

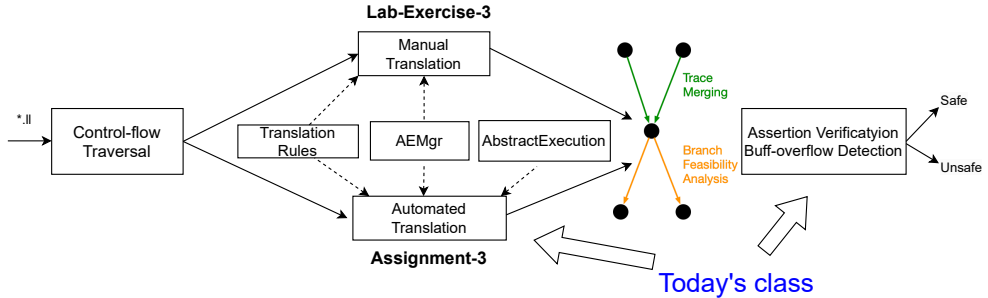
Abstract Interpretation for Code Analysis and Verification

(Week 9)

Yulei Sui

School of Computer Science and Engineering
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

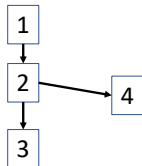
? How to analyze a program **free of loop**?

✓ 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.

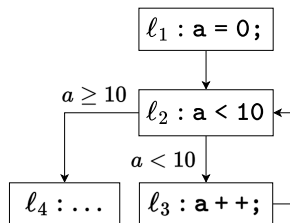
Weak Topological Order

Analysis Order of Nodes on Control-Flow Graph

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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

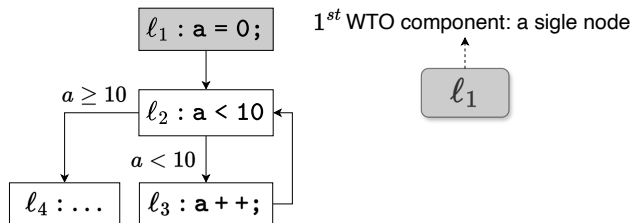
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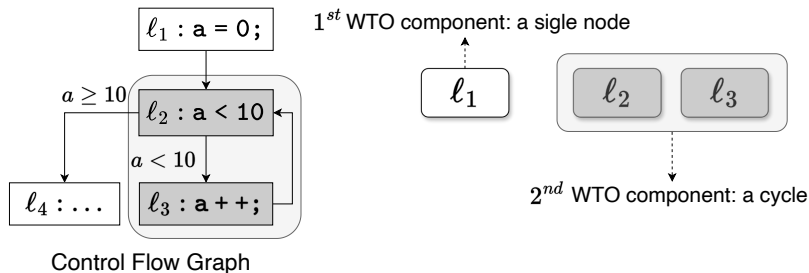
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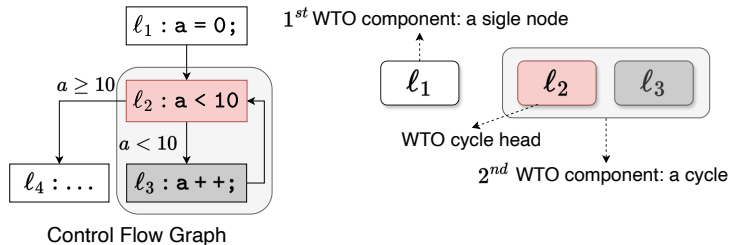
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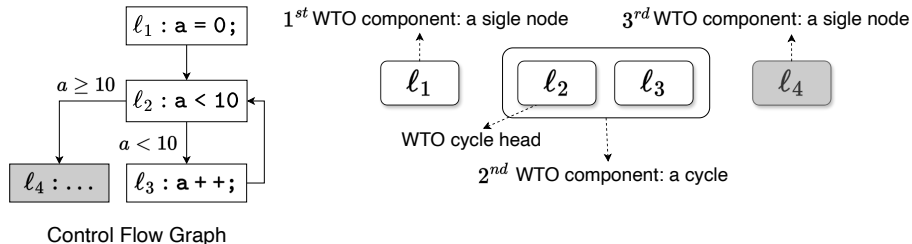
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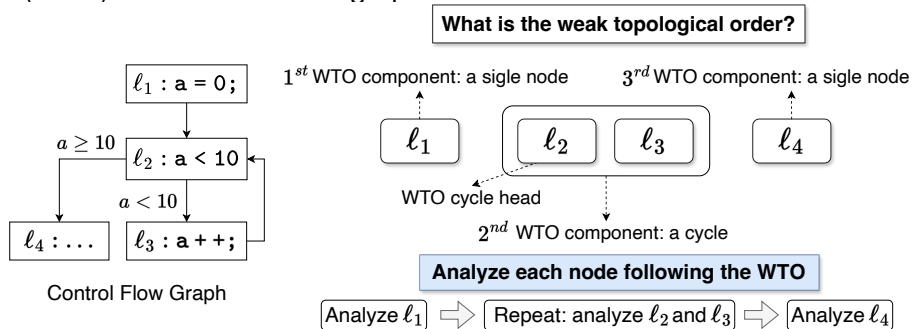


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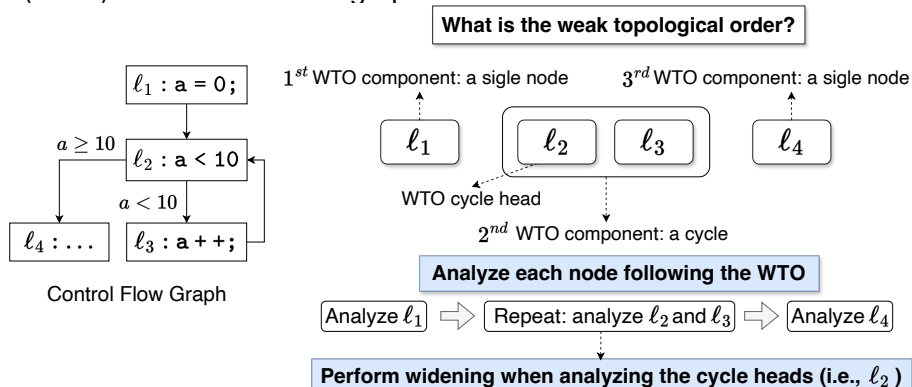


Weak Topological Order

Analysis Order of Nodes on Control-Flow Graph

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WTO, Widening and Narrowing

Why Weak Topological Order?

- Handling cyclic dependencies
- Efficient fixed-point computation

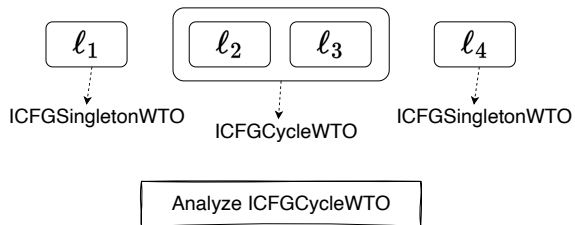
Why Widening?

- 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

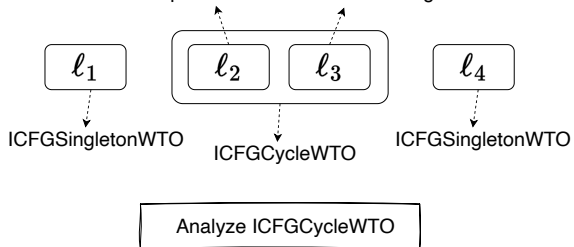


Algorithm 12: Handle Cycle WTO

```
1 Function handleCycleWTO(cycle):  
2   cycle_head := cycle → head() → node();  
3   increasing := true;  
4   cur_iter := 0;  
5   while true do  
6     if cur_iter ≥ Options :: WidenDelay() then  
7       prev_head_state := postAbsTrace[cycle_head];  
8       handleICFGNode(cycle → head());  
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Widening and Narrowing

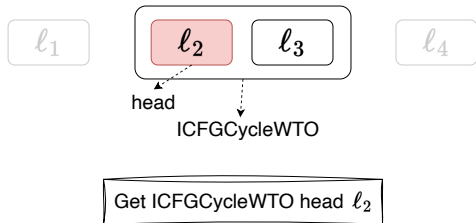
Sub WTO Components: each is an ICFGSingletonWTO



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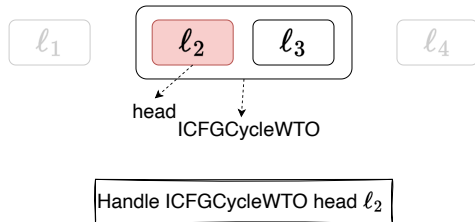
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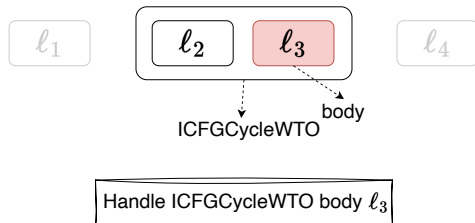

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Widening and Narrowing

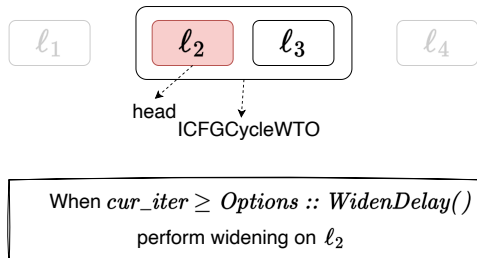


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Note: getWTOComponents returns Cycle WTO body, i.e., ℓ_3

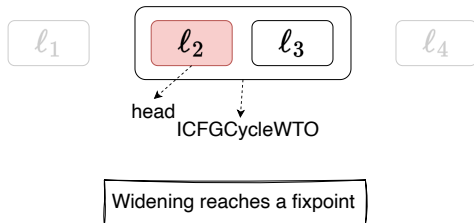
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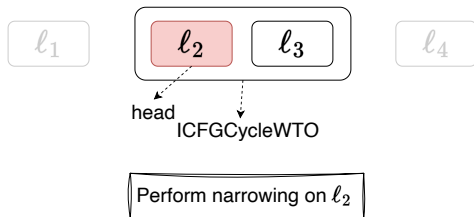
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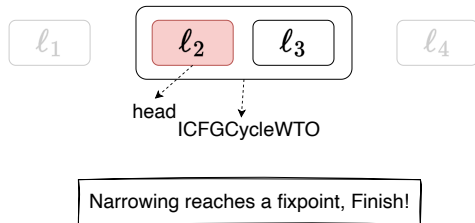
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Abstract Interpretation on SVFIR

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

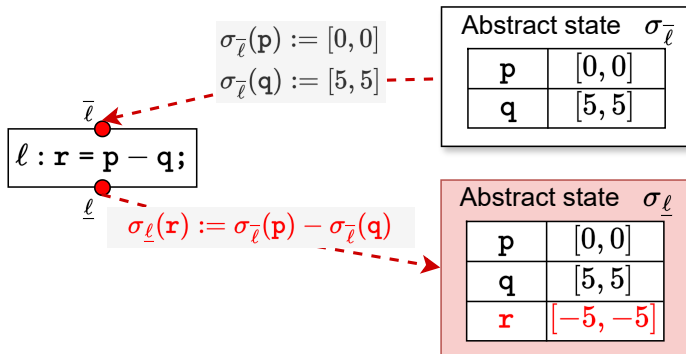
Interval Domain

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	$\ell_1 : \text{if}(x < c) \text{ then } \ell_2 \text{ else } \ell_3$	$\sigma_{\underline{\ell}_2}(x) := \sigma_{\underline{\ell}_1}(x) \sqcap [-\infty, c - 1], \text{ if } \sigma_{\underline{\ell}_1}(x) \sqcap [-\infty, c - 1] \neq \perp$ $\sigma_{\underline{\ell}_3}(x) := \sigma_{\underline{\ell}_1}(x) \sqcap [c, +\infty], \text{ if } \sigma_{\underline{\ell}_1}(x) \sqcap [c, +\infty] \neq \perp$

Abstract Interpretation on BINARYSTMT

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

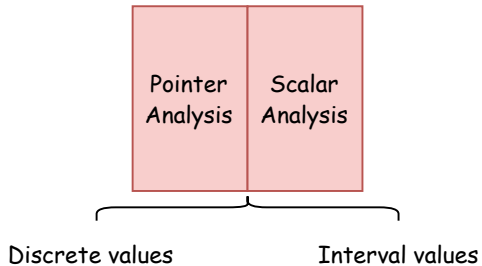


Abstract Interpretation in the Presence of Pointers

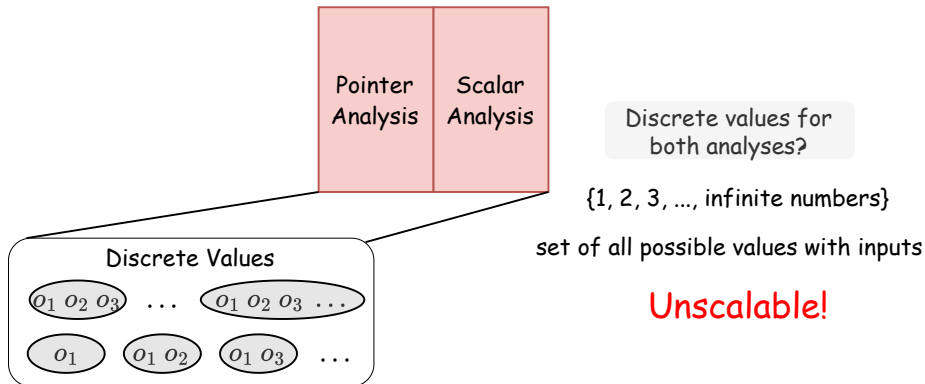
- SVFIR in the presence of pointers contain pointer-related statements including ADDRSTMT, GEPSTMT, LOADSTMT and STORESTMT.
- Abstract interpretation needs to be performed on **a combined domain of intervals and addresses**.

SVFSTMT	C-Like form
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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	$\ell : *p = q$

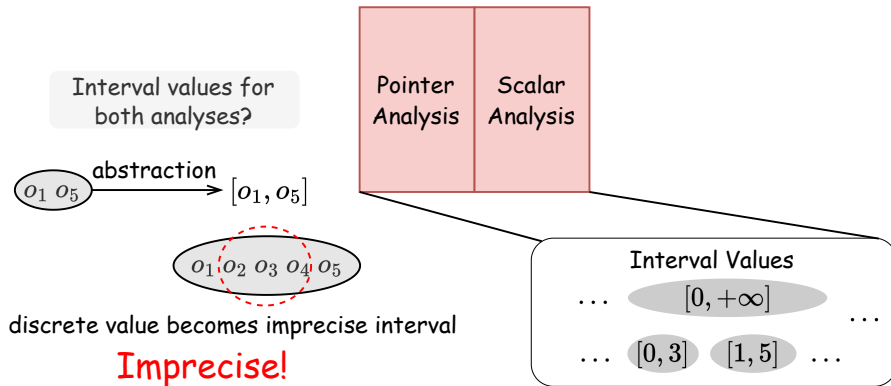
Combined Analysis



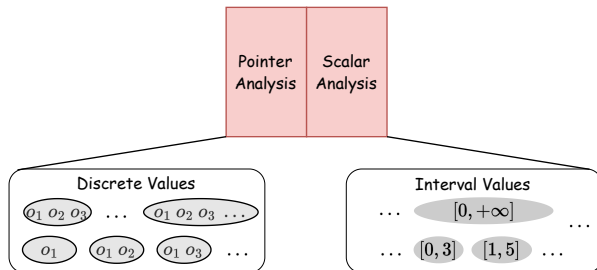
Combined Analysis Using Discrete Values



Combined Analysis Using Interval Values



Abstract Interpretation Over a Combined Domain



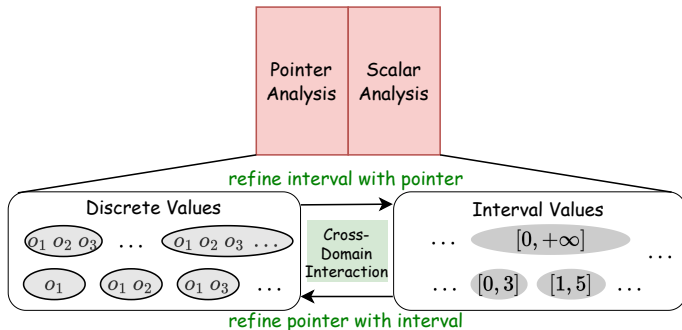
$p = \text{malloc}(\textcolor{blue}{m} * \text{sizeof}(\text{int}));$ // p points to an array of size m

$q = \text{malloc}(n * \text{sizeof}(\text{int}));$ // 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),

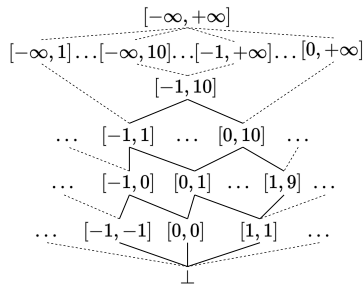
Abstract Interpretation Over a Combined Domain



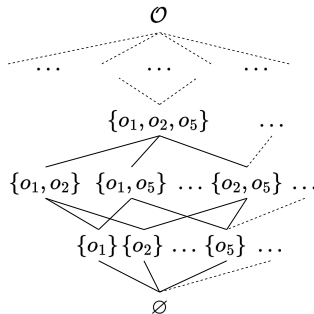
We require **a combination of interval and memory address domains** to precisely and efficiently perform abstract execution on SVFIR in the presence of pointers.

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

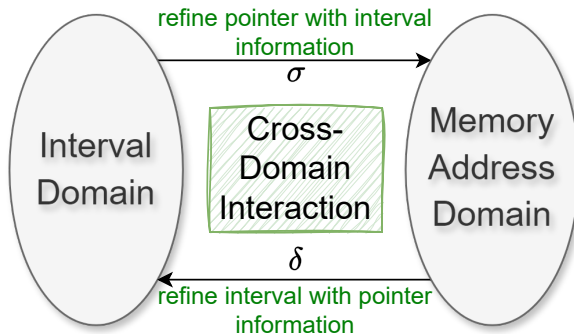
	Notation	Domain	Data Structure Implementation
Abstract trace	σ	$\mathbb{L} \times \mathbb{P} \rightarrow Interval \times MemAddress$	$preAbsTrace, postAbsTrace$
	δ	$\mathbb{L} \times \mathbb{O} \rightarrow Interval \times MemAddress$	
Abstract state	σ_L	$\mathbb{P} \rightarrow Interval \times MemAddress$	$AbstractState.varToAbsVal$
	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



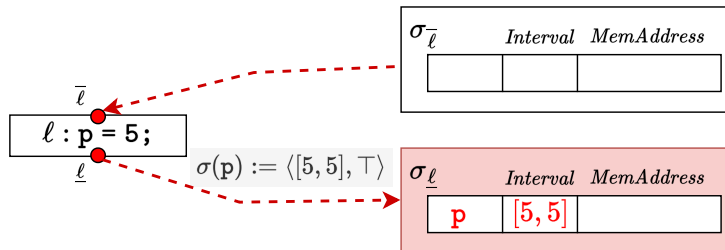
Abstract Execution Rules on SVFIR in the Presence of Pointers

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
CONSTMT	$\ell : p = c$	$\sigma_{\ell}(p) := \langle [c, c], \perp \rangle$
COPYSTMT	$\ell : p = q$	$\sigma_{\ell}(p) := \sigma_{\ell}(q)$
BINARYSTMT	$\ell : r = p \otimes q$	$\sigma_{\ell}(r) := \sigma_{\ell}(p) \hat{\otimes} \sigma_{\ell}(q)$
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	$\ell : p = \text{alloc}_{o_i}$	$\sigma_{\ell}(p) := \langle \top, \{o_i\} \rangle$
GEPSTMT	$\ell : p = \&(q \rightarrow i) \text{ or } p = \&q[i]$	$\sigma_{\ell}(p) := \bigsqcup_{o \in \gamma(\sigma_{\ell}(q))} \bigsqcup_{j \in \gamma(\sigma_{\ell}(i))} \langle \top, \{o.\text{fld}_j\} \rangle$
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 Execution on CONSTMT

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



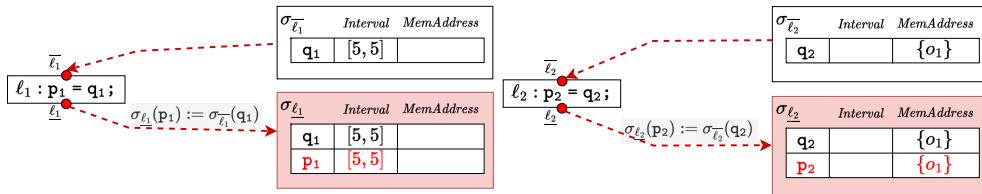
Algorithm 13: Abstract Execution Rule for CONSTMT

```

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 Execution 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

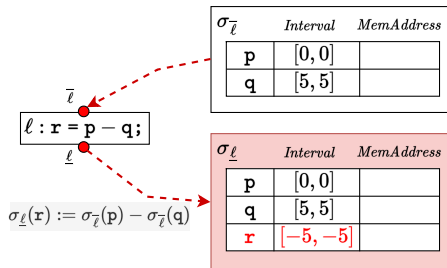
```

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 Execution 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

```

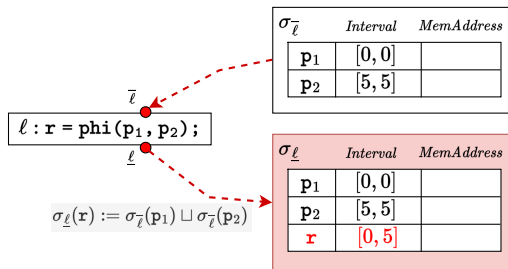
1 Function updateStateOnBinary(binary):
2   node = binary → getICFGNode();
3   as = getAbsStateFromTrace(node);
4   op0 = binary → getOpVarID(0);
5   op1 = binary → getOpVarID(1);
6   res = binary → getResID();
7   as[res] = as[op0]  $\hat{\otimes}$  as[op1]

```

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

Abstract Execution on PHISTMT

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



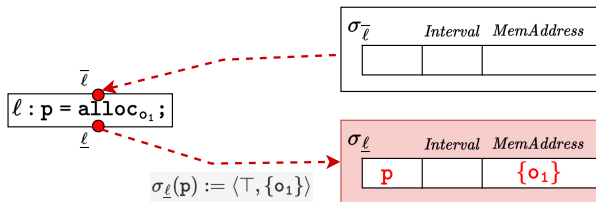
Algorithm 16: Abstract Execution Rule for PHISTMT

```

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 Execution on ADDRSTMT

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



Algorithm 17: Abstract Execution Rule for ADDRSTMT

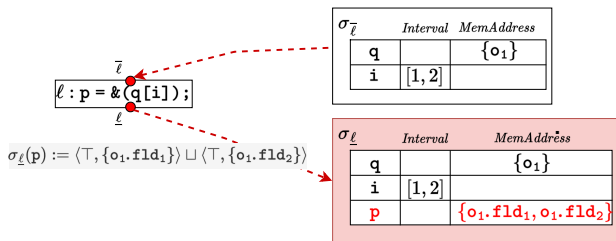
```

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 Execution on GEPSTMT

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



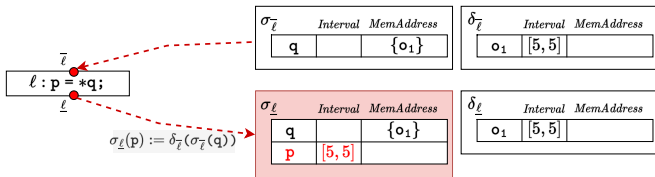
Algorithm 18: Abstract Execution Rule for GEPSTMT

```

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 Execution 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 19: Abstract Execution Rule for LOADSTMT

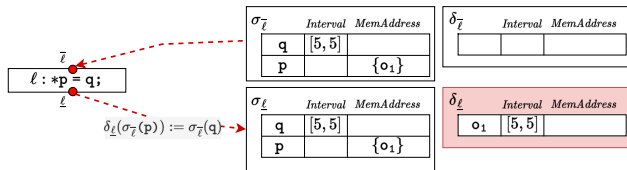
```

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 Execution 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 20: 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])
    
```

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 ++;
```

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

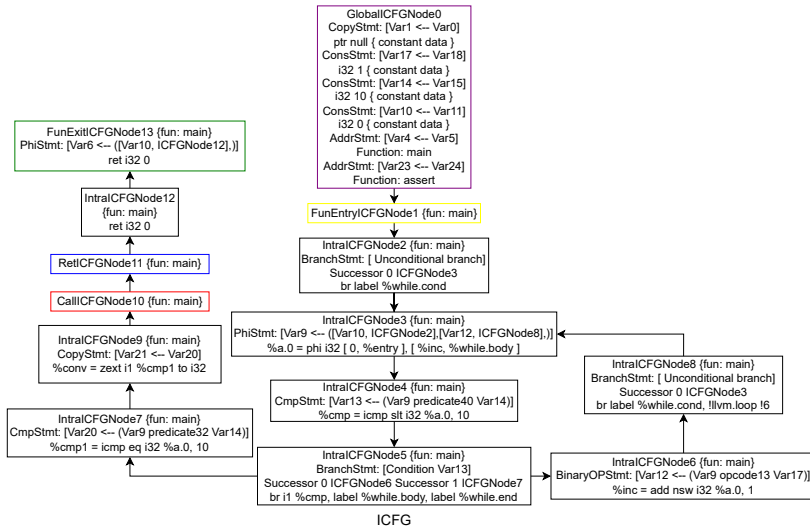
Compile to LLVM IR



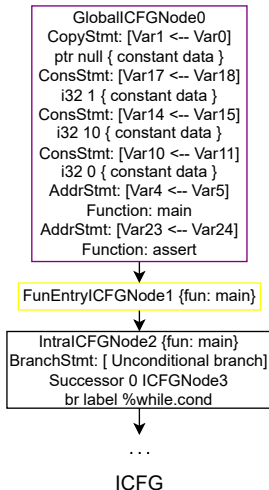
```
define dso_local i32 @main() {
entry:
    br label %while.cond
while.cond:
    %a.0 = phi i32 [ 0, %entry ], [ %inc, %while.body ]
    %cmp = icmp slt i32 %a.0, 10
    br i1 %cmp, label %while.body, label %while.end
while.body:
    %inc = add nsw i32 %a.0, 1
    br label %while.cond,
while.end:
    %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



Algorithm 5: 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   ...;
  
```

$postAbsTrace[\ell_0].varToAbsVal$:

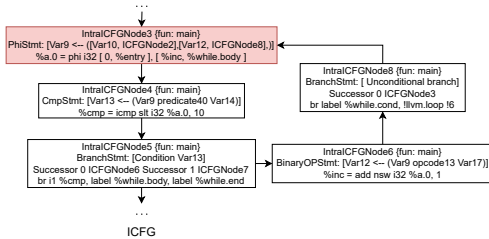
SVFVar	AbstractValue $\langle Interval, MemAddress \rangle$
Var0	$\langle \perp, \{0x7f00\} \rangle$
Var1	$\langle \perp, \{0x7f00\} \rangle$
Var18	$\langle [1, 1], \perp \rangle$
Var17	$\langle [1, 1], \perp \rangle$
Var14	$\langle [10, 10], \perp \rangle$
Var15	$\langle [10, 10], \perp \rangle$
Var10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



$\text{postAbsTrace}[\ell_3].\text{varToAbsVal}$:

SVFVar	AbstractValue $\langle \text{Interval}, \text{MemAddress} \rangle$
...	
Var10	$\langle [0, 0], \perp \rangle$
Var9	$\langle [0, 0], \perp \rangle$
...	

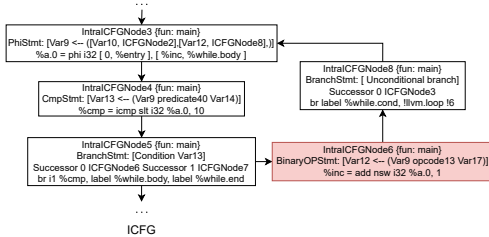
Algorithm 12: Handle Cycle WTO

```

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       handleICFGNode(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      handleICFGNode(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)



$postAbsTrace[\ell_6].varToAbsVal :$

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

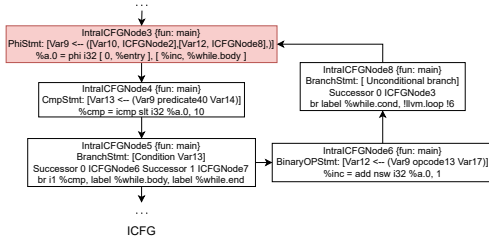
Algorithm 12: Handle Cycle WTO

```

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       handleICFGNode(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      handleICFGNode(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)



$postAbsTrace[\ell_3].varToAbsVal :$

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

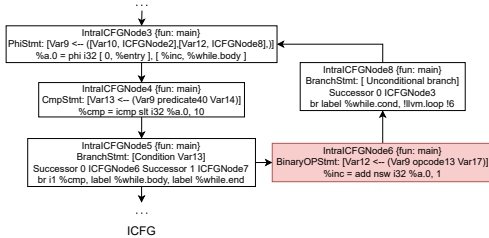
Algorithm 12: Handle Cycle WTO

```

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       handleICFGNode(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      handleICFGNode(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)



$\text{postAbsTrace}[\ell_6].\text{varToAbsVal}$:

SVFVar	AbstractValue $\langle \text{Interval}, \text{MemAddress} \rangle$
...	...
Var9	$\langle [0, 1], \perp \rangle$
Var12	$\langle [1, 2], \perp \rangle$
...	...

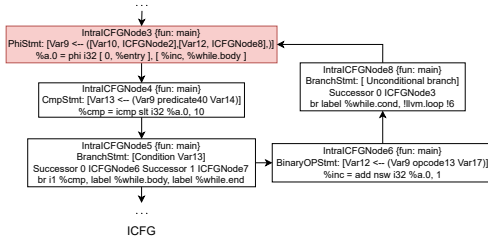
Algorithm 12: Handle Cycle WTO

```

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       handleICFGNode(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      handleICFGNode(cycle → head());
22    handleWTOComponents(cycle → getWTOComponents());
23    cur_iter++;
  
```

An Example: Abstract Trace σ for Top-level Variables

Widen Phase (cur_iter is 2)



$postAbsTrace[\ell_3].varToAbsVal :$

SVFVar	$\langle Interval, MemAddress \rangle$
...	...

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

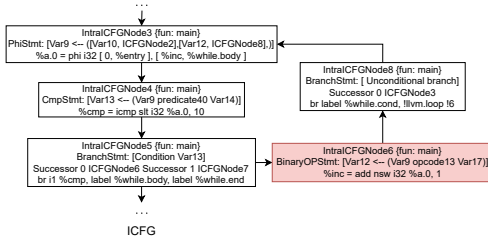
Algorithm 12: Handle Cycle WTO

```

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       handleICFGNode(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        handleICFGNode(cycle → head());
22      handleWTOComponents(cycle → getWTOComponents());
23      cur_iter++;
  
```


An Example: Abstract Trace σ for Top-level Variables

Widen Phase (cur_iter is 2)



$\text{postAbsTrace}[\ell_6].\text{varToAbsVal}$:

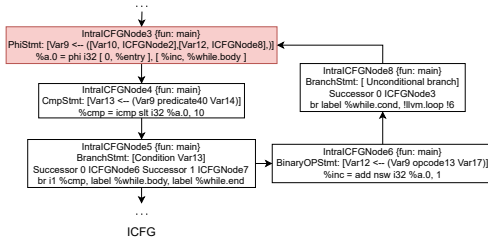
SVFVar	AbstractValue<Interval, MemAddress>
...	
Var9	$\langle [0, 9], \perp \rangle$
Var12	$\langle [1, 10], \perp \rangle$
...	

Algorithm 12: Handle Cycle WTO

```
1 Function handleCycleWTO(cycle):
2   cycle_head := cycle → 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       handleICFGNode(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      handleICFGNode(cycle → head());
22      handleWTOComponents(cycle → getWTOComponents())
23      cur_iter++;
```

An Example: Abstract Trace σ for Top-level Variables

Widen Phase Fixed Point



$postAbsTrace[\ell_3].varToAbsVal :$

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

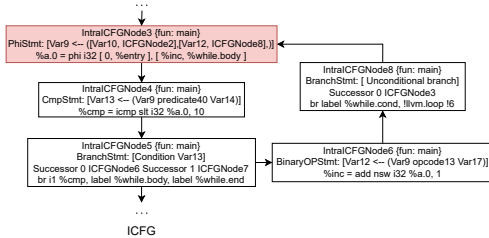
Algorithm 12: Handle Cycle WTO

```

1 Function handleCycleWTO(cycle):
2   cycle_head := cycle → head() → node() ;
3   increasing := true ;
4   cur_iter := 0;
5   while true do
6     // cur_iter ≡ 3, Options :: WidenDelay() ≡ 2
7     if cur_iter ≥ Options :: WidenDelay() then
8       prev_head_state := postAbsTrace[cycle_head];
9       handleICFGNode(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        handleICFGNode(cycle → head());
22      handleWTOComponents(cycle → getWTOComponents());
23      cur_iter++;
    
```

An Example: Abstract Trace σ for Top-level Variables

Narrow Phase



$postAbsTrace[\ell_3].varToAbsVal :$

SVFVar	$\langle Interval, MemAddress \rangle$
...	

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

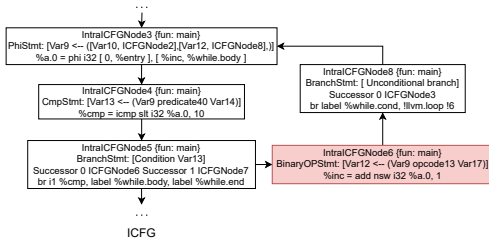
Algorithm 12: Handle Cycle WTO

```

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       handleICFNode(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        handleICFNode(cycle → head());
22      handleWTOComponents(cycle → getWTOComponents());
23      cur_iter++;
  
```

An Example: Abstract Trace σ for Top-level Variables

Narrow Phase



$postAbsTrace[\ell_6].varToAbsVal :$

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

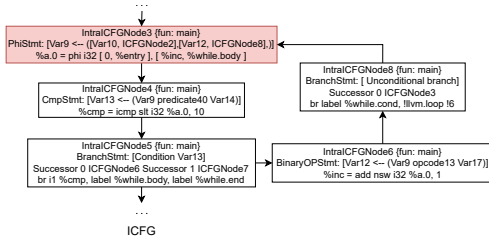
Algorithm 12: Handle Cycle WTO

```

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       handleICFGNode(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      handleICFGNode(cycle → head());
22    handleWTOComponents(cycle → getWTOComponents());
23    cur_iter++;
  
```

An Example: Abstract Trace σ for Top-level Variables

Narrow Phase Fixed Point



$postAbsTrace[\ell_3].varToAbsVal :$

SVFVar	$\langle Interval, MemAddress \rangle$
...	...

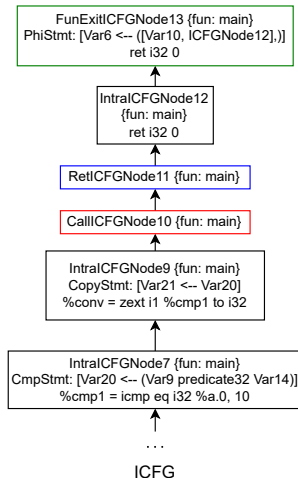
Var9	$\langle [0, 10], \perp \rangle$
Var12	$\langle [1, 10], \perp \rangle$
...	...

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       handleICFGNode(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        handleICFGNode(cycle → head());
22      handleWTOComponents(cycle → getWTOComponents());
23      cur_iter++;
  
```

An Example: Abstract Trace σ for Top-level Variables



Algorithm 13: Abstract execution guided by WTO

```

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

$postAbsTrace[\ell_7].varToAbsVal$:

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