

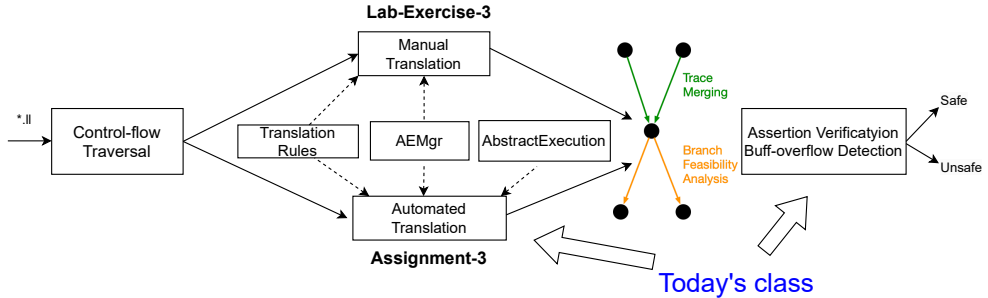
Abstract Interpretation for Code Analysis and Verification

(Week 9)

Yulei Sui

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University of New South Wales, Australia

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

Analysis Order of Nodes on Control-Flow Graph

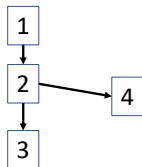
? How to analyze a program **free of loop**?

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

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

How About Analyzing Loops?

- **Topological Order** can only be used for directed acyclic graphs (DAGs).
- **Weak Topological Order (WTO)** is a relaxation of the more stringent topological order for graphs with loops.
 - **Cycles Permitted:** allows for cycles within the graph.
 - **Hierarchical Decomposition:** A graph is decomposed into a hierarchical structure where each node or a strongly connected component (SCC) can contain subnodes.
 - **Weak Topological Order or Partial Order:** In a WTO, nodes and SCCs are arranged in a partial order (not enumerating possible infinite loop paths). This order respects the dependencies in a way that allows for iterative analysis.
 - We will practice loop handling using WTO in Assignment-3. Function recursions will not be handled in this Assignment.

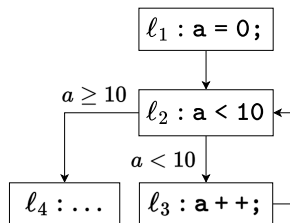
Weak Topological Order

Analysis Order of Nodes on Control-Flow Graph

? How to analyze a program **containing loops**?

✓ 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

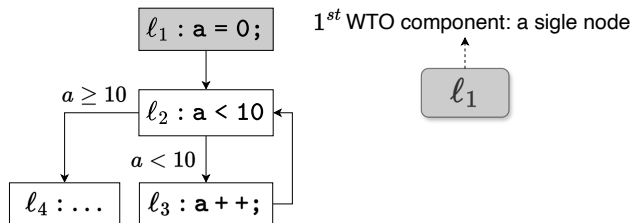
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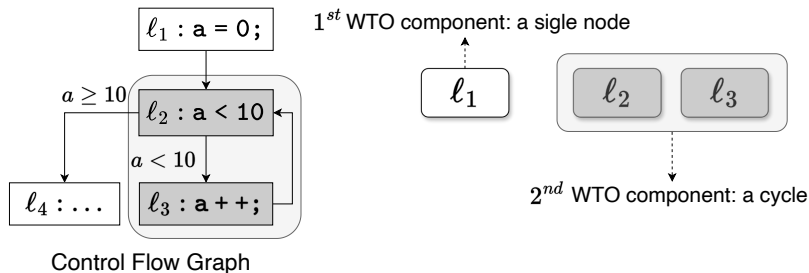
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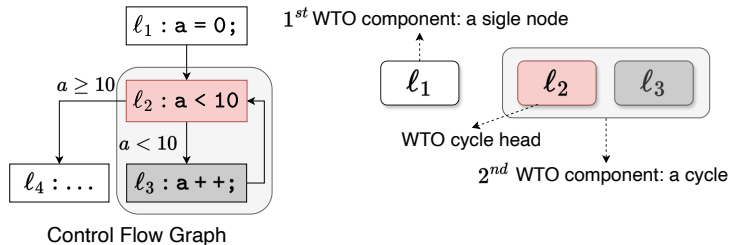
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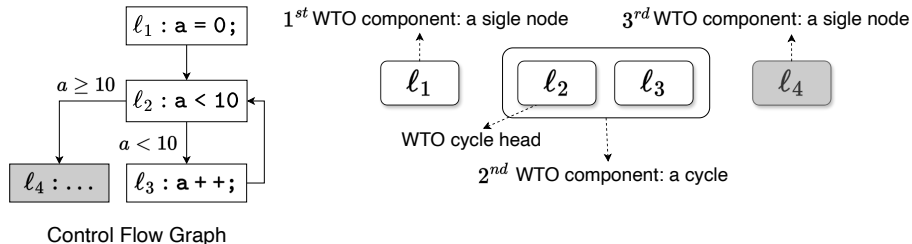
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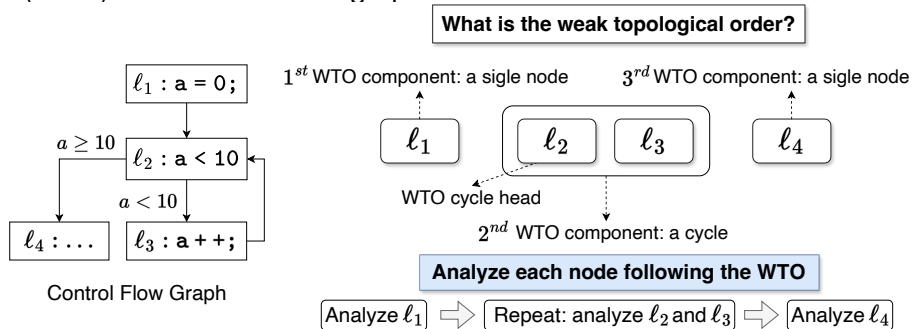


Weak Topological Order

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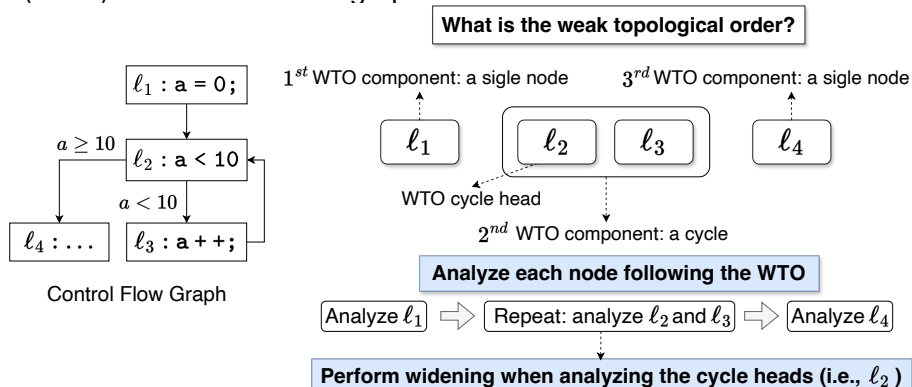


Weak Topological Order

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.



WTO, Widening and Narrowing

Why Weak Topological Order (WTO)?

- 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)

Overall Algorithm of Abstract Interpretation in Assignment-3

Algorithm 1: Analyse from main function

```
1 Function analyse() // driver function to start the analysis:
2   initWTO();
3   handleGlobalNode();
4   if getSVFFunction (main) then
5     wto := funcToWTO[main];
6     handleWTOComponents(wto → getWTOComponents());
```

Algorithm 2: Handle WTO components

```
1 Function handleWTOComponents (wtoComps):
2   for wtoNode ∈ wtoComps do
3     if node = SVFUtil :: dyn.cast(ICFGSingletonWTO)(wtoNode) then
4       handleSingletonWTO(node)
5     else if cycle = SVFUtil :: dyn.cast(ICFGCycleWTO)(wtoNode) then
6       handleCycleWTO(cycle)
7     else
8       assert(false && "unknownWTOtype!")
```

Algorithm 3: Handle Singleton WTO

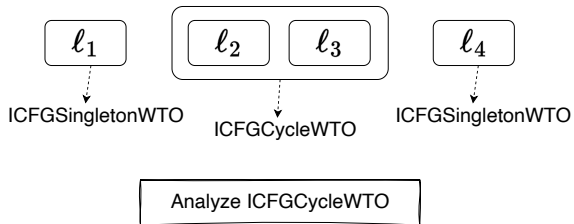
```
1 Function handleSingletonWTO(singletonWTO):
2   node := singletonWTO → node();
3   feasible := mergeStatesFromPredecessors(node, preAbsTrace[node]);
4   if feasible then
5     postAbsTrace[node] := preAbsTrace[node];
6   else
7     return;
8   foreach stmt ∈ node → getSVFStmts() do
9     updateAbsState(stmt);
10    bufOverflowDetection(stmt);
11   if callnode = SVFUtil :: dyn.cast(CallICFGNode)(node) then
12     funName := callnode → getCallSite() → getCallee() → getName()
13     if funName == "OVERFLOW" && funName == "svf_assert" then
14       // Handle svf_assert and OVERFLOW stub function for
15       correctness validation;
16       handleStubFunctions(callnode);
17     else
18       // Does not analyze recursive functions in this course;
19       handleCallSite(callnode);
```

Overall Algorithm of Abstract Interpretation in Assignment-3

Algorithm 4: Handle Cycle WTO

```
1 Function handleCycleWTO (cycle):
2   feasible := mergeStatesFromPredecessors(cycle.head, preAbsTrace[cycle.head]);
3   increasing := true;
4   if !feasible then
5     return;
6   else
7     cur_iter := 0;
8     while true do
9       if cur_iter >= Options.WidenDelay() then
10         prev_head_as := postAbsTrace[cycle.head];
11         handleSingletonWTO(cycle.head());
12         cur_head_as := postAbsTrace[cycle.head];
13         if increasing then
14           postAbsTrace[cycle.head] := prev_head_as.widening(cur_head_as);
15           if postAbsTrace[cycle.head] == prev_head_as then
16             increasing := false;
17             Continue;
18           else
19             postAbsTrace[cycle.head] := prev_head_as.narrowing(cur_head_as);
20             if postAbsTrace[cycle.head] == prev_head_as then
21               Break;
22         else
23           handleSingletonWTO(cycle.head());
24       cur_iter ++;
```

Widening and Narrowing

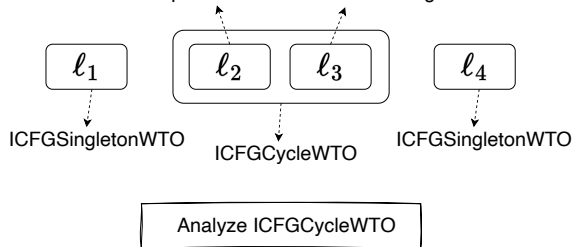


Algorithm 12: Handle Cycle WTO

```
1 Function handleCycleWTO(cycle):  
2   ... ;  
3   cycle_head := cycle→head()→node() ;  
4   increasing := true ;  
5   cur_iter := 0 ;  
6   while true do  
7     if cur_iter ≥ Options :: WidenDelay() then  
8       prev_head_state := postAbsTrace[cycle_head];  
9       handleSingletonWTO(cycle→head()) ;  
10      cur_head_state := postAbsTrace[cycle_head];  
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12        postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state) ;  
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15          continue ;  
16        else  
17          postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state) ;  
18          if postAbsTrace[cycle_head] == prev_head_state then  
19            break ;  
20      else  
21        handleSingletonWTO(cycle→head()) ;  
22      handleWTOComponents(cycle→getWTOComponents()) ;  
23      cur_iter++ ;
```


Widening and Narrowing

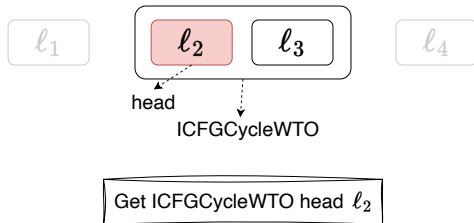
Sub WTO Components: each is an ICFGSingletonWTO



Algorithm 12: Handle Cycle WTO

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6   while true do  
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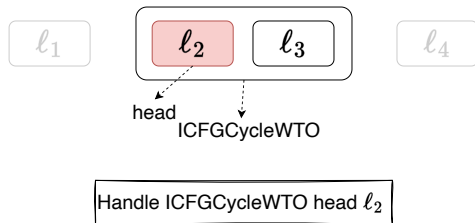
Weak Topological Order



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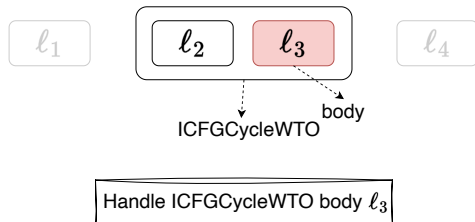
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Widening and Narrowing

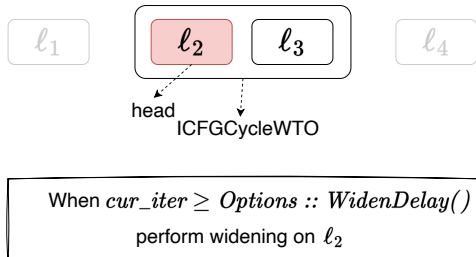


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```

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

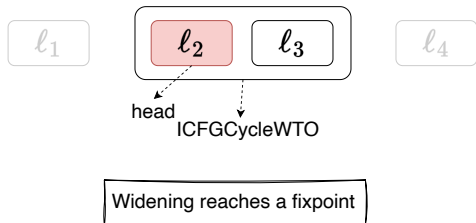
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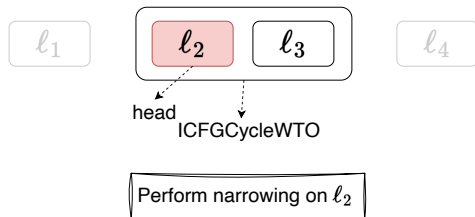
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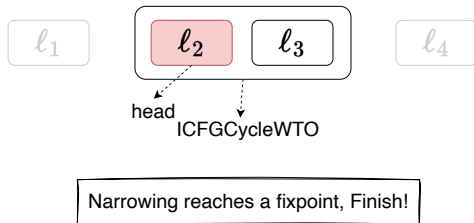
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Widening and Narrowing



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```


Abstract Interpretation on SVFIR

Week 9

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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 $p = \text{alloc}_o$) 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
CONSTMT	$\ell : p = c$
COPYSTMT	$\ell : p = q$
BINARYSTMT	$\ell : r = p \otimes q$
PHISTMT	$\ell : r = \text{phi}(p_1, p_2, \dots, p_n)$
SEQUENCE	$\ell_1; \ell_2$
BRANCHSTMT	$\ell_1 : \text{if}(x < c) \text{ then } \ell_2 \text{ else } \ell_3$

Abstract Interpretation on Pointer-Free SVFIR

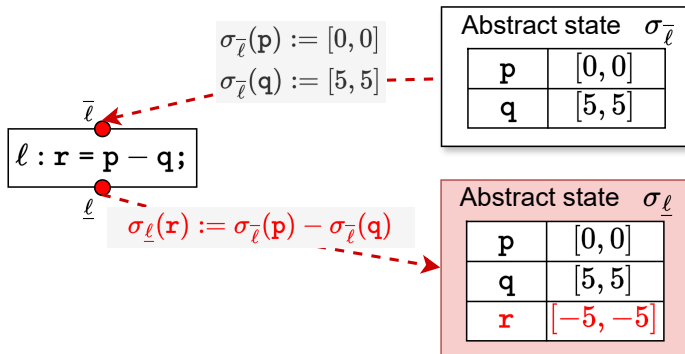
Interval Domain

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
CONSTMT	$\ell : p = c$	$\sigma_{\underline{\ell}}(p) := [c, c]$
COPYSTMT	$\ell : p = q$	$\sigma_{\underline{\ell}}(p) := \sigma_{\underline{\ell}}(q)$
BINARYSTMT	$\ell : r = p \otimes q$	$\sigma_{\underline{\ell}}(r) := \sigma_{\underline{\ell}}(p) \hat{\otimes} \sigma_{\underline{\ell}}(q)$
PHISTMT	$\ell : r = \text{phi}(p_1, p_2, \dots, p_n)$	$\sigma_{\underline{\ell}}(r) := \bigsqcup_{i=1}^n \sigma_{\underline{\ell}}(p_i)$
SEQUENCE	$\ell_1; \ell_2$	$\forall v \in \mathbb{V}, \sigma_{\underline{\ell}_2}(v) \supseteq \sigma_{\underline{\ell}_1}(v)$
BRANCHSTMT	$\ell_1 : \text{if}(x < c) \text{ then } \ell_2 \text{ else } \ell_3$	$\begin{aligned} \sigma_{\underline{\ell}_2}(x) &:= \sigma_{\underline{\ell}_1}(x) \sqcap [-\infty, c - 1], \text{ if } \sigma_{\underline{\ell}_1}(x) \sqcap [-\infty, c - 1] \neq \perp \\ \sigma_{\underline{\ell}_3}(x) &:= \sigma_{\underline{\ell}_1}(x) \sqcap [c, +\infty], \text{ if } \sigma_{\underline{\ell}_1}(x) \sqcap [c, +\infty] \neq \perp \end{aligned}$

Abstract Interpretation on BINARYSTMT

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

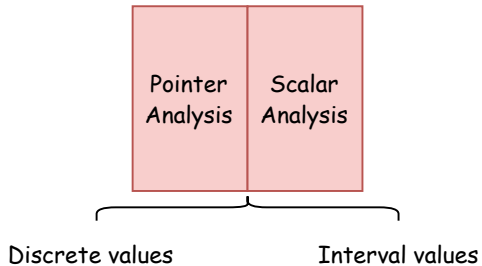


Abstract Interpretation in the Presence of Pointers

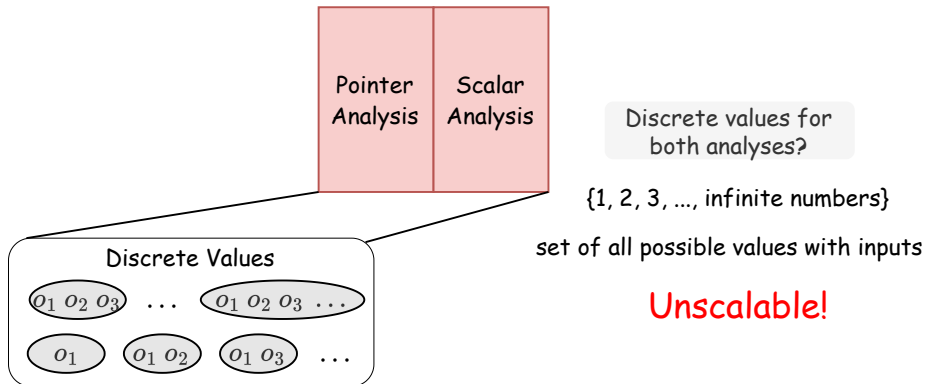
- SVFIR in the presence of pointers contain pointer-related statements including ADDRSTMT, GEPSTMT, LOADSTMT and STORESTMT.
- Abstract interpretation needs to be performed on **a combined domain of intervals and addresses**.

SVFSTMT	C-Like form
CONSTMT	$\ell : p = c$
COPYSTMT	$\ell : p = q$
BINARYSTMT	$\ell : r = p \otimes q$
PHISTMT	$\ell : r = \text{phi}(p_1, p_2, \dots, p_n)$
SEQUENCE	$\ell_1; \ell_2$
BRANCHSTMT	$\ell_1 : \text{if}(x < c) \text{ then } \ell_2 \text{ else } \ell_3$
ADDRSTMT	$\ell : p = \text{alloc}$
GEPSTMT	$\ell : p = \&(q \rightarrow i) \text{ or } p = \&q[i]$
LOADSTMT	$\ell : p = *q$
STORESTMT	$\ell : *p = q$

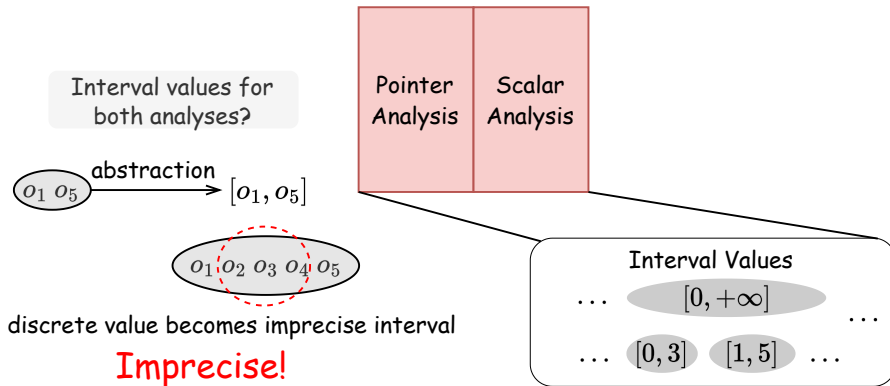
Combined Analysis



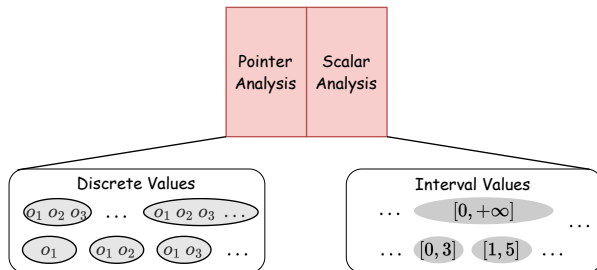
Combined Analysis Using Discrete Values



Combined Analysis Using Interval Values



Abstract Interpretation Over a Combined Domain



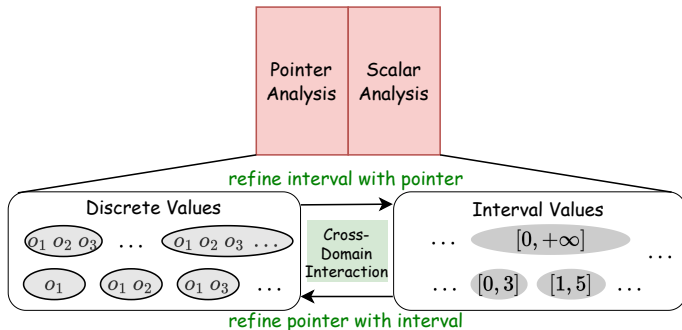
$p = \text{malloc}(\textcolor{red}{m} * \text{sizeof}(\text{int}));$ // p points to an array of size m

$q = \text{malloc}(n * \text{sizeof}(\text{int}));$ // q points to an array of size n

$\textcolor{red}{m} = r[\textcolor{blue}{i}];$

- 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 $\textcolor{blue}{blue}$ and $\textcolor{red}{red}$ denote the discrete values and interval values dependent),

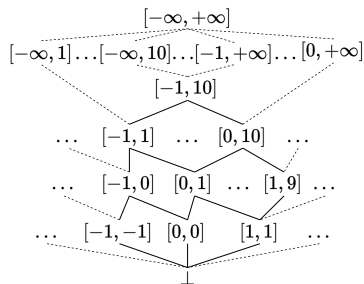
Abstract Interpretation Over a Combined Domain



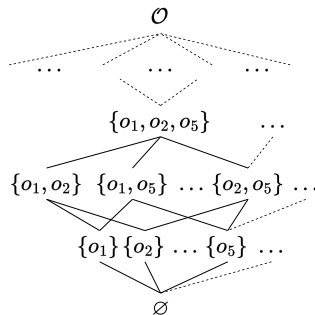
We require **a combination of interval and memory address domains** to precisely and efficiently perform abstract execution on SVFIR in the presence of pointers.

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	$\mathbf{o} \in (\mathbb{S} \cup \mathbb{G} \cup \mathbb{H})$	A single (base) memory object
GepObjVar	$\mathbf{o}_i \in (\mathbb{S} \cup \mathbb{G} \cup \mathbb{H}) \times \mathbb{P}$	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 $\sigma \in \mathbb{L} \times \mathbb{P} \rightarrow Interval \times MemAddress$ to track the memory addresses or interval values of these variables.
- For memory objects \mathbb{O} , we use $\delta \in \mathbb{L} \times \mathbb{O} \rightarrow Interval \times MemAddress$ to track their abstract values

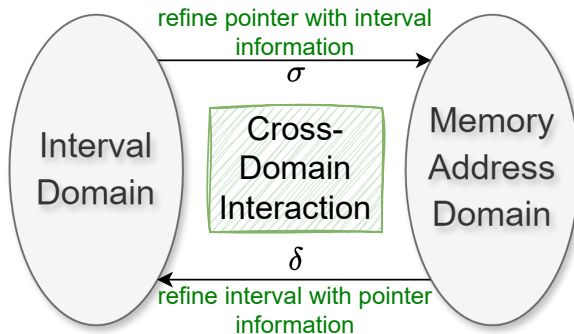
	Notation	Domain	Data Structure Implementation
Abstract trace	σ	$\mathbb{L} \times \mathbb{P} \rightarrow Interval \times MemAddress$	$preAbsTrace, postAbsTrace$
	δ	$\mathbb{L} \times \mathbb{O} \rightarrow Interval \times MemAddress$	
Abstract state	σ_L	$\mathbb{P} \rightarrow Interval \times MemAddress$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

- *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 Trace and State in Assignment-3

- For a program point L , the abstract state is an instance of class *AEState*, consisting of:
 - Top-level variable, *varToAbsVal* : $\sigma_L \in \mathbb{P} \rightarrow Interval \times MemAddress$
 - Memory object, *addrToAbsVal* : $\delta_L \in MemAddress \rightarrow Interval \times MemAddress$
- 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 $\langle \sigma_{\bar{\ell}}, \delta_{\bar{\ell}} \rangle$, and *postAbsTrace*(ℓ) represents $\langle \sigma_{\underline{\ell}}, \delta_{\underline{\ell}} \rangle$.
 - For each abstract state $\langle \sigma_{\bar{\ell}}, \delta_{\bar{\ell}} \rangle$ we use *as*[*varId*] to operate $\sigma_{\bar{\ell}}$ and use *storeValue* and *loadValue* to operate $\delta_{\bar{\ell}}$.
 - 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 an address set *as*[*VarId*].*getAddrs()*.
 - Print out *SVFVars* and their *AbstractValues* in an *AbstractState* by invoking *as.printAbstractState()*

Abstract Trace for The Combined Domain



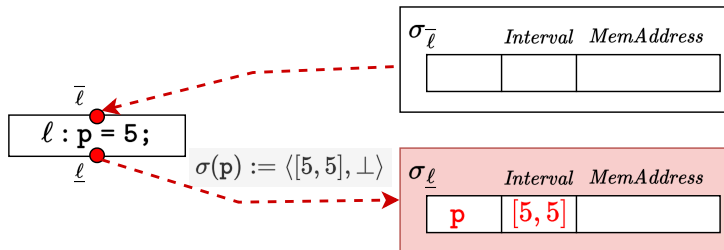
Abstract Execution Rules on SVFIR in the Presence of Pointers

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
CONSTSTMT	$\ell : p = c$	$\sigma_{\ell}(p) := \langle [c, c], \perp \rangle$
COPYSTMT	$\ell : p = q$	$\sigma_{\ell}(p) := \sigma_{\ell}(q)$
BINARYSTMT	$\ell : r = p \otimes q$	$\sigma_{\ell}(r) := \sigma_{\ell}(p) \hat{\otimes} \sigma_{\ell}(q)$
CMPSTMT	$\ell : r = p \odot q$	$\sigma_{\ell}(r) := \sigma_{\ell}(p) \hat{\odot} \sigma_{\ell}(q)$
PHISTMT	$\ell : r = \text{phi}(p_1, p_2, \dots, p_n)$	$\sigma_{\ell}(r) := \bigsqcup_{i=1}^n \sigma_{\ell}(p_i)$
BRANCHSTMT	$\ell_1 : \text{if}(x < c) \text{ then } \ell_2 \text{ else } \ell_3$	$\begin{aligned} \sigma_{\ell_2}(x) &:= \sigma_{\ell_1}(x) \sqcap [-\infty, c - 1], \text{ if } \sigma_{\ell_1}(x) \sqcap [-\infty, c - 1] \neq \perp \\ \sigma_{\ell_3}(x) &:= \sigma_{\ell_1}(x) \sqcap [c, +\infty], \text{ if } \sigma_{\ell_1}(x) \sqcap [c, +\infty] \neq \perp \end{aligned}$
SEQUENCE	$\ell_1; \ell_2$	$\delta_{\ell_2} \sqsupseteq \delta_{\ell_1}, \sigma_{\ell_2} \sqsupseteq \sigma_{\ell_1}$
ADDRSTMT	$\ell : p = \text{alloc}_{o_i}$	$\sigma_{\ell}(p) := \langle \perp, \{o_i\} \rangle$
GEPSTMT	$\ell : p = \&(q \rightarrow i) \text{ or } p = \&q[i]$	$\sigma_{\ell}(p) := \bigsqcup_{o \in \gamma(\sigma_{\ell}(q))} \bigsqcup_{j \in \gamma(\sigma_{\ell}(i))} \langle \perp, \{\text{offset}_j\} \rangle$
LOADSTMT	$\ell : p = *q$	$\sigma_{\ell}(p) := \bigsqcup_{o \in \{o \mid o \in \sigma_{\ell}(q)\}} \delta_{\ell}(o)$
STORESTMT	$\ell : *p = q$	$\delta_{\ell} := (\{o \mapsto \sigma_{\ell}(q) \mid o \in \gamma(\sigma_{\ell}(p))\}) \sqcup \delta_{\ell}$

Abstract Interpretation on CONSTMT

SVFSTMT	C-Like form	Abstract Execution Rule
CONSTMT	$\ell : p = c$	$\sigma_{\underline{\ell}}(p) := \langle [c, c], \perp \rangle$



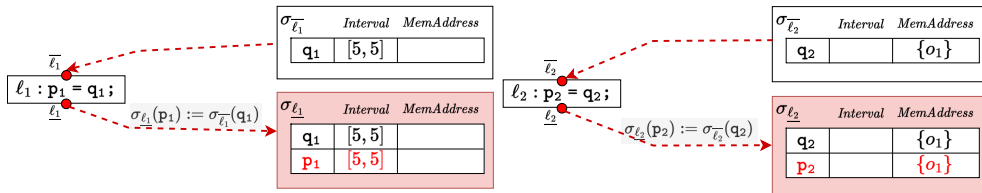
Algorithm 13: Abstract Execution Rule for CONSTMT

```

1 Function updateStateOnAddr(addr):
2   node = addr → getICFGNode();
3   as = getAbsStateFromTrace(node);
4   initObjVar(as, SVFUtil :: cast(ObjVar)(addr → getRHSVar()));
5   as[addr → getLHSVarID()] = as[addr → getRHSVarID()];
  
```

Abstract Interpretation on COPYSTMT

SVFSTMT	C-Like form	Abstract Execution Rule
COPYSTMT	$\ell : p = q$	$\sigma_{\underline{\ell}}(p) := \sigma_{\bar{\ell}}(q)$



Algorithm 14: Abstract Execution Rule for COPYSTMT

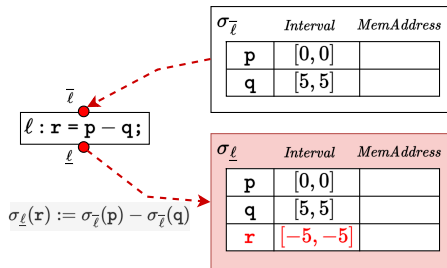
```

1 Function updateStateOnCopy(copy):
2   node = copy → getICFGNode();
3   as = getAbsStateFromTrace(node);
4   lhs = copy → getLHSVarID();
5   rhs = copy → getRHSVarID();
6   as[lhs] = as[rhs];

```

Abstract Interpretation on BINARYSTMT

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



Algorithm 15: Abstract Execution Rule for BINARYSTMT

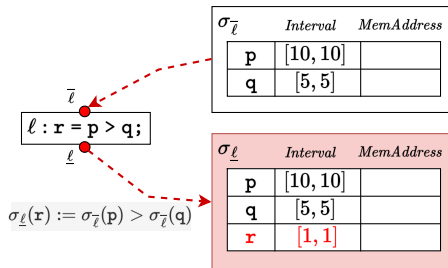
```

1 Function updateStateOnBinary(binary):
2   node = binary → getICFGNode();
3   as = getAbsStateFromTrace(node);
4   op0 = binary → getOpVarID(0);
5   op1 = binary → getOpVarID(1);
6   res = binary → getResID();
7   as[res] = as[op0]  $\hat{\otimes}$  as[op1]
  
```

Operands op0 and op1 are assumed to be properly initialized (no uninitialized variables or randomization).

Abstract Interpretation on CMPSTMT

SVFSTMT	C-Like form	Abstract Execution Rule
CMPSTMT	$\ell : r = p \odot q$	$\sigma_{\underline{\ell}}(r) := \sigma_{\bar{\ell}}(p) \hat{\odot} \sigma_{\bar{\ell}}(q)$



Algorithm 16: Abstract Execution Rule for CMPSTMT

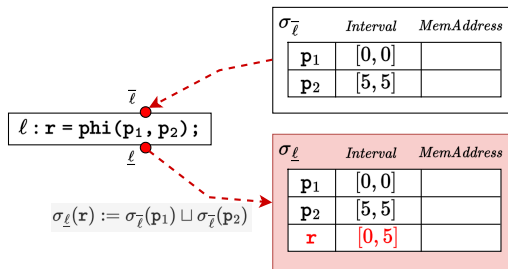
```

1 Function updateStateOnCmp(cmp):
2   node = cmp → getICFGNode();
3   as = getAbsStateFromTrace(node);
4   op0 = cmp → getOpVarID(0);
5   op1 = cmp → getOpVarID(1);
6   res = cmp → getResID();
7   as[res] = as[op0]  $\hat{\odot}$  as[op1]
  
```

Operands op0 and op1 are assumed to be properly initialized (no uninitialized variables or randomization).

Abstract Interpretation on PHISTMT

SVFSTMT	C-Like form	Abstract Execution Rule
PHISTMT	$\ell : r = \text{phi}(p_1, p_2, \dots, p_n)$	$\sigma_{\underline{\ell}}(r) := \bigsqcup_{i=1}^n \sigma_{\bar{\ell}}(p_i)$



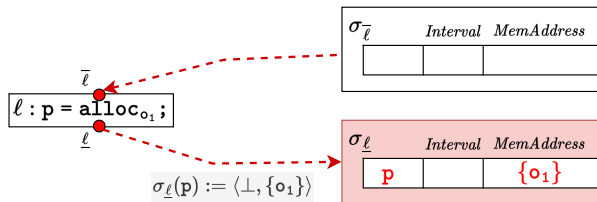
Algorithm 17: Abstract Execution Rule for PHISTMT

```

1 Function updateStateOnPhi(phi):
2   node = phi → getICFGNode();
3   as = getAbsStateFromTrace(node);
4   res = phi → getResID();
5   rhs = AbstractValue();
6   for i = 0; i < phi → getOpVarNum(); i ++ do
7     curId = phi → getOpVarID(i);
8     rhs.join_with(as[curId])
9   as[res] = rhs
    
```

Abstract Interpretation on ADDRSTMT

SVFSTMT	C-Like form	Abstract Execution Rule
ADDRSTMT	$\ell : p = \text{alloc}_{o_1}$	$\sigma_{\underline{\ell}}(p) := \langle \perp, \{o_1\} \rangle$



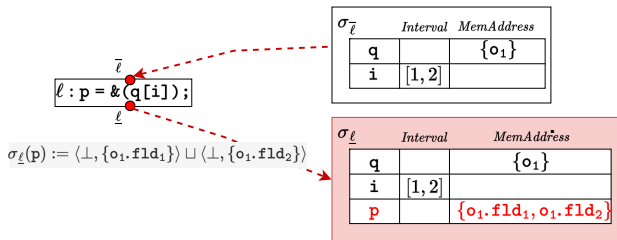
Algorithm 18: Abstract Execution Rule for ADDRSTMT

```

1 Function updateStateOnAddr(addr):
2   node = addr → getICFGNode();
3   as = getAbsStateFromTrace(node);
4   initObjVar(as, SVFUtil :: cast<ObjVar>(addr → getRHSVar()));
5   as[addr → getLHSVarID()] = as[addr → getRHSVarID()];
  
```

Abstract Interpretation on GEPSTMT

SVFSTMT	C-Like form	Abstract Execution Rule
GEPSTMT	$\ell : p = \&(q \rightarrow i) \text{ or } p = \&q[i]$	$\sigma_{\underline{\ell}}(p) := \bigsqcup_{o \in \gamma(\sigma_{\underline{\ell}}(q))} \bigsqcup_{j \in \gamma(\sigma_{\underline{\ell}}(i))} \langle \perp, \{o.fld_j\} \rangle$



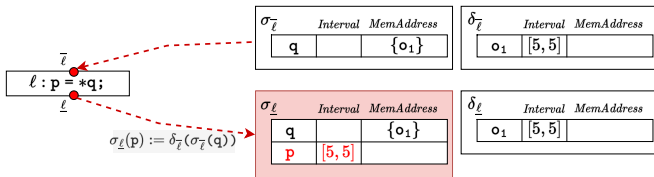
Algorithm 19: Abstract Execution Rule for GEPSTMT

```

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

Abstract Interpretation on LOADSTMT

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



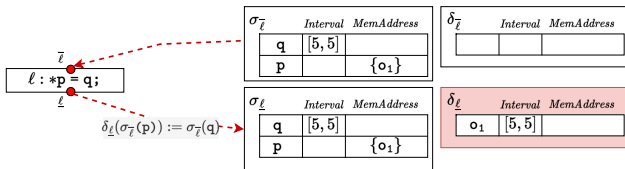
Algorithm 20: Abstract Execution Rule for LOADSTMT

```

1 Function updateStateOnLoad(load):
2   node = load → getICFGNode();
3   as = getAbsStateFromTrace(node);
4   rhs = load → getRHSVarID();
5   lhs = load → getLHSVarID();
6   as[lhs] = as.loadValue(rhs)
  
```


Abstract Interpretation on STORESTMT

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



Algorithm 21: Abstract Execution Rule for STORESTMT

```

1 Function updateStateOnStore(store):
2   node = store → getICFGNode();
3   as = getAbsStateFromTrace(node);
4   rhs = store → getRHSVarID();
5   lhs = store → getLHSVarID();
6   as.storeValue(lhs, as[rhs])
  
```

An Example: Abstract Trace σ for Top-level Variables

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

Source Code

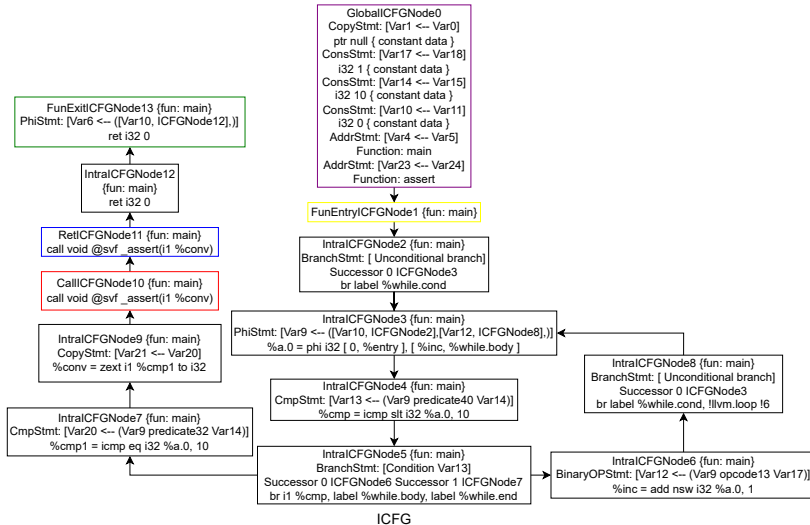
Compile to LLVM IR



```
define dso_local i32 @main() {  
entry:  
    br label %while.cond  
while.cond:  
    %a.0 = phi i32 [ 0, %entry ], [ %inc, %while.body ]  
    %cmp = icmp slt i32 %a.0, 10  
    br i1 %cmp, label %while.body, label %while.end  
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  
}
```

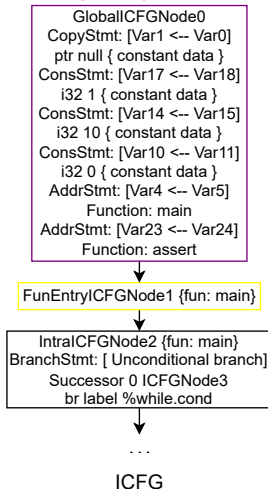
LLVM IR

An Example: Abstract Trace σ for Top-level Variables



An Example: Abstract Trace σ for Top-level Variables

Before Entering Loop



Algorithm 22: Abstract execution guided by WTO

```
1 Function handleStatement( $\ell$ ):  
2   tmpAS := preAbsTrace[ $\ell$ ];  
3   if  $\ell$  is CONSTMT or ADDRSTMT then  
4     updateStateOnAddr( $\ell$ );  
5   else if  $\ell$  is COPYSTMT then  
6     updateStateOnCopy( $\ell$ );  
7   ...;
```

postAbsTrace[ICFGNode0].varToAbsVal :

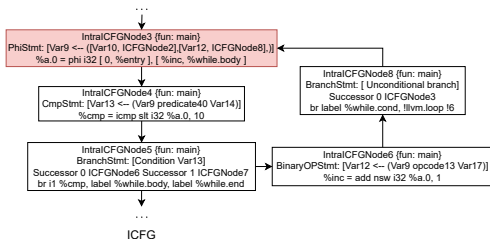
SVFVar	AbstractValue(<i>Interval</i> , <i>MemAddress</i>)
Var0	$\langle \perp, \{0x7f00\} \rangle$
Var1	$\langle \perp, \{0x7f00\} \rangle$
Var18	$\langle [1, 1], \perp \rangle$
Var17	$\langle [1, 1], \perp \rangle$
Var14	$\langle [10, 10], \perp \rangle$
Var15	$\langle [10, 10], \perp \rangle$
Var10	$\langle [0, 0], \perp \rangle$
Var11	$\langle [0, 0], \perp \rangle$

...

Print out the table via `as.printAbstractState()`. The AbstractValue can **either be an interval or addresses**, but not both!

An Example: Abstract Trace σ for Top-level Variables

Widen Delay Phase (cur_iter is 0)



$postAbsTrace[ICFGNode3].varToAbsVal$:

SVFVar	AbstractValue<Interval, MemAddress>
...	...
Var10	$\langle [0, 0], \perp \rangle$
Var9	$\langle [0, 0], \perp \rangle$
...	...

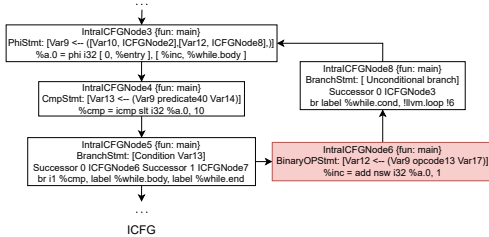
Algorithm 12: Handle Cycle WTO

```

1 Function handleCycleWTO(cycle):
2   cycle_head := cycle→head()→node();
3   increasing := true;
4   cur_iter := 0;
5   while true do
6     // cur_iter == 0, Options :: WidenDelay() == 2
7     if cur_iter ≥ Options :: WidenDelay() then
8       prev_head_state := postAbsTrace[cycle_head];
9       handleSingletonWTO(cycle→head());
10      cur_head_state := postAbsTrace[cycle_head];
11      if increasing then
12        postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state);
13        if postAbsTrace[cycle_head] == prev_head_state then
14          increasing := false;
15          continue;
16      else
17        postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state);
18        if postAbsTrace[cycle_head] == prev_head_state then
19          break;
20      else
21        handleSingletonWTO(cycle→head());
22      handleWTOComponents(cycle→getWTOComponents());
23      cur_iter++;
    
```

An Example: Abstract Trace σ for Top-level Variables

Widen Delay Phase (cur_iter is 0)



$postAbsTrace[ICFGNode6].varToAbsVal :$

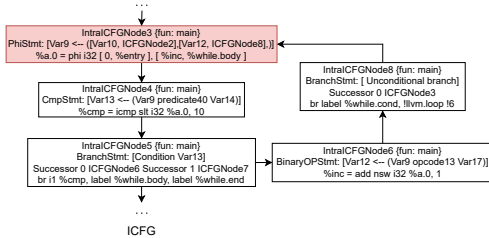
SVFVar	AbstractValue<Interval, MemAddress>
...	
Var10	$\langle [0, 0], \perp \rangle$
Var9	$\langle [0, 0], \perp \rangle$
Var12	$\langle [1, 1], \perp \rangle$
...	

Algorithm 12: Handle Cycle WTO

```
1 Function handleCycleWTO(cycle):
2   cycle_head := cycle → head() → node();
3   increasing := true;
4   cur_iter := 0;
5   while true do
6     // cur_iter ≡ 0. Options :: WidenDelay() ≡ 2;
7     if cur_iter ≥ Options :: WidenDelay() then
8       prev_head_state := postAbsTrace[cycle_head];
9       handleSingletonWTO(cycle → head());
10      cur_head_state := postAbsTrace[cycle_head];
11      if increasing then
12        postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state);
13        if postAbsTrace[cycle_head] == prev_head_state then
14          increasing := false;
15          continue;
16      else
17        postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state);
18        if postAbsTrace[cycle_head] == prev_head_state then
19          break;
20    else
21      handleSingletonWTO(cycle → head());
22    handleWTOComponents(cycle → getWTOComponents());
23    cur_iter++;
```

An Example: Abstract Trace σ for Top-level Variables

Widen Delay Phase (cur_iter is 1)



$postAbsTrace[ICFGNode3].varToAbsVal$:

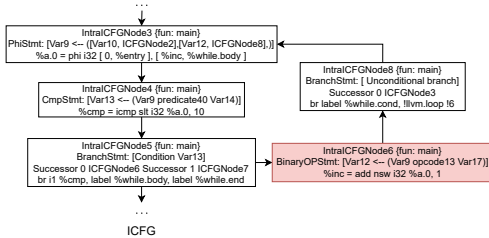
SVFVar	AbstractValue<Interval, MemAddress>
...	
Var9	$\langle [0, 1], \perp \rangle$
Var12	$\langle [1, 1], \perp \rangle$
...	

Algorithm 12: Handle Cycle WTO

```
1 Function handleCycleWTO(cycle):
2   cycle_head := cycle → head() → node();
3   increasing := true;
4   cur_iter := 0;
5   while true do
6     // cur_iter == 1, Options :: WidenDelay() == 2;
7     if cur_iter ≥ Options :: WidenDelay() then
8       prev_head_state := postAbsTrace[cycle_head];
9       handleSingletonWTO(cycle → head());
10      cur_head_state := postAbsTrace[cycle_head];
11      if increasing then
12        postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state);
13        if postAbsTrace[cycle_head] == prev_head_state then
14          increasing := false;
15          continue;
16      else
17        postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state);
18        if postAbsTrace[cycle_head] == prev_head_state then
19          break;
20    else
21      handleSingletonWTO(cycle → head());
22  handleWTOComponents(cycle → getWTOComponents());
23  cur_iter++;
```

An Example: Abstract Trace σ for Top-level Variables

Widen Delay Phase (cur_iter is 1)



$postAbsTrace[ICFGNode6].varToAbsVal$:

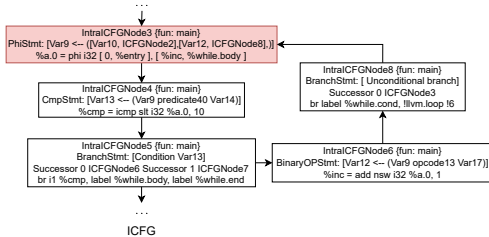
SVFVar	AbstractValue<Interval, MemAddress>
...	
Var9	$\langle [0, 1], \perp \rangle$
Var12	$\langle [1, 2], \perp \rangle$
...	

Algorithm 12: Handle Cycle WTO

```
1 Function handleCycleWTO(cycle):
2   cycle_head := cycle → head() → node();
3   increasing := true;
4   cur_iter := 0;
5   while true do
6     // cur_iter ≡ 1, Options :: WidenDelay() ≡ 2;
7     if cur_iter ≥ Options :: WidenDelay() then
8       prev_head_state := postAbsTrace[cycle_head];
9       handleSingletonWTO(cycle → head());
10      cur_head_state := postAbsTrace[cycle_head];
11      if increasing then
12        postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state);
13        if postAbsTrace[cycle_head] == prev_head_state then
14          increasing := false;
15          continue;
16      else
17        postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state);
18        if postAbsTrace[cycle_head] == prev_head_state then
19          break;
20    else
21      handleSingletonWTO(cycle → head());
22    handleWTOComponents(cycle → getWTOComponents());
23    cur_iter++;
```


An Example: Abstract Trace σ for Top-level Variables

Widen Phase (cur_iter is 2)



$postAbsTrace[ICFGNode3].varToAbsVal :$

SVFVar	$\langle Interval, MemAddress \rangle$
...	...
Var9	$\langle [0, +\infty], \perp \rangle$
Var12	$\langle [1, +\infty], \perp \rangle$
...	...

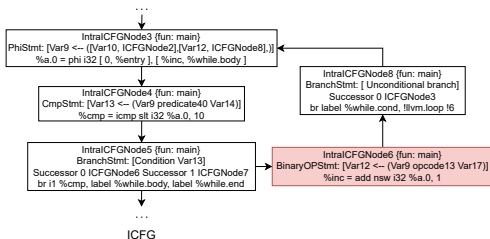
Algorithm 12: Handle Cycle WTO

```

1  Function handleCycleWTO(cycle):
2      cycle_head := cycle → head() → node();
3      increasing := true;
4      cur_iter := 0;
5      while true do
6          // cur_iter ≡ 2, Options :: WidenDelay() ≡ 2
7          if cur_iter ≥ Options :: WidenDelay() then
8              prev_head_state := postAbsTrace[cycle_head];
9              handleSingletonWTO(cycle → head());
10             cur_head_state := postAbsTrace[cycle_head];
11             if increasing then
12                 postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state);
13                 if postAbsTrace[cycle_head] == prev_head_state then
14                     increasing := false;
15                     continue;
16             else
17                 postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state);
18                 if postAbsTrace[cycle_head] == prev_head_state then
19                     break;
20             else
21                 handleSingletonWTO(cycle → head());
22             handleWTOComponents(cycle → getWTOComponents());
23             cur_iter++;
    
```

An Example: Abstract Trace σ for Top-level Variables

Widen Phase (cur_iter is 2)



$postAbsTrace[ICFGNode6].varToAbsVal$:

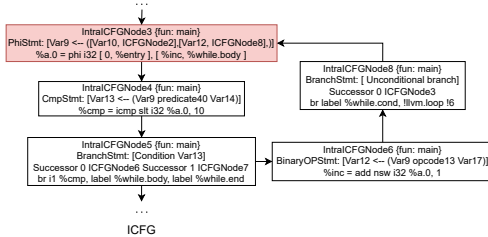
SVFVar	AbstractValue<Interval, MemAddress>
...	
Var9	$\langle [0, 9], \perp \rangle$
Var12	$\langle [1, 10], \perp \rangle$
...	

Algorithm 12: Handle Cycle WTO

```
1 Function handleCycleWTO( $cycle$ ):
2    $cycle\_head := cycle \rightarrow head() \rightarrow node()$ ;
3    $increasing := true$ ;
4    $cur\_iter := 0$ ;
5   while true do
6     //  $cur\_iter \equiv 2$ , Options :: WidenDelay() = 2
7     if  $cur\_iter \geq Options :: WidenDelay()$  then
8        $prev\_head\_state := postAbsTrace[cycle\_head]$ ;
9        $handleSingletonWTO(cycle \rightarrow head())$ ;
10       $cur\_head\_state := postAbsTrace[cycle\_head]$ ;
11      if increasing then
12         $postAbsTrace[cycle\_head] := prev\_head\_state.widen(cur\_head\_state)$ ;
13        if  $postAbsTrace[cycle\_head] == prev\_head\_state$  then
14           $increasing := false$ ;
15          continue;
16      else
17         $postAbsTrace[cycle\_head] := prev\_head\_state.narrow(cur\_head\_state)$ ;
18        if  $postAbsTrace[cycle\_head] == prev\_head\_state$  then
19          break;
20    else
21       $handleSingletonWTO(cycle \rightarrow head())$ ;
22     $handleWTOComponents(cycle \rightarrow getWTOComponents())$ 
23     $cur\_iter++$ ;
```

An Example: Abstract Trace σ for Top-level Variables

Widen Phase Fixed Point



$postAbsTrace[ICFGNode3].varToAbsVal :$

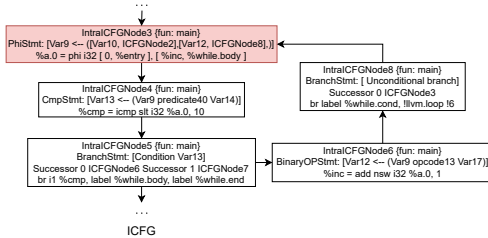
SVFVar	$\langle Interval, MemAddress \rangle$
...	...
Var9	$\langle [0, +\infty], \perp \rangle$
Var12	$\langle [1, +\infty], \perp \rangle$
...	...

Algorithm 12: Handle Cycle WTO

```
1 Function handleCycleWTO(cycle):
2   cycle_head := cycle → head() → node();
3   increasing := true;
4   cur_iter := 0;
5   while true do
6     // cur_iter  $\equiv$  3, Options :: WidenDelay()  $\equiv$  2
7     if cur_iter  $\geq$  Options :: WidenDelay() then
8       prev_head_state := postAbsTrace[cycle_head];
9       handleSingletonWTO(cycle → head());
10      cur_head_state := postAbsTrace[cycle_head];
11      if increasing then
12        postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state);
13        if postAbsTrace[cycle_head] == prev_head_state then
14          increasing := false;
15          continue;
16      else
17        postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state);
18        if postAbsTrace[cycle_head] == prev_head_state then
19          break;
20      else
21        handleSingletonWTO(cycle → head());
22      handleWTOComponents(cycle → getWTOComponents());
23      cur_iter++;
```

An Example: Abstract Trace σ for Top-level Variables

Narrow Phase



$postAbsTrace[ICFGNode3].varToAbsVal :$

SVFVar	$\langle Interval, MemAddress \rangle$
...	...
<i>Var9</i>	$\langle [0, 10], \perp \rangle$
<i>Var12</i>	$\langle [1, 10], \perp \rangle$
...	...

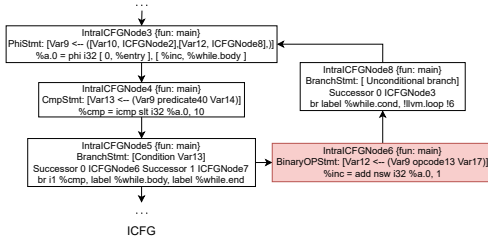
Algorithm 12: Handle Cycle WTO

```

1 Function handleCycleWTO(cycle):
2   cycle_head := cycle → head() → node();
3   increasing := true;
4   cur_iter := 0;
5   while true do
6     // cur_iter ≡ 3, Options :: WidenDelay() ≡ 2
7     if cur_iter ≥ Options :: WidenDelay() then
8       prev_head_state := postAbsTrace[cycle_head];
9       handleSingletonWTO(cycle → head()) // increasing ≡ false;
10      cur_head_state := postAbsTrace[cycle_head];
11      if increasing then
12        postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state);
13        if postAbsTrace[cycle_head] == prev_head_state then
14          increasing := false;
15          continue;
16      else
17        postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state);
18        if postAbsTrace[cycle_head] == prev_head_state then
19          break;
20      else
21        handleSingletonWTO(cycle → head());
22      handleWTOComponents(cycle → getWTOComponents());
23      cur_iter++;
  
```

An Example: Abstract Trace σ for Top-level Variables

Narrow Phase



$postAbsTrace[ICFGNode6].varToAbsVal :$

SVFVar	$\langle Interval, MemAddress \rangle$
...	...
Var9	$\langle [0, 9], \perp \rangle$
Var12	$\langle [1, 10], \perp \rangle$
...	...

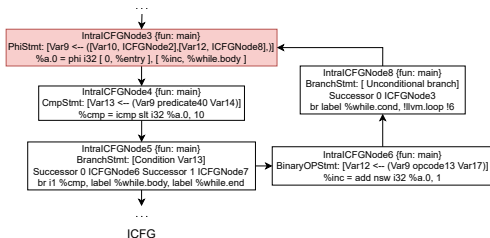
Algorithm 12: Handle Cycle WTO

```

1 Function handleCycleWTO(cycle):
2   cycle_head := cycle → head() → node();
3   increasing := true;
4   cur_iter := 0;
5   while true do
6     // cur_iter ≡ 3, Options :: WidenDelay() = 2
7     if cur_iter ≥ Options :: WidenDelay() then
8       prev_head_state := postAbsTrace[cycle_head];
9       handleSingletonWTO(cycle → head());
10      cur_head_state := postAbsTrace[cycle_head];
11      if increasing then
12        postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state);
13        if postAbsTrace[cycle_head] == prev_head_state then
14          increasing := false;
15          continue;
16      else
17        postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state);
18        if postAbsTrace[cycle_head] == prev_head_state then
19          break;
20    else
21      handleSingletonWTO(cycle → head());
22    handleWTOComponents(cycle → getWTOComponents());
23    cur_iter++;
  
```

An Example: Abstract Trace σ for Top-level Variables

Narrow Phase Fixed Point



$postAbsTrace[ICFGNode3].varToAbsVal :$

SVFVar	$\langle Interval, MemAddress \rangle$
...	...
Var9	$\langle [0, 10], \perp \rangle$
Var12	$\langle [1, 10], \perp \rangle$
...	...

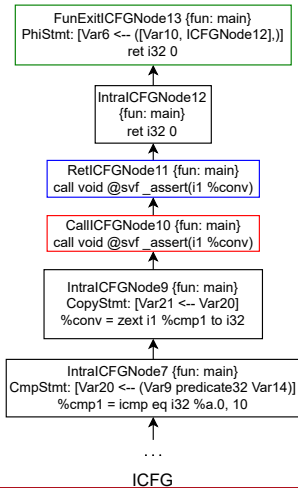
Algorithm 12: Handle Cycle WTO

```

1 Function handleCycleWTO(cycle):
2   cycle_head := cycle → head() → node();
3   increasing := true;
4   cur_iter := 0;
5   while true do
6     // cur_iter == 4, Options :: WidenDelay() == 2
7     if cur_iter ≥ Options :: WidenDelay() then
8       prev_head_state := postAbsTrace[cycle_head];
9       handleSingletonWTO(cycle → head()) // increasing == false;
10      cur_head_state := postAbsTrace[cycle_head];
11      if increasing then
12        postAbsTrace[cycle_head] := prev_head_state.widen(cur_head_state);
13        if postAbsTrace[cycle_head] == prev_head_state then
14          increasing := false;
15          continue;
16      else
17        postAbsTrace[cycle_head] := prev_head_state.narrow(cur_head_state);
18        if postAbsTrace[cycle_head] == prev_head_state then
19          break;
20      else
21        handleSingletonWTO(cycle → head());
22      handleWTOComponents(cycle → getWTOComponents());
23      cur_iter++;
  
```

An Example: Abstract Trace σ for Top-level Variables

After Exiting Loop



Algorithm 13: Abstract execution guided by WTO

```

1 Function handleStatement( $\ell$ ):
2    $tmpAS := preAbsTrace[\ell]$ ;
3   if  $\ell$  is CMPSTMT then
4      $updateStateOnCmp(\ell)$ ;
5   ...;
  
```

$postAbsTrace[ICFGNode7].varToAbsVal :$

SVFVar	$\langle Interval, MemAddress \rangle$
...	
$Var9$	$\langle [10, 10], \perp \rangle$
$Var20$	$\langle [1, 1], \perp \rangle$
...	