-related statements including ADDRSTMT, GEPSTMT, LOADSTMT and STORESTMT.
- Abstract interpretation needs to be performed on **a combined domain of intervals and addresses**.

SVFSTMT	**C-Like form**
CONSSTMT	$\ell : \mathtt{p} = \mathtt{c}$
COPYSTMT	$\ell : \mathtt{p} = \mathtt{q}$
BINARYSTMT	$\ell : \mathtt{r} = \mathtt{p} \otimes \mathtt{q}$
PHISTMT	$\ell : \mathtt{r} = \mathtt{phi}(\mathtt{p}_1, \mathtt{p}_2, \ldots, \mathtt{p}_n)$
SEQUENCE	$\ell_1; \ell_2$
BRANCHSTMT	ℓ_1 : if($x < c$) then ℓ_2 else ℓ_3
ADDRSTMT	$\ell : \mathtt{p} = \mathtt{alloc}$
GEPSTMT	$\ell : \mathtt{p} = \&(\mathtt{q} \rightarrow \mathtt{i})$ or $\mathtt{p} = \&\mathtt{q}[\mathtt{i}]$
LOADSTMT	$\ell : \mathtt{p} = *\mathtt{q}$
STORESTMT	$\ell : *\mathtt{p} = \mathtt{q}$

Combined Analysis



Combined Analysis Using Discrete Values



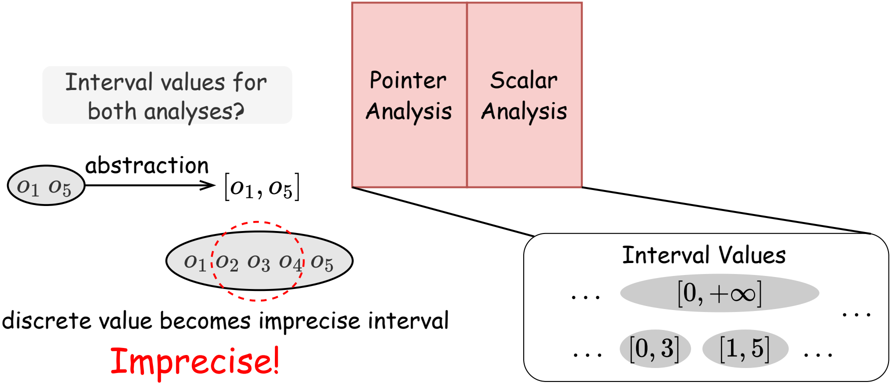
Discrete values for both analyses?

{1, 2, 3, ..., infinite numbers}

set of all possible values with inputs

Unscalable!

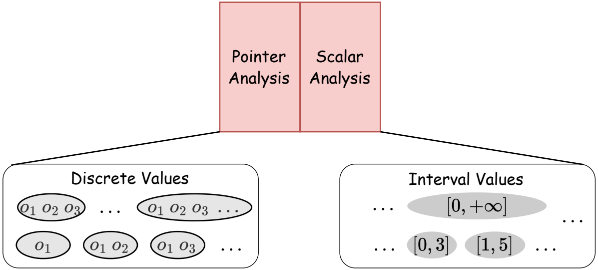
Combined Analysis Using Interval Values



discrete value becomes imprecise interval

Imprecise!

Abstract Interpretation Over a Combined Domain

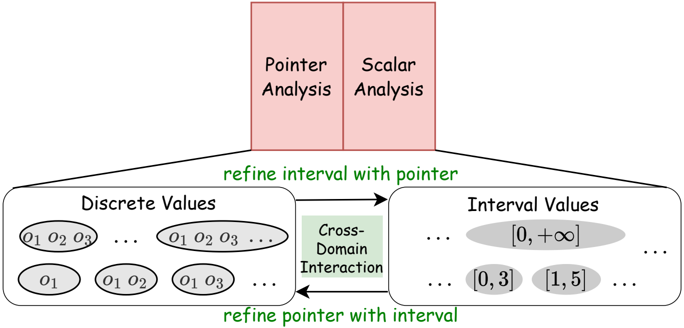


p = malloc(m*sizeof(int)); // p points to an array of size m
q = malloc(n*sizeof(int)); // q points to an array of size n

m = r[i];

- The discrete values for points-to set of `p`, `q` depend on interval values of `m` and `n`.
- The interval value of `m` depends on the pointer aliasing between `p`, `q` and `&r[i]`.
- Cyclic dependency between two domains requiring a bi-directional refinement. (variables highlighted in blue and red denote the discrete values and interval values dependent),

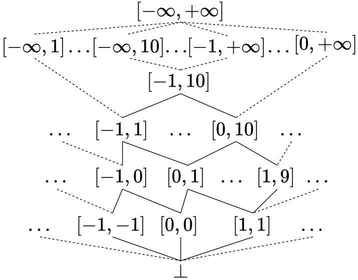
Abstract Interpretation Over a Combined Domain



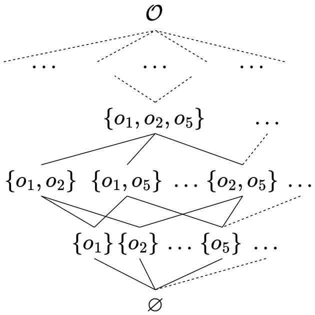
We require **a combination of interval and memory address domains** to precisely and efficiently perform abstract execution on SVFIR in the presence of pointers.

Abstract Interpretation over Interval and MemAddress Domains

A Combined Domain of Intervals and Discrete Memory Addresses



Interval domain for scalar variables



MemAddress domain for discrete memory address values

SVF Program Variables (SVFVar)

Program Variables	Domain	Meanings
`SVFVar`	$\mathbb{V} = \mathbb{P} \cup \mathbb{O}$	Program Variables
`ValVar`	$\mathbb{P}$	Top-level variables (scalars and pointers)
`ObjVar`	$\mathbb{O} = \mathbb{S} \cup \mathbb{G} \cup \mathbb{H} \cup \mathbb{C}$	Memory Objects (constant data, stack, heap, global) (function objects are considered as global objects)
`FIObjVar`	$o \in (\mathbb{S} \cup \mathbb{G} \cup \mathbb{H})$	A single (base) memory object
`GepObjVar`	$o_i \in (\mathbb{S} \cup \mathbb{G} \cup \mathbb{H}) \times \mathbb{P}$	i-th subfield/element of an (aggregate) object
`ConstantData`	$\mathbb{C}$	Constant data (e.g., numbers and strings)
Program Statement	$\ell \in \mathbb{L}$	Statements labels

Abstract Trace for The Combined Domain

- For top-level variables $\mathbb{P}$, we use $\sigma \in \mathbb{L} \times \mathbb{P} \rightarrow \mathit{Interval} \times \mathit{MemAddress}$ to track the memory addresses or interval values of these variables.
- For memory objects $\mathbb{O}$, we use $\delta \in \mathbb{L} \times \mathbb{O} \rightarrow \mathit{Interval} \times \mathit{MemAddress}$ to track their abstract values

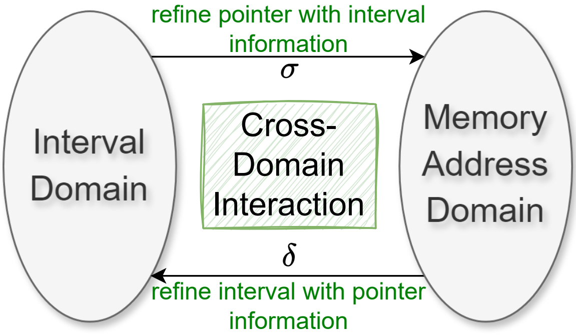
	Notation	Domain	Data Structure Implementation
Abstract trace	σ	$\mathbb{L} \times \mathbb{P} \rightarrow \mathit{Interval} \times \mathit{MemAddress}$	*preAbsTrace*, *postAbsTrace*
	δ	$\mathbb{L} \times \mathbb{O} \rightarrow \mathit{Interval} \times \mathit{MemAddress}$	
Abstract state	σ_L	$\mathbb{P} \rightarrow \mathit{Interval} \times \mathit{MemAddress}$	*AbstractState.varToAbsVal*
	δ_L	$\mathbb{O} \rightarrow \mathit{Interval} \times \mathit{MemAddress}$	*AbstractState.addrToAbsVal*
Abstract value	$\sigma_L(p)$	$\mathit{Interval} \times \mathit{MemAddress}$	*AbstractValue*
	$\delta_L(o)$		

- *Interval* is used for tracking the interval value of **scalar variables** $\mathbb{P}$.
- *MemAddress* is used for tracking the memory addresses of **memory address variables** $\mathbb{O}$.

Implementation of Abstract State and Abstract Trace

- For a program point L, the abstract state is an instance of the class named *AEState*, consisting of:
  - Top-level variable, *varToAbsVal* : $\sigma_L \in \mathbb{P} \rightarrow \mathit{Interval} \times \mathit{MemAddress}$
  - Memory object, *addrToAbsVal* : $\delta_L \in \mathit{MemAddress} \rightarrow \mathit{Interval} \times \mathit{MemAddress}$
- The abstract trace has two maps, *preAbsTrace* and *postAbsTrace*, which maintains abstract states before and after each `ICFGNode` respectively.
  - For an `ICFGNode` ℓ, *preAbsTrace*(ℓ) retrieves the abstract state $\langle \sigma_{\overline{\ell}}, \delta_{\overline{\ell}} \rangle$, and *postAbsTrace*$(\ell)$ represents $\langle \sigma_{\underline{\ell}}, \delta_{\underline{\ell}} \rangle$.
  - For each abstract state $\langle \sigma_{\overline{\ell}}, \delta_{\overline{\ell}} \rangle$ we use `as[varId]` to operate $\sigma_{\underline{\ell}}$ and use `storeValue` and `loadValue` to operate $\delta_{\underline{\ell}}$.
  - Each variable's `AbstractValue` (e.g., `as[VarId]`) is initialized as $\perp$ in an `AbstractState` before assigned a new value.
  - Each `AbstractValue` (e.g., `as[VarId]`) is a 2-element tuple consisting of an interval `as[VarId].getInterval()` and a memory address set `as[Varid].getAddrs()`.

Abstract Trace for The Combined Domain



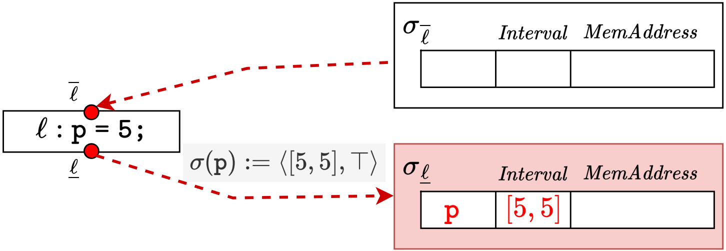
Abstract Execution Rules on SVFIR in the Presence of Pointers

Now let's use the *Interval* $\times$ *MemAddress* abstract domain to update σ and δ based on the following rules for different SVFSTMT:

SVFSTMT	**C-Like form**	**Abstract Execution Rule**
CONSSTMT	$\ell : \mathtt{p} = \mathtt{c}$	$\sigma_{\underline{\ell}}(\mathtt{p}) := \langle[\mathtt{c}, \mathtt{c}], \top\rangle$
COPYSTMT	$\ell : \mathtt{p} = \mathtt{q}$	$\sigma_{\underline{\ell}}(\mathtt{p}) := \sigma_{\overline{\ell}}(\mathtt{q})$
BINARYSTMT	$\ell : \mathtt{r} = \mathtt{p} \otimes \mathtt{q}$	$\sigma_{\underline{\ell}}(r) := \sigma_{\overline{\ell}}(p) \hat{\otimes} \sigma_{\overline{\ell}}(q)$
PHISTMT	$\ell : \mathtt{r} = \mathtt{phi}(\mathtt{p_1}, \mathtt{p_2}, \ldots, \mathtt{p_n})$	$\sigma_{\underline{\ell}}(r) := \bigsqcup_{i=1}^{n} \sigma_{\overline{\ell}}(p_i)$
BRANCHSTMT	ℓ_1 : if$(x < c)$ then ℓ_2 else ℓ_3	$\sigma_{\overline{\ell_2}}(x) := \sigma_{\underline{\ell_1}}(x) \sqcap [-\infty, c-1]$, if $\sigma_{\underline{\ell_1}}(x) \sqcap [-\infty, c-1] \neq \perp$ $\sigma_{\overline{\ell_3}}(x) := \sigma_{\underline{\ell_1}}(x) \sqcap [c, +\infty]$, if $\sigma_{\underline{\ell_1}}(x) \sqcap [c, +\infty] \neq \perp$
SEQUENCE	$\ell_1; \ell_2$	$\delta_{\overline{\ell_2}} \sqsupseteq \delta_{\underline{\ell_1}}, \sigma_{\overline{\ell_2}} \sqsupseteq \sigma_{\underline{\ell_1}}$
ADDRSTMT	$\ell : \mathtt{p} = \mathtt{alloc}_{\mathtt{o_i}}$	$\sigma_{\underline{\ell}}(\mathtt{p}) := \langle\top, \{o_i\}\rangle$
GEPSTMT	$\ell : \mathtt{p} = \&(\mathtt{q} \rightarrow \mathtt{i})$ or $\mathtt{p} = \&\mathtt{q}[\mathtt{i}]$	$\sigma_{\underline{\ell}}(\mathtt{p}) := \bigsqcup_{\mathtt{o} \in \gamma(\sigma_{\overline{\ell}}(\mathtt{q}))} \bigsqcup_{j \in \gamma(\sigma_{\overline{\ell}}(\mathtt{i}))} \langle\top, \{\mathtt{o.fld}_j\}\rangle$
LOADSTMT	$\ell : \mathtt{p} = *\mathtt{q}$	$\sigma_{\underline{\ell}}(\mathtt{p}) := \bigsqcup_{o \in \{o \mid o \in \sigma_{\overline{\ell}}(q)\}} \delta_{\overline{\ell}}(o)$
STORESTMT	$\ell : *\mathtt{p} = \mathtt{q}$	$\delta_{\underline{\ell}} := (\{o \mapsto \sigma_{\overline{\ell}}(\mathtt{q}) \mid o \in \gamma(\sigma_{\overline{\ell}}(\mathtt{p}))\} \sqcup \delta_{\underline{\ell}})$

Abstract Execution on ConsStmt

SVFStmt	C-Like form	Abstract Execution Rule
ConsStmt	$\ell : \mathtt{p} = \mathtt{c}$	$\sigma_{\underline{\ell}}(\mathtt{p}) := \langle [\mathtt{c}, \mathtt{c}], \top \rangle$

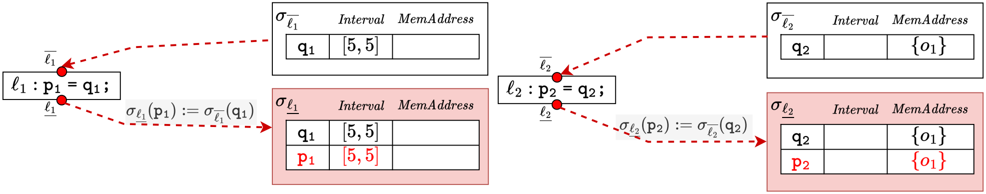


Algorithm 10: Abstract Execution Rule for ConsStmt

```
Function updateStateOnAddr(addr):
    node = addr→getICFGNode();
    as = getAbsStateFromTrace(node);
    initObjVar(as, SVFUtil :: cast⟨ObjVar⟩(addr→getRHSVar()));
    as[addr→getLHSVarID()] = as[addr→getRHSVarID()];
```

Abstract Execution on CopyStmt

SVFStmt	C-Like form	Abstract Execution Rule
CopyStmt	$\ell : \mathtt{p} = \mathtt{q}$	$\sigma_{\underline{\ell}}(\mathtt{p}) := \sigma_{\overline{\ell}}(\mathtt{q})$

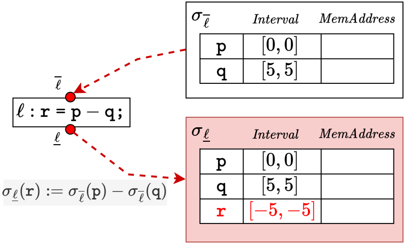


Algorithm 11: Abstract Execution Rule for CopyStmt

```
Function updateStateOnCopy(copy):
    node = copy→getICFGNode();
    as = getAbsStateFromTrace(node);
    lhs = copy→getLHSVarID();
    rhs = copy→getRHSVarID();
    as[lhs] = as[rhs];
```

Abstract Execution on BINARYSTMT

SVFSTMT	C-Like form	Abstract Execution Rule
BINARYSTMT	$\ell : \mathtt{r} = \mathtt{p} \otimes \mathtt{q}$	$\sigma_{\underline{\ell}}(r) := \sigma_{\overline{\ell}}(p) \hat{\otimes} \sigma_{\overline{\ell}}(q)$

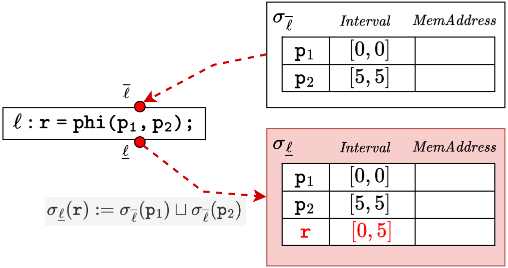


Algorithm 12: Abstract Execution Rule for BINARYSTMT

```
Function updateStateOnBinary(binary):
    node = binary→getICFGNode();
    as = getAbsStateFromTrace(node);
    op0 = binary→getOpVarID(0);
    op1 = binary→getOpVarID(1);
    res = binary→getResID();
    if !as.inVarToValTable(op0) then
        as[op0] = IntervalValue :: top()
    if !as.inVarToValTable(op1) then
        as[op1] = IntervalValue :: top()
    if
     as.inVarToValTable(op0)&&as.inVarToValTable(op1)
     then
        as[res] = as[op0] ⊗̂ as[op1]
```

Abstract Execution on PhiStmt

SVFStmt	C-Like form	Abstract Execution Rule
PhiStmt	$\ell : \mathtt{r} = \mathtt{phi}(\mathtt{p_1}, \mathtt{p_2}, \ldots, \mathtt{p_n})$	$\sigma_{\underline{\ell}}(r) := \bigsqcup_{i=1}^{n} \sigma_{\overline{\ell}}(p_i)$

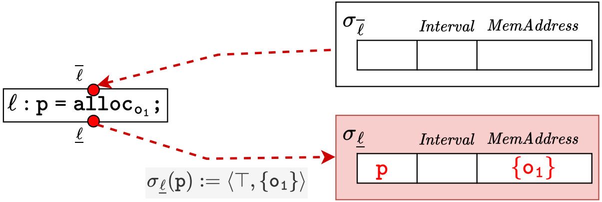


Algorithm 13: Abstract Execution Rule for PhiStmt

```
Function updateStateOnPhi(phi):
    node = phi→getICFGNode();
    as = getAbsStateFromTrace(node);
    res = phi→getResID();
    rhs = AbstractValue();
    for i = 0; i < phi→getOpVarNum(); i++ do
        curId = phi→getOpVarID(i);
        rhs.join_with(as[curId])
    as[res] = rhs
```

Abstract Execution on AddrStmt

SVFStmt	C-Like form	Abstract Execution Rule
AddrStmt	$\ell : \texttt{p} = \texttt{alloc}_{\texttt{o}_i}$	$\sigma_{\underline{\ell}}(\texttt{p}) := \langle \top, \{o_i\} \rangle$



Algorithm 14: Abstract Execution Rule for AddrStmt

Function *updateStateOnAddr(addr)*:

```
node = addr → getICFGNode();
as = getAbsStateFromTrace(node);
initObjVar(as, SVFUtil :: cast⟨ObjVar⟩(addr → getRHSVar()));
as[addr → getLHSVarID()] = as[addr → getRHSVarID()];
```

Abstract Execution on GEPSTMT

SVFSTMT	C-Like form	Abstract Execution Rule
GEPSTMT	ℓ : p = &(q → i) or p = &q[i]	$\sigma_{\underline{\ell}}(\texttt{p}) := \bigsqcup_{o \in \gamma(\sigma_{\overline{\ell}}(\texttt{q}))} \bigsqcup_{j \in \gamma(\sigma_{\overline{\ell}}(\texttt{i}))} \langle \top, \{\texttt{o.fld}_j\} \rangle$

$\overline{\ell}$

ℓ : p = &(q[i]);

$\underline{\ell}$

$\sigma_{\underline{\ell}}(\texttt{p}) := \langle \top, \{\texttt{o}_1.\texttt{fld}_1\} \rangle \sqcup \langle \top, \{\texttt{o}_1.\texttt{fld}_2\} \rangle$

$\sigma_{\overline{\ell}}$

	Interval	*MemAddress*
q		$\{\texttt{o}_1\}$
i	$[1, 2]$	

$\sigma_{\underline{\ell}}$

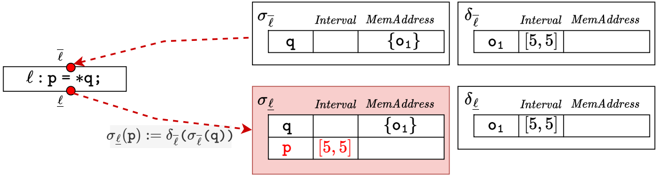
	Interval	*MemAddress*
q		$\{\texttt{o}_1\}$
i	$[1, 2]$	
p		$\{\texttt{o}_1.\texttt{fld}_1, \texttt{o}_1.\texttt{fld}_2\}$

Algorithm 15: Abstract Execution Rule for GEPSTMT

```
Function updateStateOnGep(gep):
    node = gep→getICFGNode();
    as = getAbsStateFromTrace(node);
    rhs = gep→getRHSVarID();
    lhs = gep→getLHSVarID();
    as[lhs] = as.getGepObjAddrs(rhs, as.getElementIndex(gep));;
```

Abstract Execution on LOADSTMT

SVFSTMT	C-Like form	Abstract Execution Rule
LOADSTMT	ℓ : p = *q	$\sigma_{\underline{\ell}}(\mathtt{p}) := \bigsqcup_{o \in \{o \mid o \in \sigma_{\overline{\ell}}(q)\}} \delta_{\overline{\ell}}(o)$



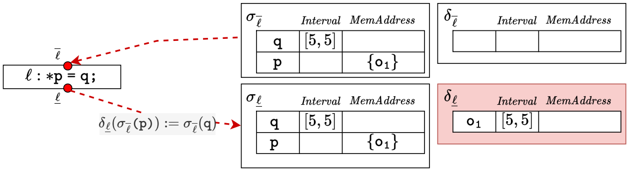
Algorithm 16: Abstract Execution Rule for LOADSTMT

Function *updateStateOnLoad(load)*:

```
node = load→getICFGNode();
as = getAbsStateFromTrace(node);
rhs = load→getRHSVarID();
lhs = load→getLHSVarID();
as[lhs] = as.loadValue(rhs)
```

Abstract Execution on STORESTMT

SVFSTMT	C-Like form	Abstract Execution Rule
STORESTMT	$\ell : *\mathtt{p} = \mathtt{q}$	$\delta_{\underline{\ell}} := (\{o \mapsto \sigma_{\overline{\ell}}(\mathtt{q}) \mid o \in \gamma(\sigma_{\overline{\ell}}(\mathtt{p}))\} \sqcup \delta_{\underline{\ell}})$



Algorithm 17: Abstract Execution Rule for STORESTMT

Function *updateStateOnStore(store)*:

```
node = store→getICFGNode();
as = getAbsStateFromTrace(node);
rhs = store→getRHSVarID();
lhs = store→getLHSVarID();
as.storeValue(lhs, as[rhs])
```

Handling Cycles (Pseudo Code)

Algorithm 18: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head());
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state)
                 ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state)
                 ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
        handleWTOComponents(cycle→getWTOComponents());
```

Algorithm 19: Handle WTO components

```
Function handleCycleBody(cycle):
    for it = cycle→begin(); it! = cycle→end(); ++it do
        cur = *it;
        if vertex = SVFUtil :: dyn_cast⟨ICFGWTONode⟩(cur) then
            handleWTONode(vertex→node())
        else if cycle2 = SVFUtil :: dyn_cast⟨ICFGWTOCycle⟩(cur) then
            handleCycle(cycle2)
        else
            assert(false&&"unknownWTOtype!")
```

An Example: Abstract Execution

```c
extern void assert(int);

int main(){
    int a = 0;
    while(a < 10) {
        a++;
    }
    assert(a == 10);
    return 0;
}
```

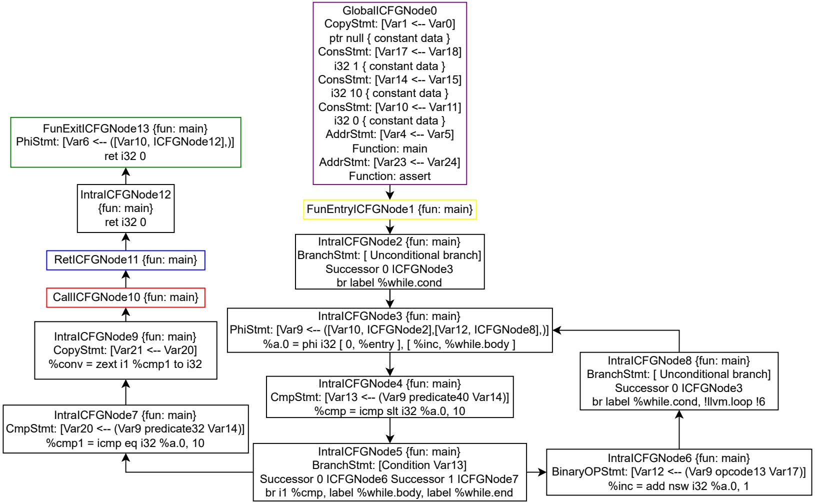
Source Code

Compile to LLVM IR

```llvm
define dso_local i32 @main() {
entry:
  br label %while.cond
while.cond:
  %a.0 = phi i32 [ 0, %entry ], [ %inc, %whil
  %cmp = icmp slt i32 %a.0, 10
  br i1 %cmp, label %while.body, label %while
while.body:
  %inc = add nsw i32 %a.0, 1
  br label %while.cond,
while.end:
  %cmp1 = icmp eq i32 %a.0, 10
  %conv = zext i1 %cmp1 to i32
  call void @assert(i32 noundef %conv)
  ret i32 0
}
```

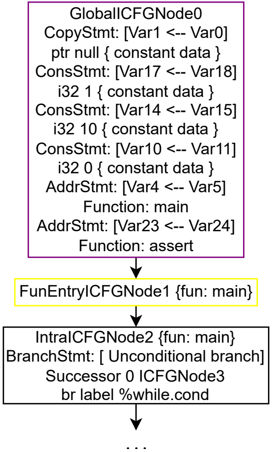
LLVM IR

An Example: Abstract Execution



ICFG

An Example: Abstract Execution



ICFG

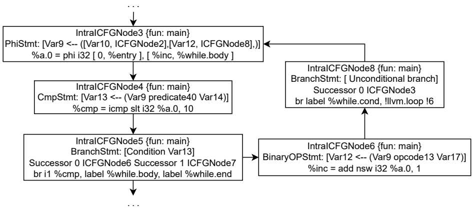
Algorithm 20: Abstract execution guided by WTO

Function `handleStatement(`ℓ`)`**:**
  $tmpAS := preAbsTrace[\ell]$;
  if ℓ *is* CONSSTMT *or* ADDRSTMT **then**
    `updateStateOnAddr(`ℓ`);`
  else if ℓ *is* COPYSTMT **then**
    `updateStateOnCopy(`ℓ`);`
  $\ldots$;

$postAbsTrace[\ell_0].varToAbsVal$:

Variable	*Interval*	*MemAddress*
Var0	$\top$	{0x7f00}
Var1	$\top$	{0x7f00}
Var18	[1,1]	$\top$
Var17	[1,1]	$\top$
Var14	[10,10]	$\top$
Var15	[10,10]	$\top$
Var10	[0,0]	$\top$
Var11	[0,0]	$\top$
...		

An Example: Abstract Execution



ICFG

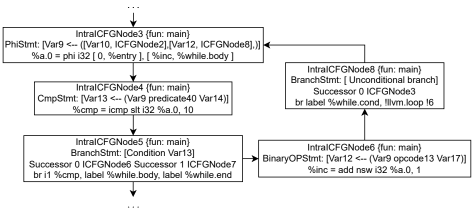
$postAbsTrace[\ell_3].varToAbsVal$:

Variable	*Interval*	*MemAddress*
	. . .	
Var10	[0,0]	$\top$
Var9	[0,0]	$\top$
	. . .	

Algorithm 12: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++ // cur_iter ≡ 1, Options :: WidenDelay() ≡ 3;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head());
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
        handleWTOComponents(cycle→getWTOComponents());
```

An Example: Abstract Execution



ICFG

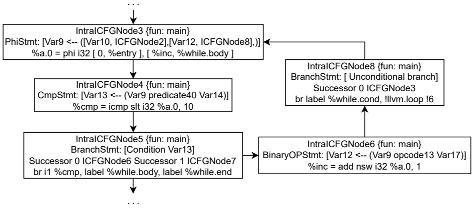
$postAbsTrace[\ell_8].varToAbsVal$:

Variable	*Interval*	*MemAddress*
	...	
Var10	[0,0]	$\top$
Var9	[0,0]	$\top$
Var12	[1,1]	$\top$
	...	

Algorithm 12: Abstract execution guided by WTO (part 2)

Function `handleCycleWTO`(*cycle*)**:**
  cycle_head := cycle→head()→node() ;
  increasing := true ;
  cur_iter := 0 // *cur_iter* $\equiv$ 1, *Options* :: *WidenDelay*() $\equiv$ 3;
  while *true* **do**
    cur_iter++;
    if *cur_iter* $\geq$ *Options* :: *WidenDelay*() **then**
      prev_head_state := *postAbsTrace*[*cycle_head*];
      `handleICFGNode`(*cycle*→*head*());
      cur_head_state := *postAbsTrace*[*cycle_head*];
      if *increasing* **then**
        postAbsTrace[*cycle_head*] := *prev_head_state.widen*(*cur_head_state*) ;
        if *postAbsTrace*[*cycle_head*] == *prev_head_state* **then**
          increasing := false;
          continue;
      else
        postAbsTrace[*cycle_head*] := *prev_head_state.narrow*(*cur_head_state*) ;
        if *postAbsTrace*[*cycle_head*] == *prev_head_state* **then**
          break ;
    else
      `handleICFGNode`(*cycle*→*head*());
    `handleWTOComponents`(*cycle*→*getWTOComponents*());

An Example: Abstract Execution



ICFG

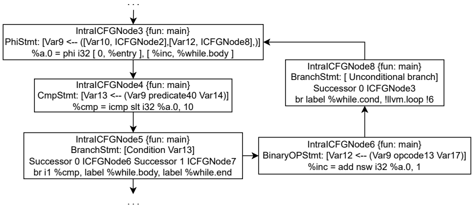
$postAbsTrace[\ell_3].varToAbsVal$:

Variable	*Interval*	*MemAddress*
	...	
Var9	[0,1]	$\top$
Var12	[1,1]	$\top$
	...	

Algorithm 12: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++ // cur_iter ≡ 2, Options :: WidenDelay() ≡ 3;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head());
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
    handleWTOComponents(cycle→getWTOComponents());
```

An Example: Abstract Execution



ICFG

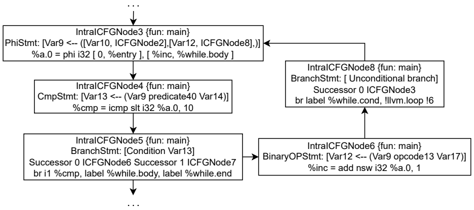
$postAbsTrace[\ell_8].varToAbsVal$:

Variable	*Interval*	*MemAddress*
...		
Var9	[0,1]	$\top$
Var12	[1,2]	$\top$
...		

Algorithm 12: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++ // cur_iter ≡ 2, Options :: WidenDelay() ≡ 3;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head());
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
        handleWTOComponents(cycle→getWTOComponents());
```

An Example: Abstract Execution



ICFG

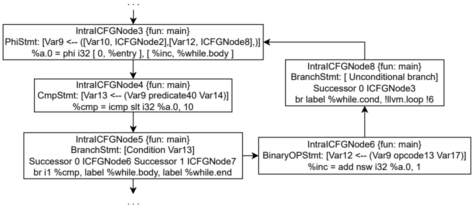
$postAbsTrace[\ell_3].varToAbsVal$:

Variable	*Interval*	*MemAddress*
	...	
Var9	$[0, +\infty]$	$\top$
Var12	[1,2]	$\top$
	...	

Algorithm 12: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++ // cur_iter ≡ 3, Options :: WidenDelay ≡ 3;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head());
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
        handleWTOComponents(cycle→getWTOComponents());
```

An Example: Abstract Execution



ICFG

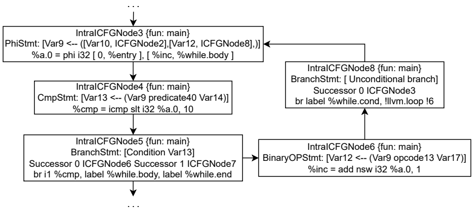
$postAbsTrace[\ell_8].varToAbsVal$:

Variable	*Interval*	*MemAddress*
	...	
Var9	[0,9]	$\top$
Var12	[1,10]	$\top$
	...	

Algorithm 12: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head());
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
        handleWTOComponents(cycle→getWTOComponents()) // cur_iter ≡ 3;
```

An Example: Abstract Execution



ICFG

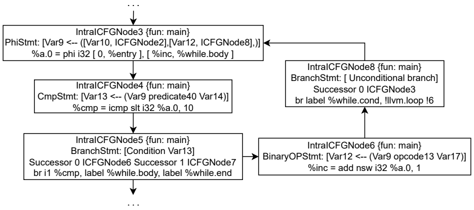
$postAbsTrace[\ell_3].varToAbsVal$:

Variable	*Interval*	*MemAddress*
	...	
Var9	$[0, +\infty]$	$\top$
Var12	[1,10]	$\top$
	...	

Algorithm 12: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0;
    while true do
        cur_iter++ // cur_iter ≡ 4;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head());
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
        handleWTOComponents(cycle→getWTOComponents());
```

An Example: Abstract Execution



ICFG

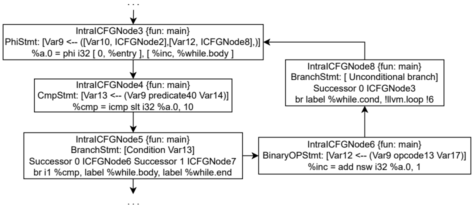
$postAbsTrace[\ell_3].varToAbsVal$:

Variable	*Interval*	*MemAddress*
	...	
Var9	[0, 10]	$\top$
Var12	[1,10]	$\top$
	...	

Algorithm 12: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++ // cur_iter ≡ 5;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head()) // increasing ≡ false;
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
        handleWTOComponents(cycle→getWTOComponents());
```

An Example: Abstract Execution



ICFG

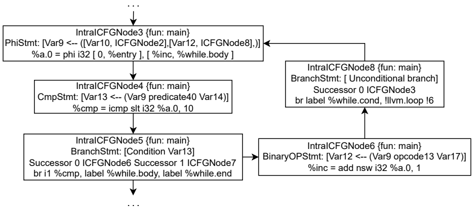
$postAbsTrace[\ell_8].varToAbsVal$:

Variable	*Interval*	*MemAddress*
	...	
Var9	[0,9]	$\top$
Var12	[1,10]	$\top$
	...	

Algorithm 12: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head());
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
        handleWTOComponents(cycle→getWTOComponents()) // cur_iter ≡ 5;
```

An Example: Abstract Execution



ICFG

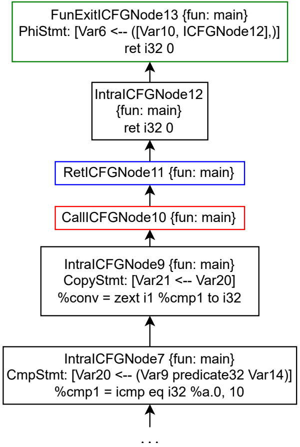
$postAbsTrace[\ell_3].varToAbsVal$:

Variable	*Interval*	*MemAddress*
	. . .	
Var9	[0, 10]	$\top$
Var12	[1,10]	$\top$
	. . .	

Algorithm 12: Abstract execution guided by WTO (part 2)

```
Function handleCycleWTO(cycle):
    cycle_head := cycle→head()→node() ;
    increasing := true ;
    cur_iter := 0 ;
    while true do
        cur_iter++ // cur_iter ≡ 6;
        if cur_iter ≥ Options :: WidenDelay() then
            prev_head_state := postAbsTrace[cycle_head];
            handleICFGNode(cycle→head()) // increasing ≡ false;
            cur_head_state := postAbsTrace[cycle_head];
            if increasing then
                postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    increasing := false;
                    continue;
            else
                postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;
                if postAbsTrace[cycle_head] == prev_head_state then
                    break ;
        else
            handleICFGNode(cycle→head());
        handleWTOComponents(cycle→getWTOComponents());
```

An Example: Abstract Execution



ICFG

Algorithm 13: Abstract execution guided by WTO

Function `handleStatement`(ℓ):
  tmpAS := *preAbsTrace*[ℓ];
  if ℓ *is* BINARYSTMT **then**
    `updateStateOnBinary`(ℓ);
  . . . ;

postAbsTrace[ℓ_7].*varToAbsVal* :

Variable	*Interval*	*MemAddress*
	. . .	
Var9	[10,10]	$\top$
Var20	[1,1]	$\top$
	. . .	