中国科学技术大学
University of Science and Technology of China

Interprocedural Analysis

Most content comes from http://cs.au.dk/~amoeller/spa/

张昱

yuzhang@ustc.edu.cn
中国科学技术大学
计算机科学与技术学院

Interprocedural Analysis

- **Analyzing the body of a single function**
  - *intra*procedural analysis
- **Analyzing the whole program with function calls**
  - *inter*procedural analysis
- **For now, we consider TIP without function pointers and indirect calls (so we only have direct calls)**
- **A naive approach:**
  - analyze each function in isolation
  - be maximally pessimistic about results of function calls
  - rarely sufficient precision…

CFG for Whole Programs

The idea:

- ☐ Construct a CFG for each function
- ☐ Then glue them together to reflect function calls and returns

We need to take care of:

- ☐ parameter passing
- ☐ return values
- ☐ values of local variables across calls (including recursive functions, so not enough to assume unique variable names)

A Simplifying Assumption

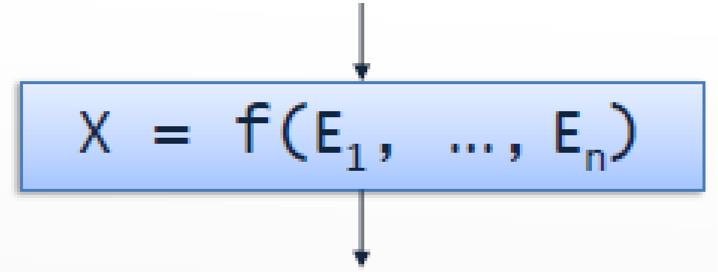
- ☐ **Assume that all function calls are of the form**

$$X= f(E_1, \ldots,E_n);$$

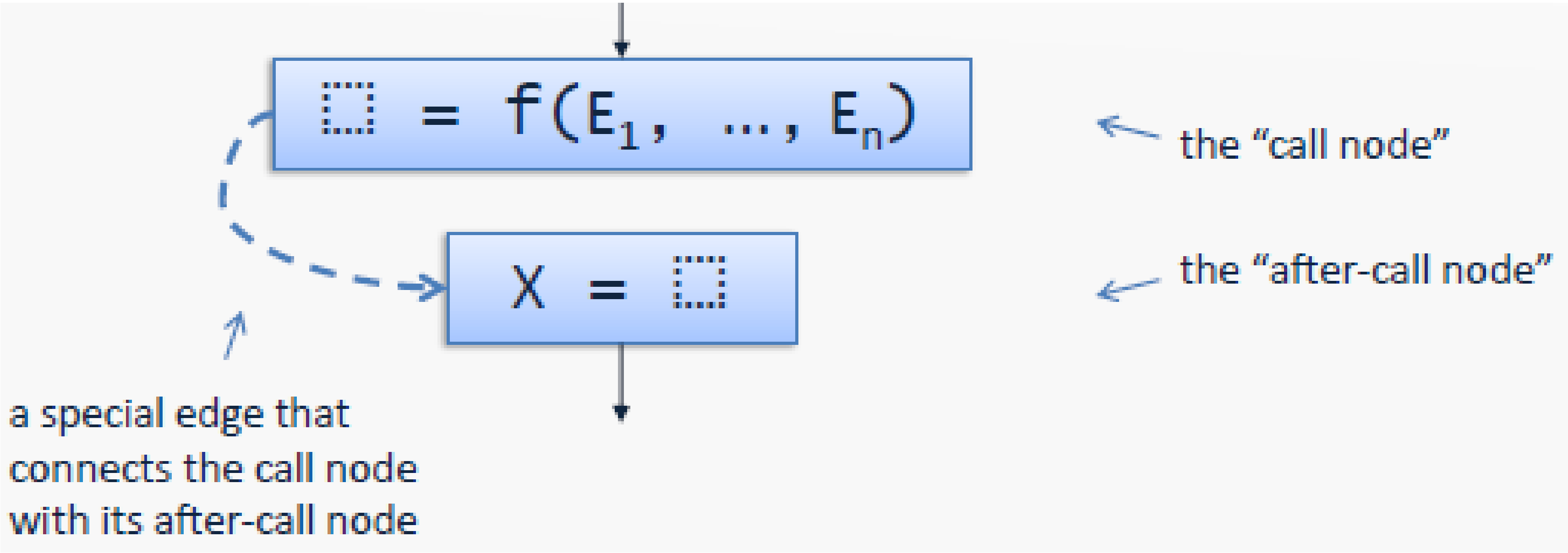
- ☐ **This can always be obtained by normalization**

Interprocedural CFGs (1/3)

Split each original call node



into two nodes:



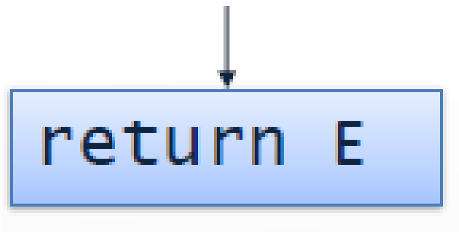
the “call node”

the “after-call node”

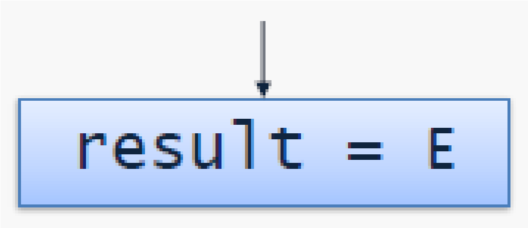
a special edge that connects the call node with its after-call node

Interprocedural CFGs (2/3)

Change each return node



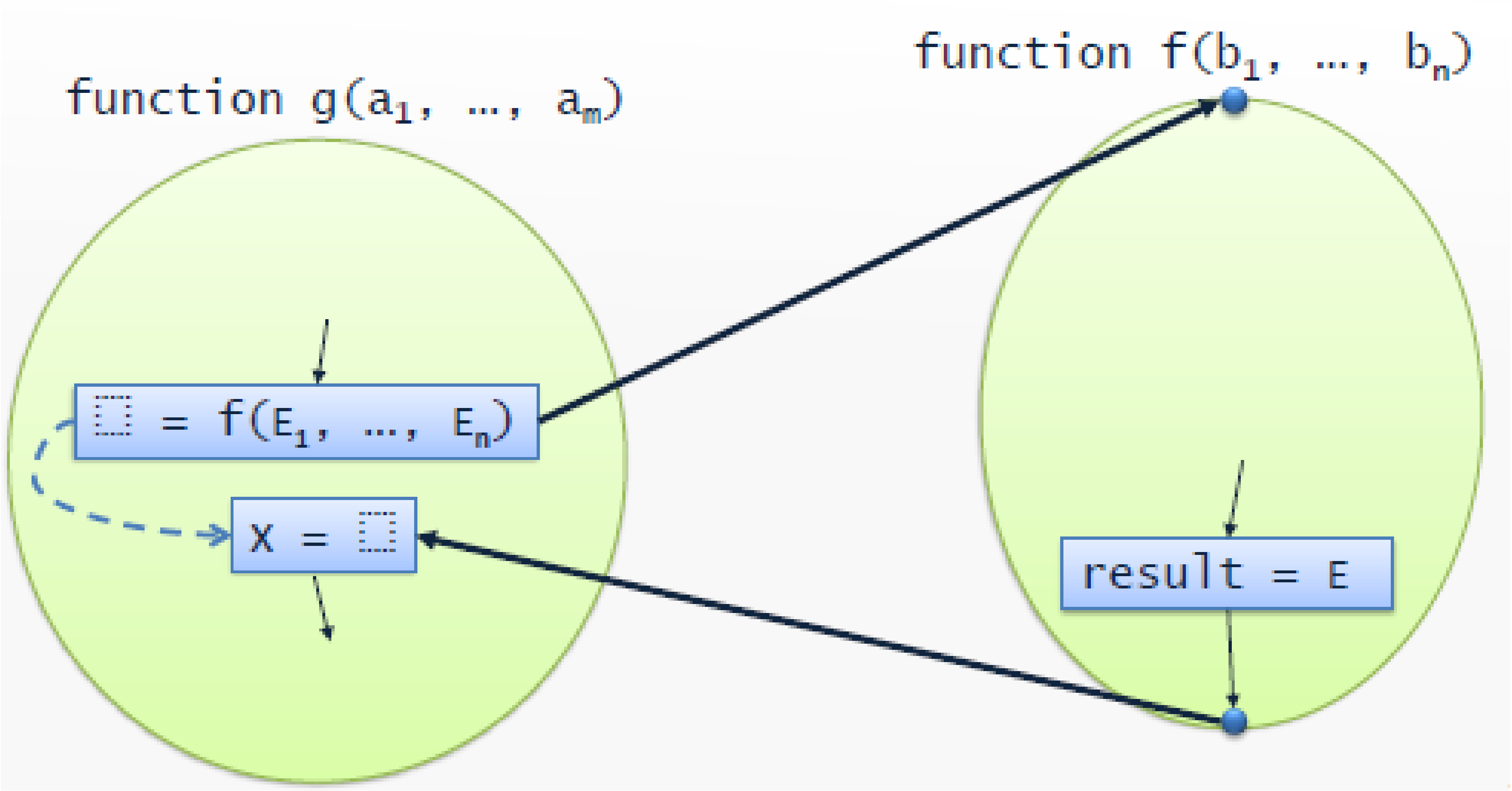
into an assignment:



(where result is a fresh variable)

Interprocedural CFGs (3/3)

Add call edges and return edges:



Constraints

☐ For call/entry nodes:

- be careful to model evaluation of *all* the actual parameters before binding them to the formal parameter names (otherwise, it may fail for recursive functions)

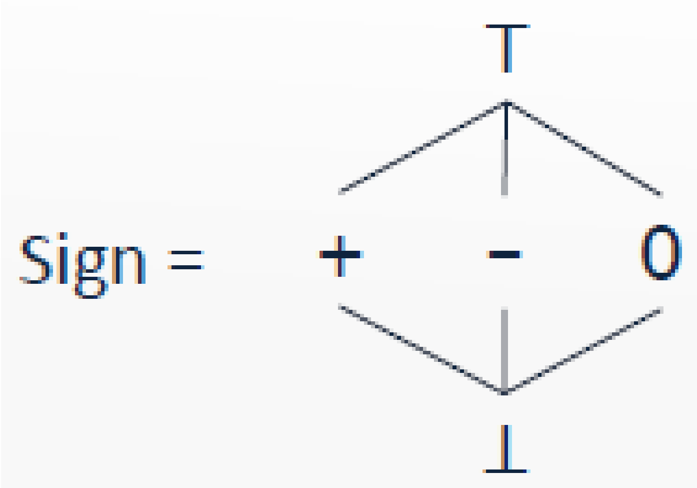
☐ For after-call/exit nodes:

- like an assignment: X = **result**
- but also restore local variables from before the call using the call ↷ after-call edge

☐ The details depend on the specific analysis…

Example: Interprocedural Sign Analysis

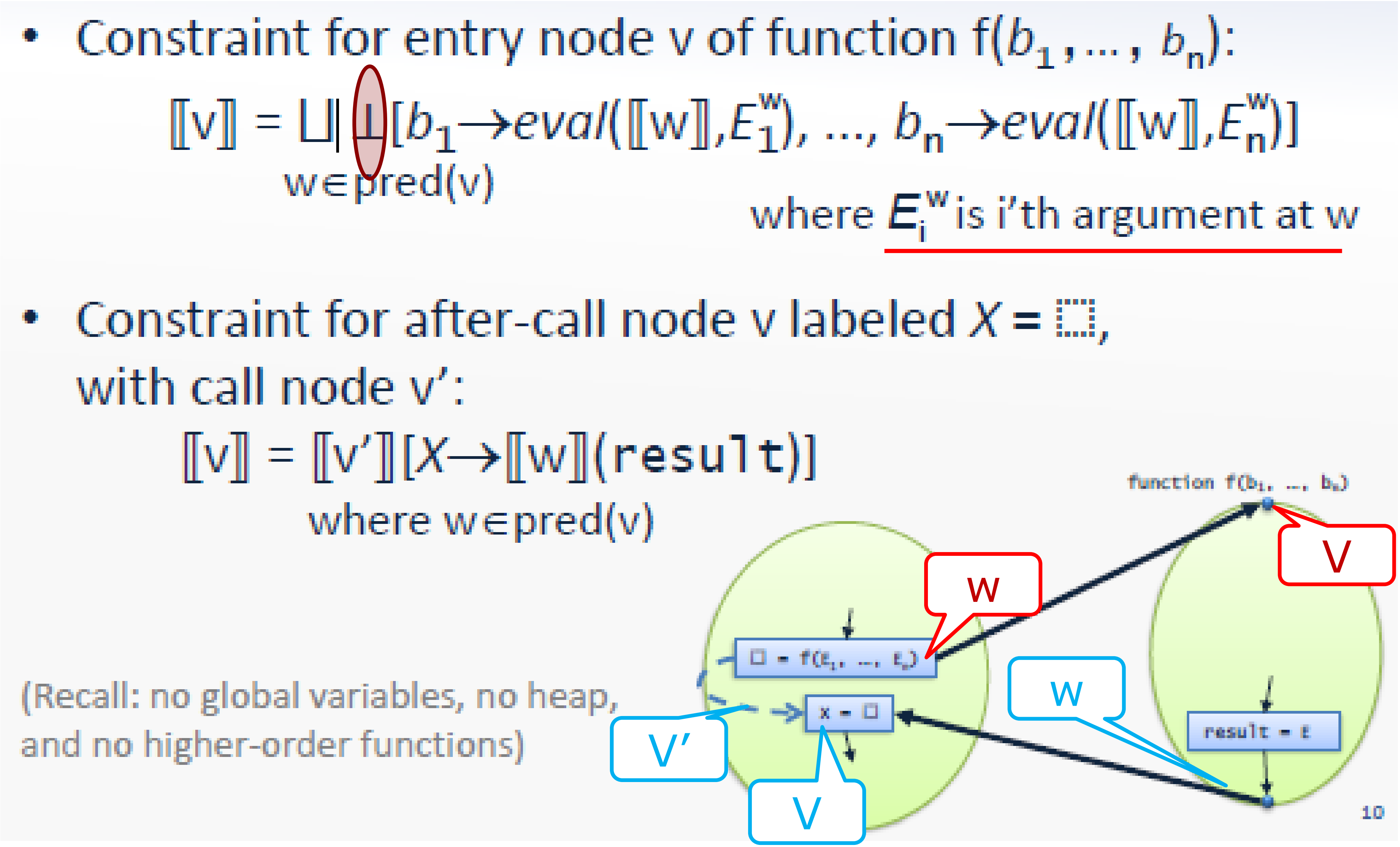
- **Recall the intraprocedural sign analysis…**
- **Lattice for abstract values:**



- **Lattice for abstract states:**

  Vars→Sign

Example: Interprocedural Sign Analysis



- Constraint for entry node v of function $f(b_1, \ldots, b_n)$:

$$[\![v]\!] = \bigsqcup_{w \in pred(v)} \bot[b_1 \to eval([\![w]\!], E_1^w), \ldots, b_n \to eval([\![w]\!], E_n^w)]$$

where E_i^w is i'th argument at w

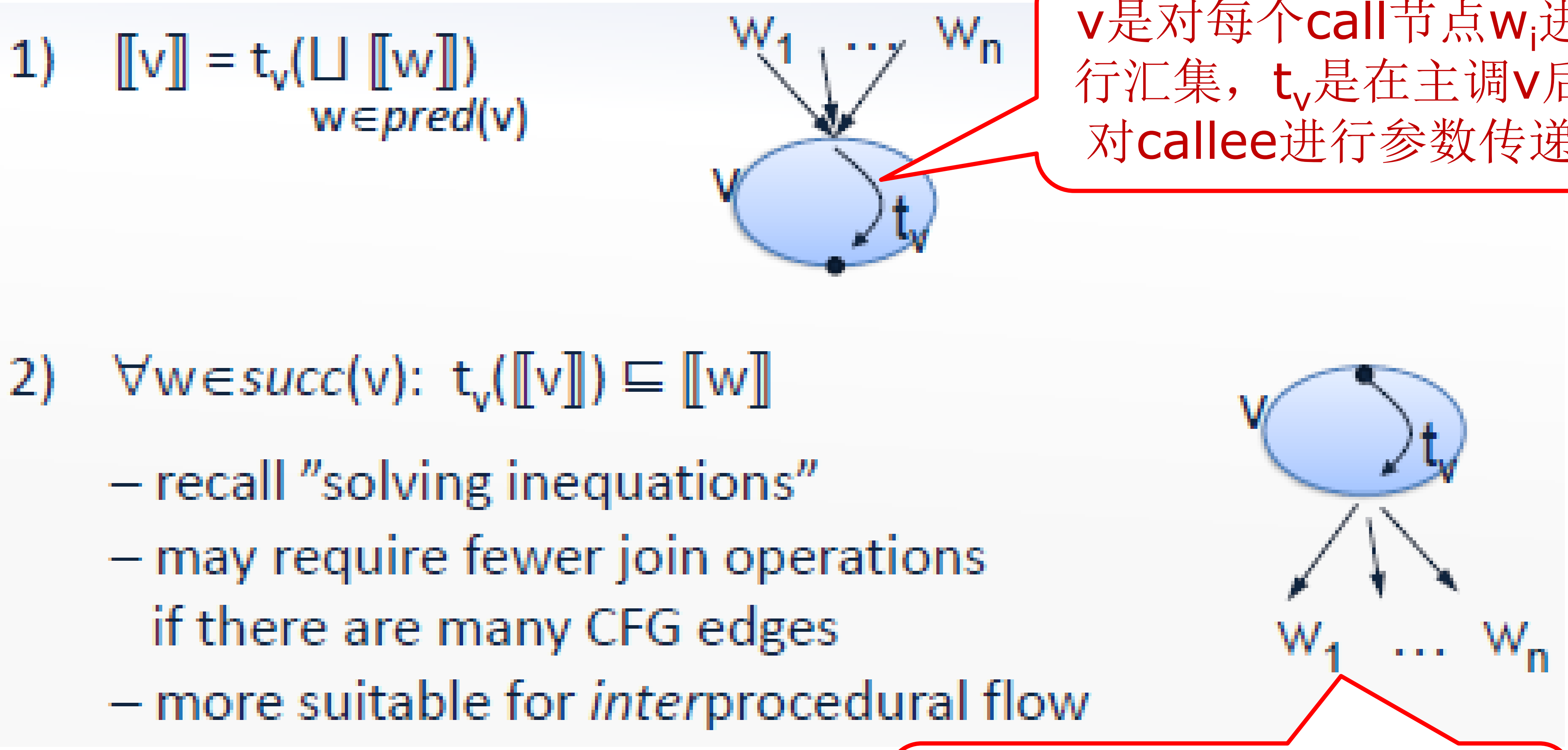
- Constraint for after-call node v labeled $X = ⬚$, with call node v':

$$[\![v]\!] = [\![v']\!][X \to [\![w]\!](\texttt{result})]$$

where $w \in pred(v)$

(Recall: no global variables, no heap, and no higher-order functions)

Alternative Formulations



1) $[\![v]\!] = t_v(\bigsqcup_{w \in pred(v)} [\![w]\!])$

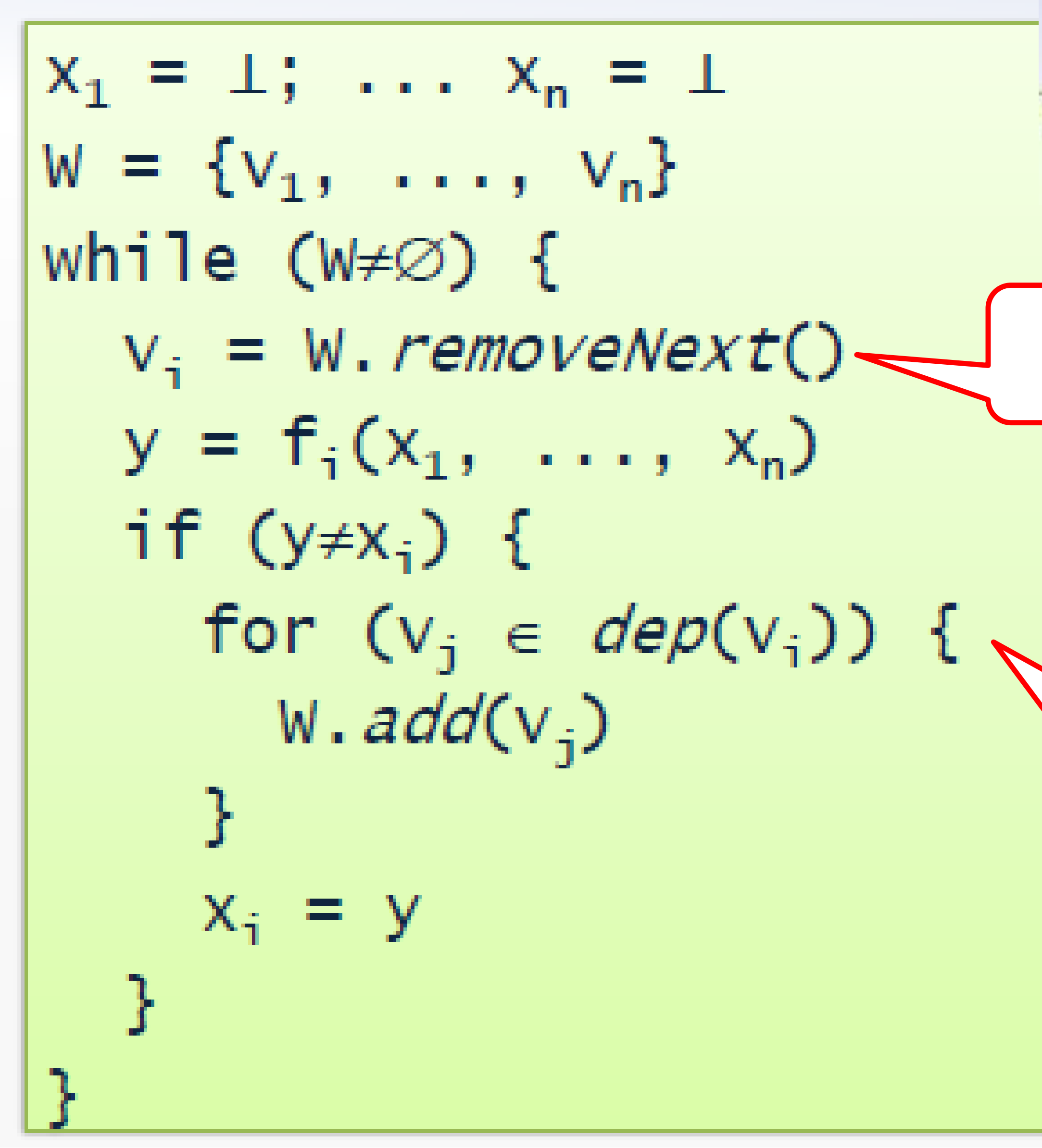
2) $\forall w \in succ(v):\ t_v([\![v]\!]) \sqsubseteq [\![w]\!]$

- recall "solving inequations"
- may require fewer join operations if there are many CFG edges
- more suitable for *inter*procedural flow

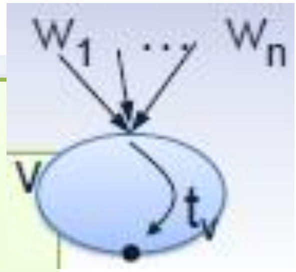
v是对每个call节点w_i进行汇集，t_v是在主调v后对callee进行参数传递

t_v是将返回的退出点v应用到每个主调的after-call节点w_i进行返回值的接收处理

The Worklist Algorithm (original version)



```
x₁ = ⊥; ... xₙ = ⊥
W = {v₁, ..., vₙ}
while (W≠∅) {
   vᵢ = W.removeNext()
   y = fᵢ(x₁, ..., xₙ)
   if (y≠xᵢ) {
      for (vⱼ ∈ dep(vᵢ)) {
         W.add(vⱼ)
      }
      xᵢ = y
   }
}
```

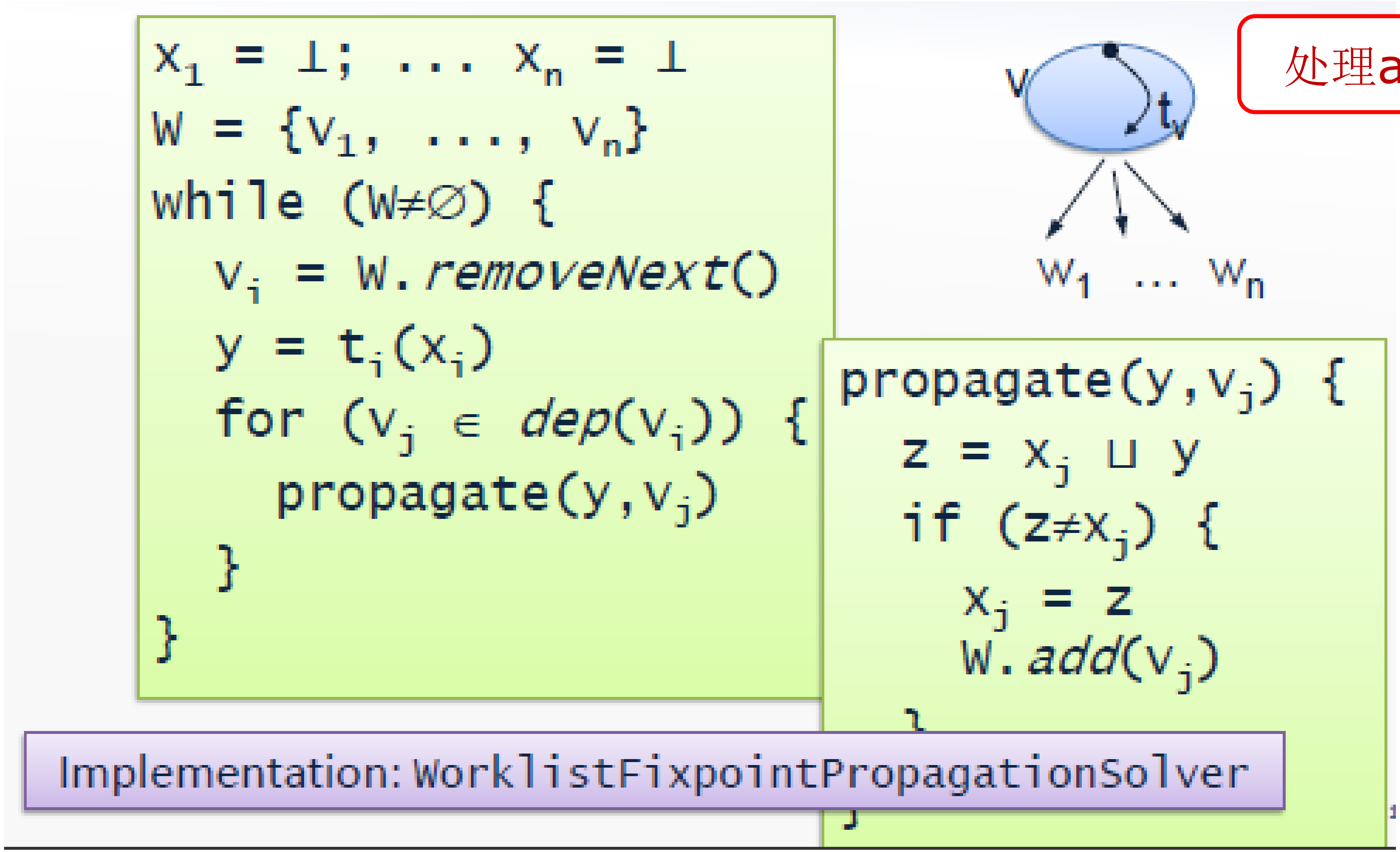


基于过程间的大CFG
处理call节点

CFG结点vi 的变迁函数

如果CFG结点vi
的语义值发生变化，
则将计算vi 语义
值所依赖的结点vj
加入到worklist

The Worklist Algorithm (alternative version)

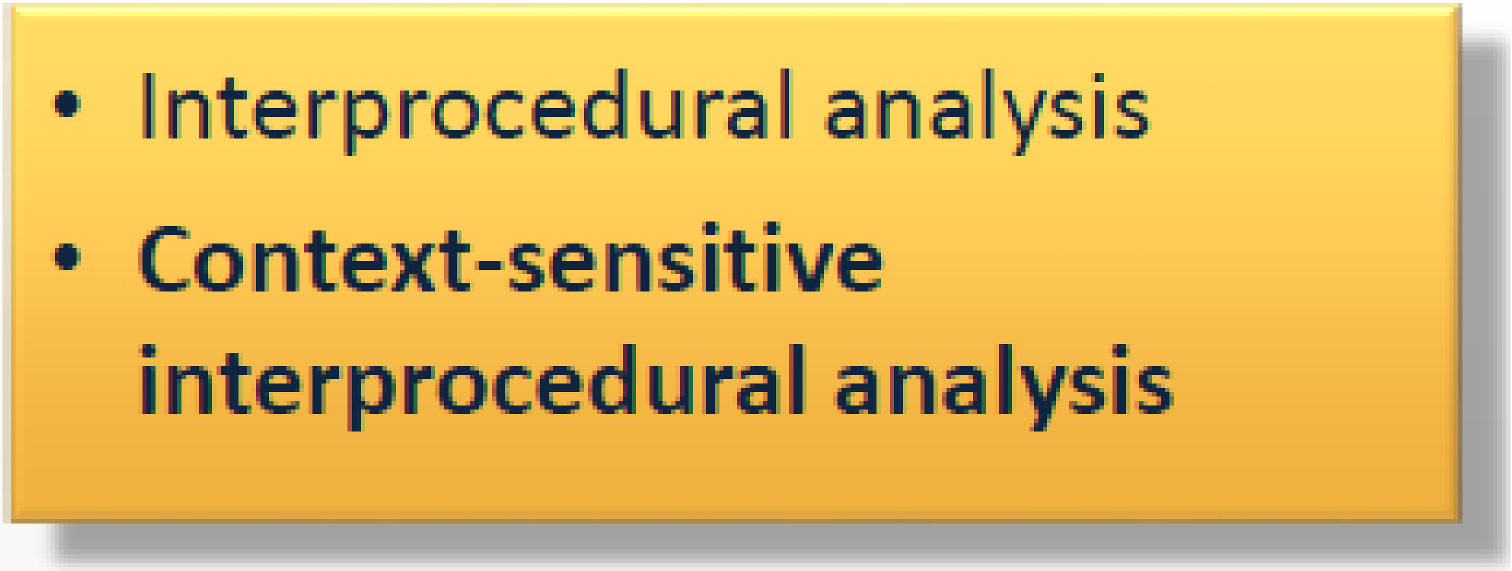


```
$x_1 = \bot$; ... $x_n = \bot$
W = {$v_1$, ..., $v_n$}
while ($W \neq \emptyset$) {
   $v_i$ = W.removeNext()
   y = $t_i(x_i)$
   for ($v_j \in dep(v_i)$) {
      propagate(y,$v_j$)
   }
}
```

```
propagate(y,$v_j$) {
   z = $x_j \sqcup y$
   if ($z \neq x_j$) {
      $x_j$ = z
      W.add($v_j$)
   }
}
```

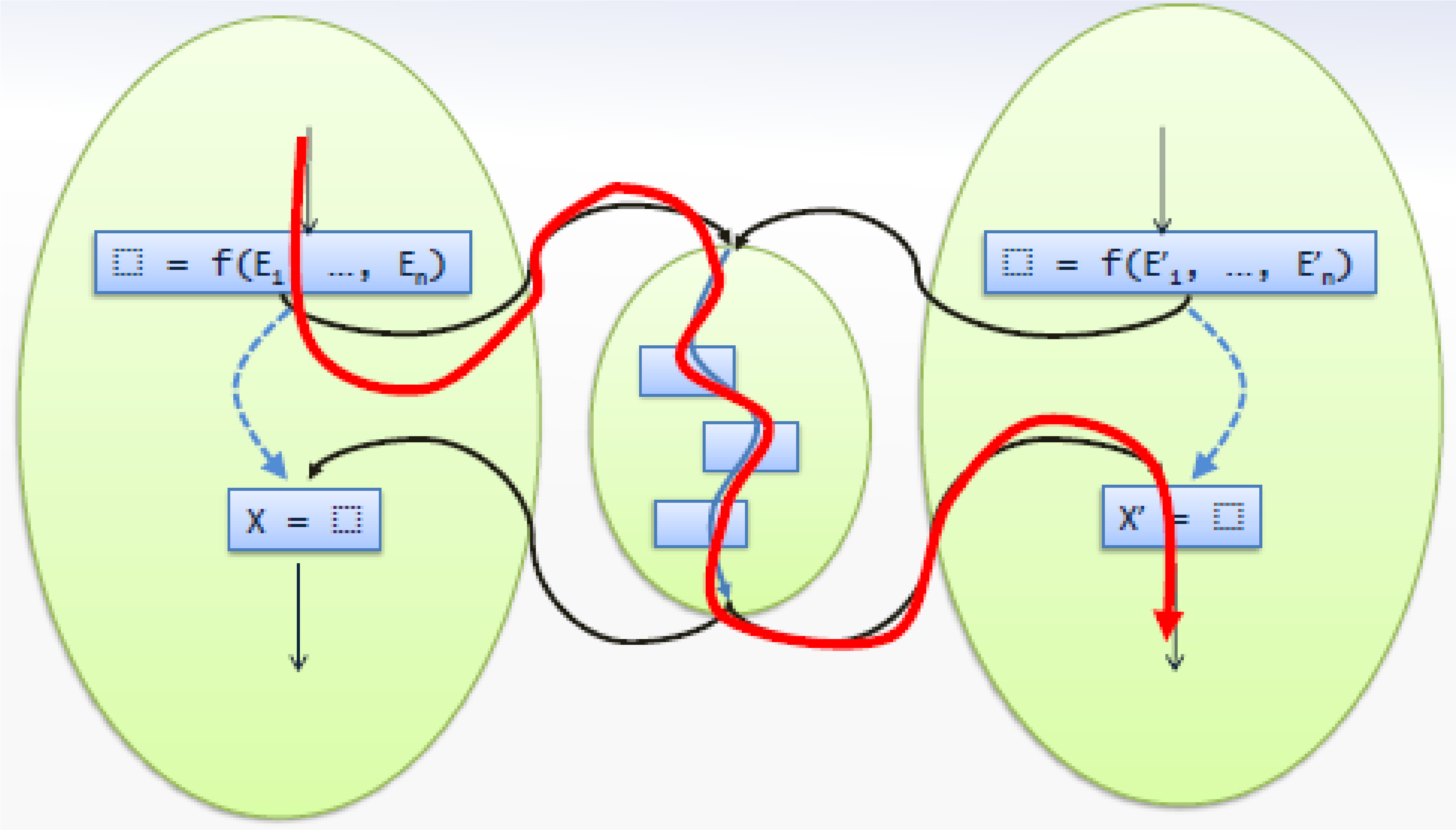
处理after-call节点

Implementation: WorklistFixpointPropagationSolver



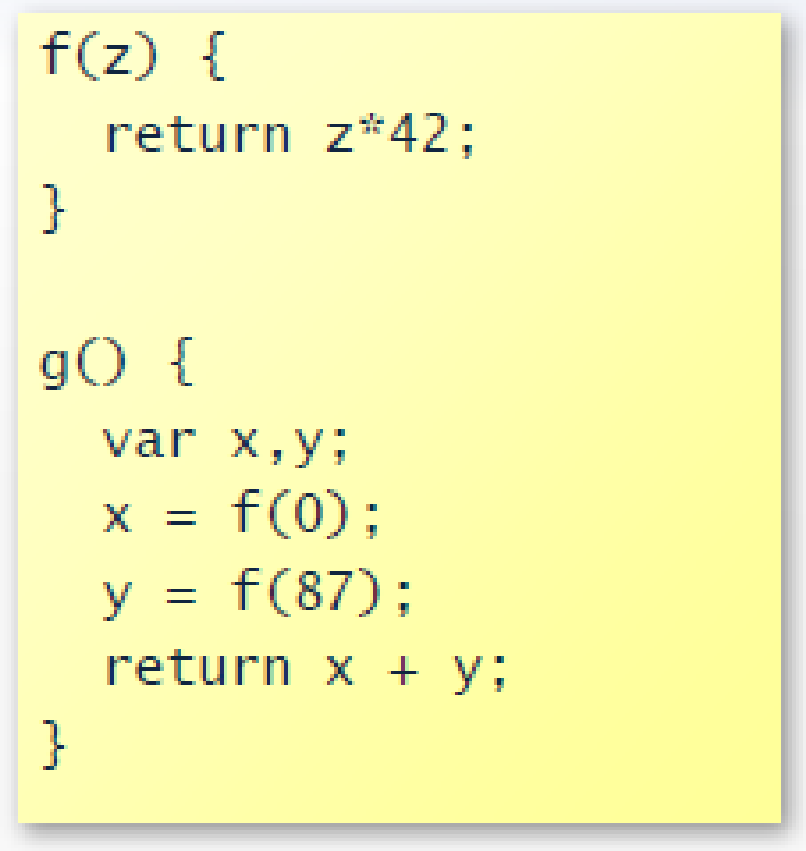
- Interprocedural analysis
- **Context-sensitive interprocedural analysis**

Interprocedurally Invalid Paths



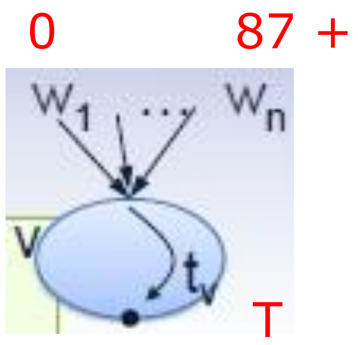
Example

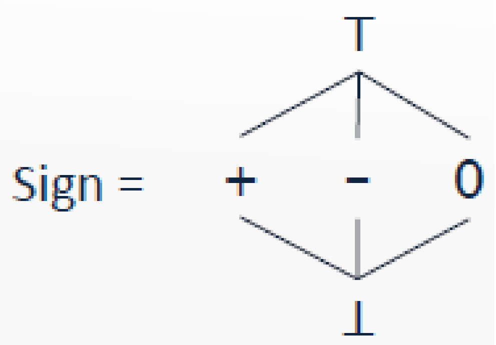
What is the **sign** of the **return value** of g?



```
f(z) {
  return z*42;
}

g() {
  var x,y;
  x = f(0);
  y = f(87);
  return x + y;
}
```





Our current analysis says “⊤”

Function Cloning(alternatively, function inlining)

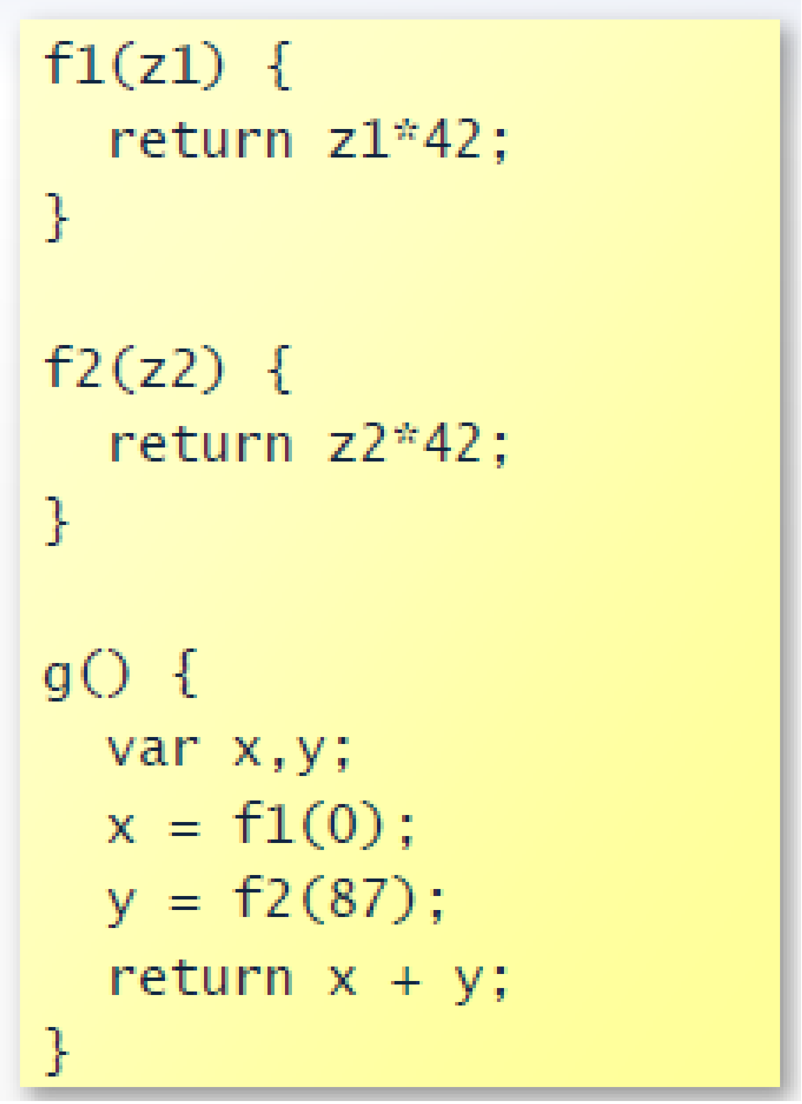
- ☐ **Clone functions such that each function has only one callee**

- ☐ **Can avoid interprocedurally invalid paths☺**
- ☐ **For high nesting depths, give exponential blow-up☺**
- ☐ **Don’t work on (mutually) recursive functions ☺**

- ☐ **Use heuristics to determine when to apply (trade-off between CFG size and precision)**

Example, with cloning

- □ What is the sign of the return value of g?



```
f1(z1) {
  return z1*42;
}

f2(z2) {
  return z2*42;
}

g() {
  var x,y;
  x = f1(0);
  y = f2(87);
  return x + y;
}
```

对副本的调用

优点：分析精度提升
缺点：代码膨胀

Context Sensitive Analysis

- **Function cloning provides a kind of context sensitivity (also called polyvariant analysis)**
- **Instead of physically copying the function CFGs, do it *logically***
- **Replace the lattice for abstract states, States, by**

  Contexts → lift(States)

  where Contexts is a set of *call contexts*
  - The contexts are abstractions of the state at function entry
  - Contexts must be finite to ensure finite height of the lattice
  - The bottom element of lift(States) represents “unreachable” contexts
- **Different strategies for choosing the set Contexts…**

Constraints for CFG nodes that do not involve function calls and returns

Easily adjusted to Contexts → lift(States)

- ☐ **Example if v is an assignment node *x =E* in sign analysis:**

  $[\![v]\!] = JOIN(v)[x \mapsto eval(JOIN(v), E)]$

  becomes

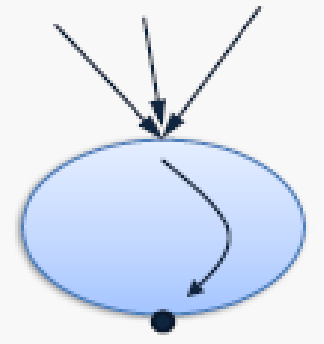
$$[\![v]\!](c) = \begin{cases} s[x \mapsto eval(s, E)] & \text{if } s = JOIN(\mathrm{v}, \mathrm{c}) \in \text{States} \\ \text{unreachable} & \text{if } JOIN(v, c) = \text{unreachable} \end{cases}$$

and

$$JOIN(v) = \bigsqcup_{w \in pred(v)} [\![w]\!]$$

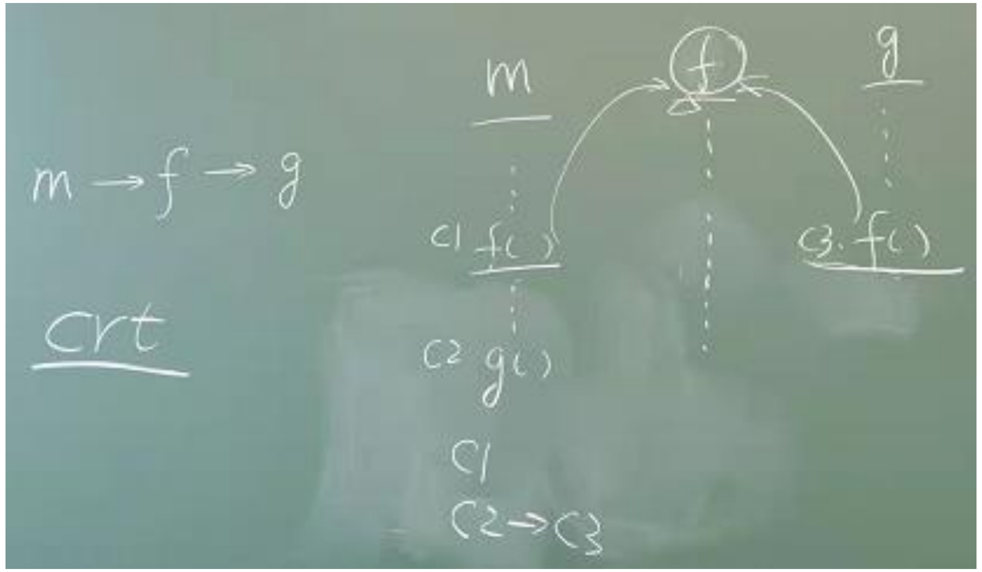
becomes

$$JOIN(v,c) = \bigsqcup_{w \in pred(v)} [\![w]\!](c)$$



One-level Cloning

- **Let $c_1,\ldots,c_n$ be the call nodes in the program**
- **Define Contexts=$\{c_1,\ldots,c_n\}\cup\{\varepsilon\}$**
  - each call node now defines its own “call context”(using ε to represent the call context at the main function)
  - the context is then like the return address of the top-most stack frame in the call stack



crt：C RunTime

a set of execution startup routines linked into a C program that performs any initialization work required before calling the program's main function.

One-level Cloning

- **Let $c_1,\ldots,c_n$ be the call nodes in the program**
- **Define Contexts=$\{c_1,\ldots,c_n\}\cup\{\varepsilon\}$**
  - each call node now defines its own “call context”(using ε to represent the call context at the main function)
  - the context is then like the return address of the top-most stack frame in the call stack
- **Same effect as one-level cloning, but without actually copying the function CFGs**
- **Usually straightforward to generalize the constraints for a context insensitive analysis to this lattice**
- **(Example: context-sensitive sign analysis –later…)**

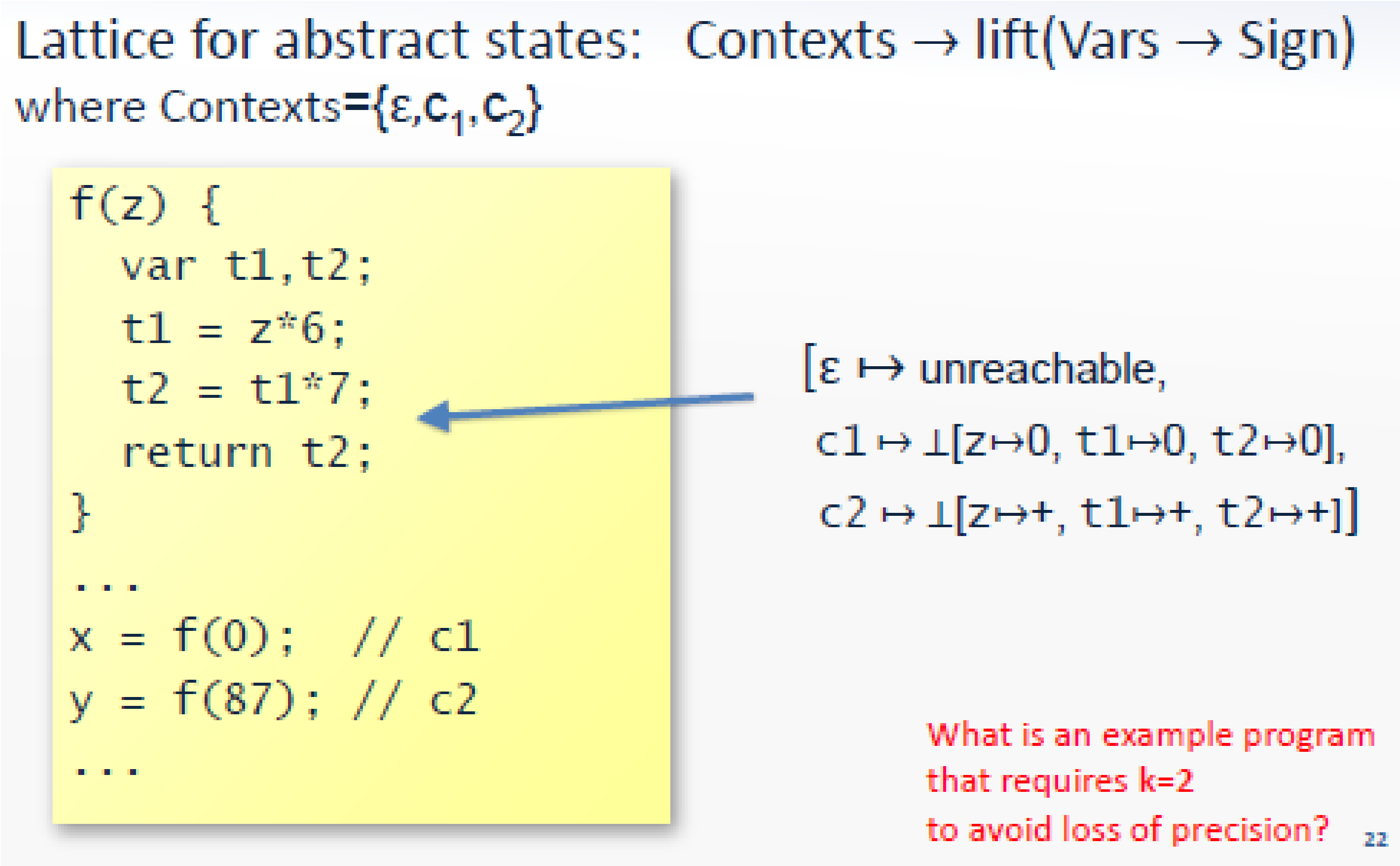
The Call String Approach

- Let $c_1,\ldots,c_n$ be the call nodes in the program
- Define Contexts as the set of strings over $\{c_1,\ldots,c_n\}$ of length $\leq k$
  - such a string represents the top-most k call locations on the call stack
  - the empty string ε again represents the call context at the main function
- For k=1 this amounts to one-level cloning

Implementation: CallStringSignAnalysis

Example:

Interprocedural sign analysis with call strings (k=1)



Lattice for abstract states: Contexts → lift(Vars → Sign)

where Contexts=$\{\varepsilon, c_1, c_2\}$

```
f(z) {
  var t1,t2;
  t1 = z*6;
  t2 = t1*7;
  return t2;
}
...
x = f(0);  // c1
y = f(87); // c2
...
```

$[\varepsilon \mapsto$ unreachable,
$c1 \mapsto \bot[z \mapsto 0, t1 \mapsto 0, t2 \mapsto 0]$,
$c2 \mapsto \bot[z \mapsto +, t1 \mapsto +, t2 \mapsto +]]$

What is an example program
that requires k=2
to avoid loss of precision?

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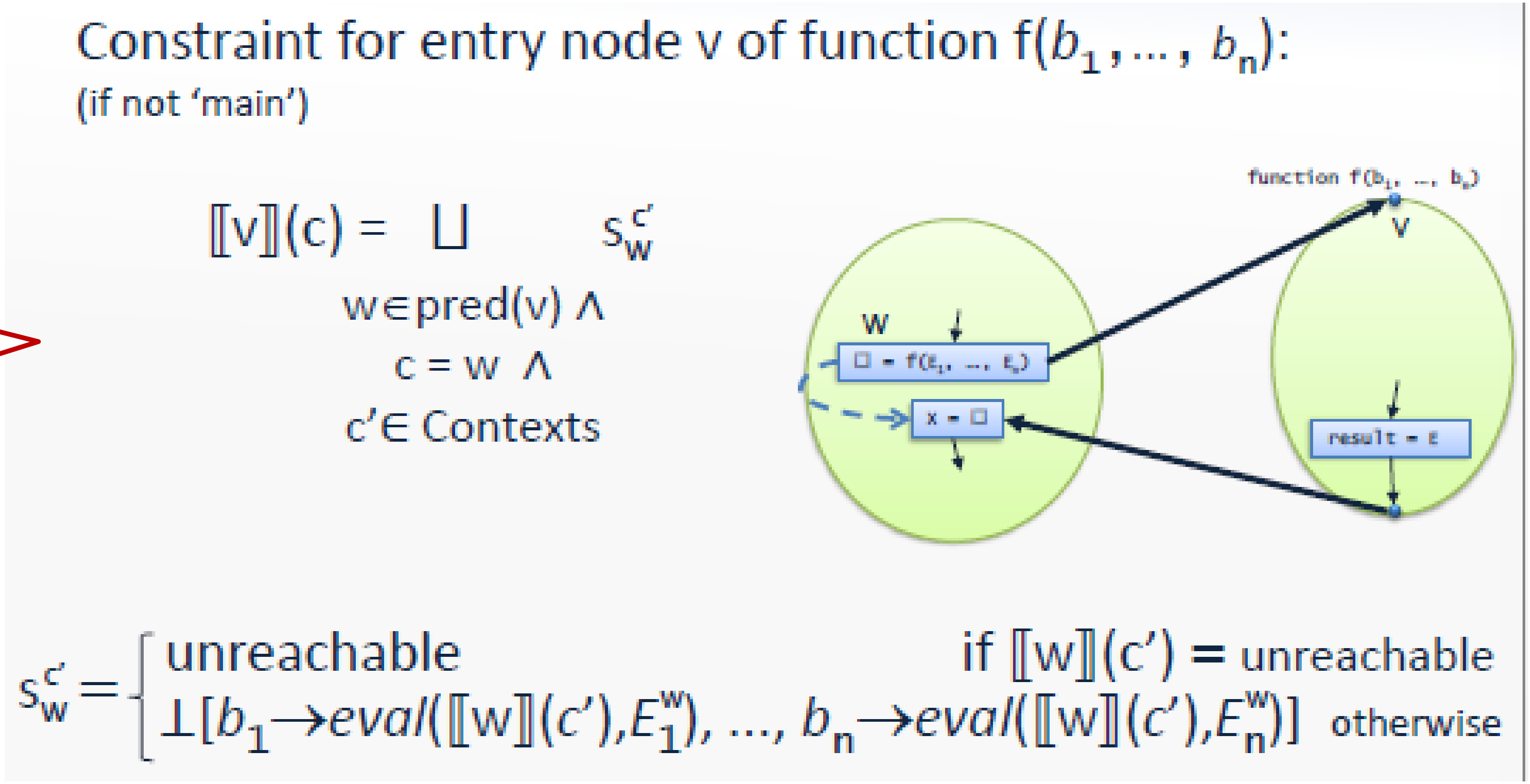
Context Sensitivity with Call Strings
function entry nodes, for k=1



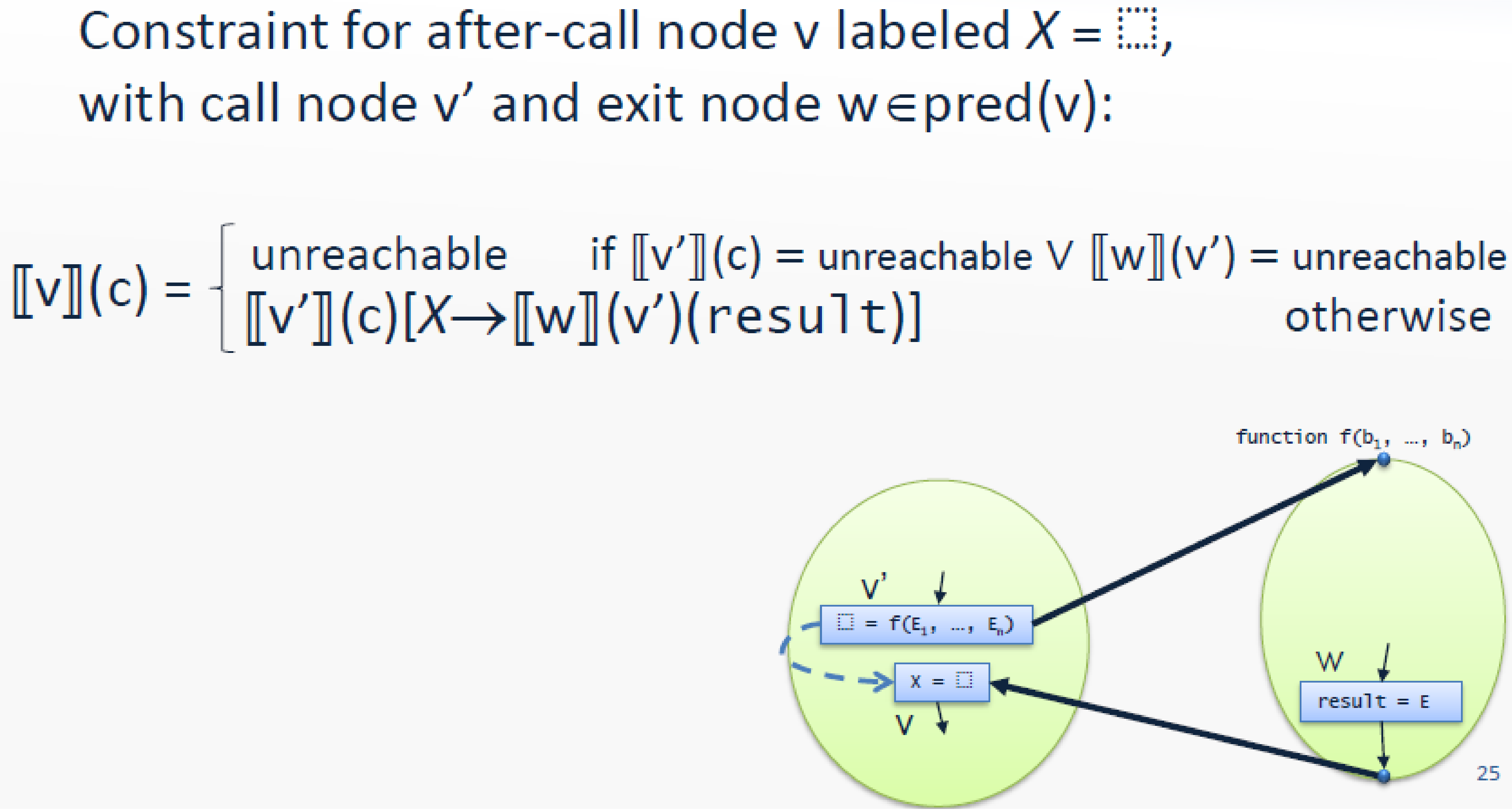
Constraint for entry node v of function f(b_1, …, b_n):
(if not 'main')

$$[\![v]\!](c) = \bigsqcup_{\substack{w \in pred(v)\ \wedge \\ c = w\ \wedge \\ c' \in Contexts}} s_w^{c'}$$

$$s_w^{c'} = \begin{cases} \text{unreachable} & \text{if } [\![w]\!](c') = \text{unreachable} \\ \bot[b_1 \rightarrow eval([\![w]\!](c'), E_1^w), \ldots, b_n \rightarrow eval([\![w]\!](c'), E_n^w)] & \text{otherwise} \end{cases}$$

Only consider the call node w that matches the context c

Context Sensitivity with Call Strings
after-call nodes, for k=1



Constraint for after-call node v labeled $X = ⬚$, with call node v' and exit node $w \in pred(v)$:

$$[\![v]\!](c) = \begin{cases} \text{unreachable} & \text{if } [\![v']\!](c) = \text{unreachable} \vee [\![w]\!](v') = \text{unreachable} \\ [\![v']\!](c)[X \to [\![w]\!](v')(\mathtt{result})] & \text{otherwise} \end{cases}$$

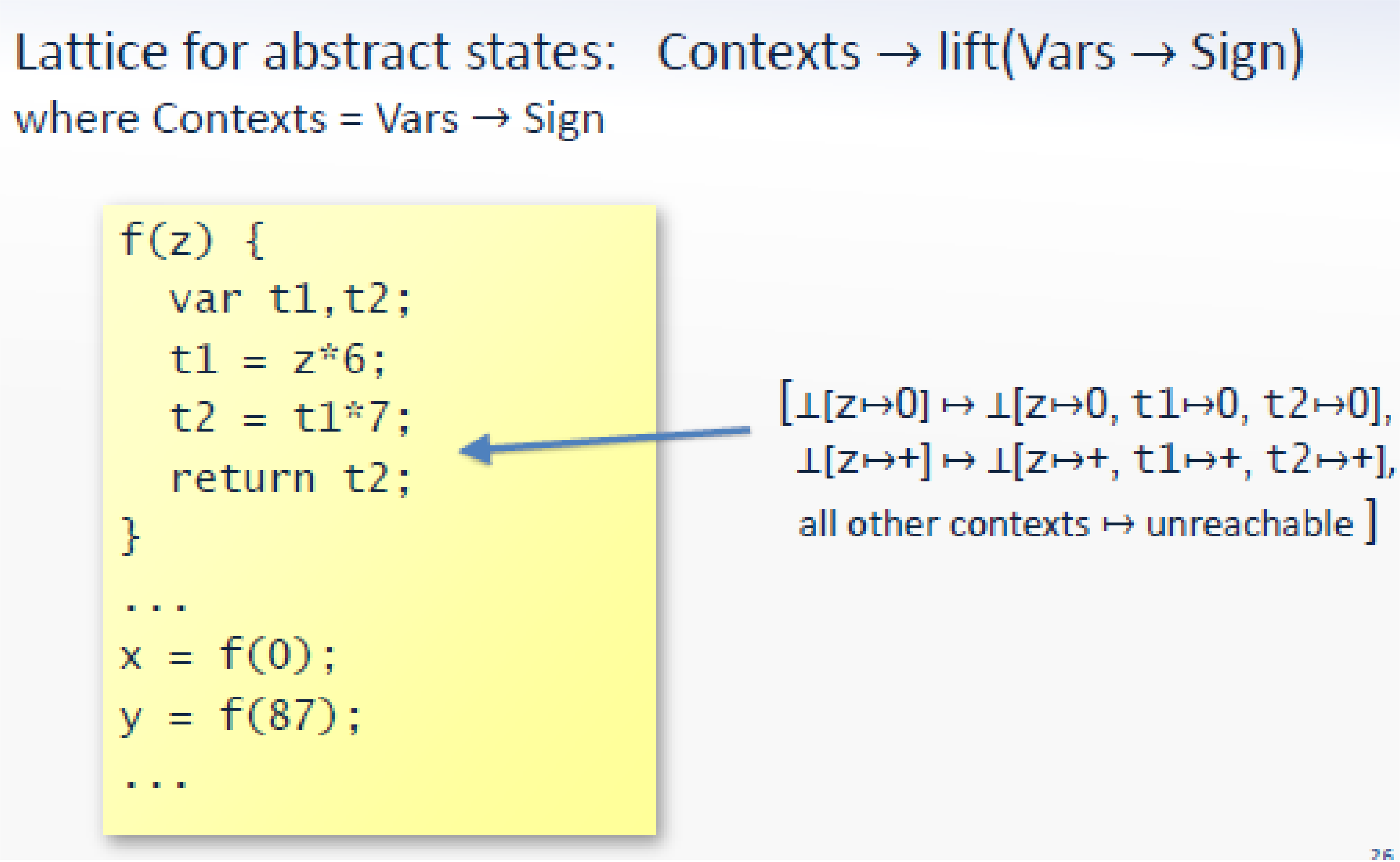
The Functional Approach

- **The call string approach considers *control flow***
  - but why distinguish between two different call sites if their abstract states are the same?
- **The functional approach instead considers *data***
- **In the most general form, choose**

  Contexts = States

  (requires States to be finite)
- **Each element of the lattice States → lift(States) is now a map m that provides an element m(x) from States (or "unreachable") for each possible x where x describes the state at function entry**

Interprocedural sign analysis with the functional approach



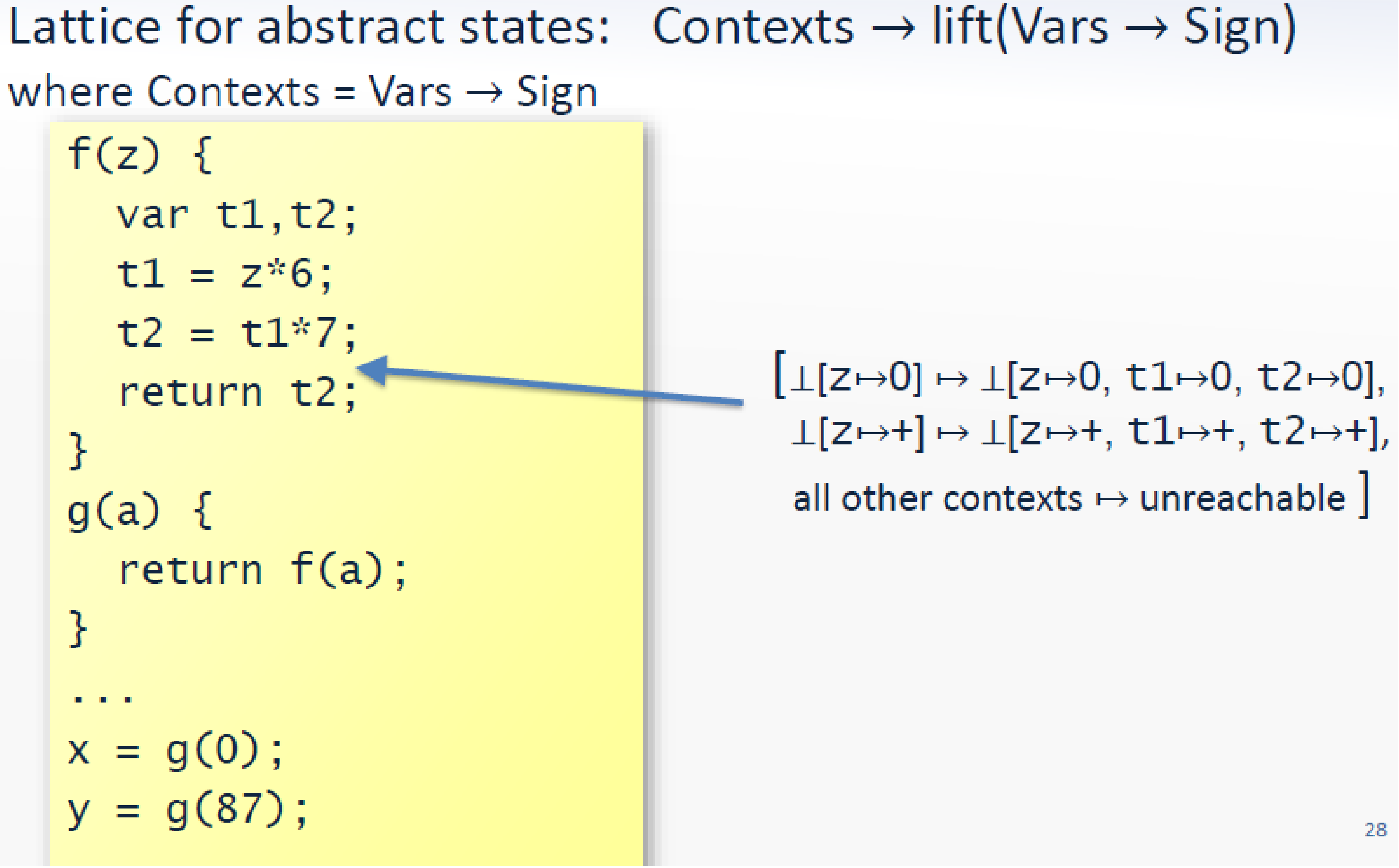
Lattice for abstract states: Contexts → lift(Vars → Sign)

where Contexts = Vars → Sign

```
f(z) {
  var t1,t2;
  t1 = z*6;
  t2 = t1*7;
  return t2;
}
...
x = f(0);
y = f(87);
...
```

$$\Big[\bot[z\mapsto 0] \mapsto \bot[z\mapsto 0,\ t1\mapsto 0,\ t2\mapsto 0],$$
$$\bot[z\mapsto +] \mapsto \bot[z\mapsto +,\ t1\mapsto +,\ t2\mapsto +],$$
$$\text{all other contexts} \mapsto \text{unreachable}\ \Big]$$

Interprocedural sign analysis with the functional approach



Lattice for abstract states: Contexts → lift(Vars → Sign)

where Contexts = Vars → Sign

```
f(z) {
  var t1,t2;
  t1 = z*6;
  t2 = t1*7;
  return t2;
}
g(a) {
  return f(a);
}
...
x = g(0);
y = g(87);
```

$[\bot[z \mapsto 0] \mapsto \bot[z \mapsto 0,\ t1 \mapsto 0,\ t2 \mapsto 0],$

$\bot[z \mapsto +] \mapsto \bot[z \mapsto +,\ t1 \mapsto +,\ t2 \mapsto +],$

all other contexts ↦ unreachable]

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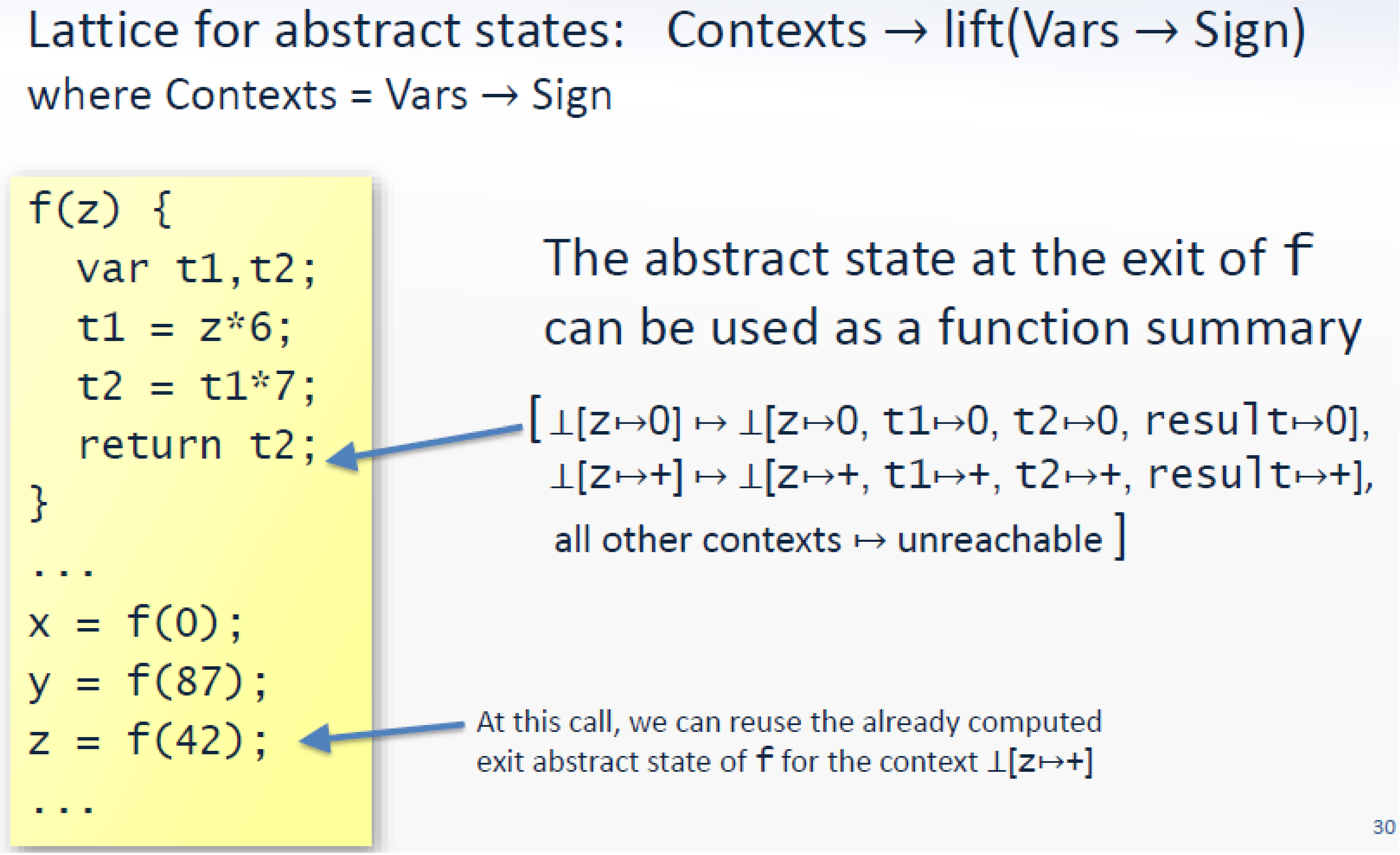
The Functional Approach

- ☐ **The lattice element for a function exit node is thus a *function summary* that maps abstract function input to abstract function output**
- ☐ **This can be exploited at call nodes!**
- ☐ **When entering a function with abstract state x:**
  - consider the function summary s for that function
  - if s(x) already has been computed, use that to model the entire function body, then proceed directly to the after-call node
- ☐ **Avoids the problem with interprocedurally invalid paths!**
- ☐ **…but may be expensive if States is large**

Implementation: FunctionalSignAnalysis

Example: Interprocedural sign analysis with the functional approach



Lattice for abstract states: Contexts → lift(Vars → Sign)

where Contexts = Vars → Sign

```
f(z) {
  var t1,t2;
  t1 = z*6;
  t2 = t1*7;
  return t2;
}
...
x = f(0);
y = f(87);
z = f(42);
...
```

The abstract state at the exit of `f` can be used as a function summary

$$\big[\, \bot[z\mapsto 0] \mapsto \bot[z\mapsto 0,\ \texttt{t1}\mapsto 0,\ \texttt{t2}\mapsto 0,\ \texttt{result}\mapsto 0],$$
$$\bot[z\mapsto +] \mapsto \bot[z\mapsto +,\ \texttt{t1}\mapsto +,\ \texttt{t2}\mapsto +,\ \texttt{result}\mapsto +],$$
$$\text{all other contexts} \mapsto \text{unreachable}\,\big]$$

At this call, we can reuse the already computed exit abstract state of `f` for the context $\bot[z\mapsto +]$

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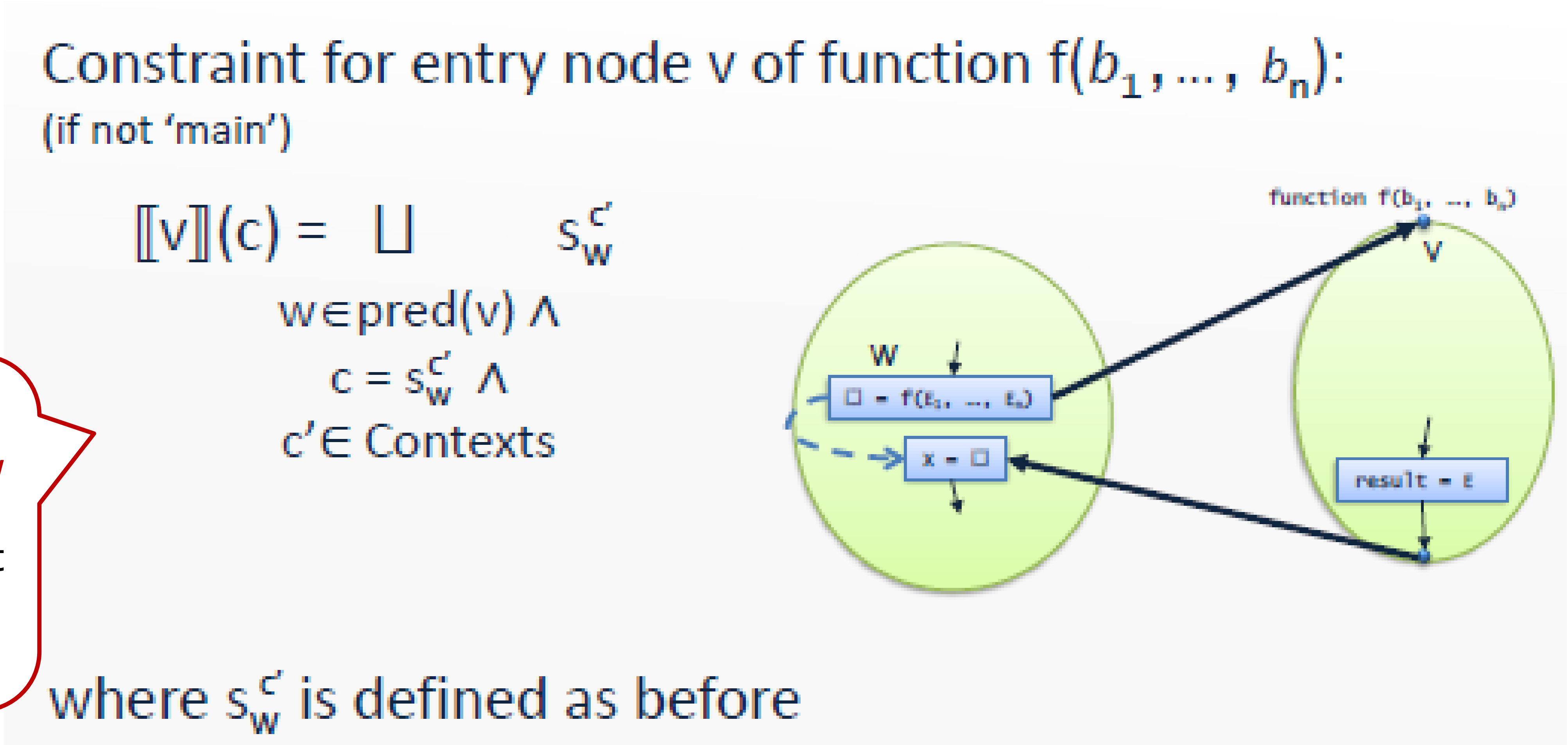
Context sensitivity with the functional approach function entry nodes



Constraint for entry node v of function f($b_1, \ldots, b_n$):

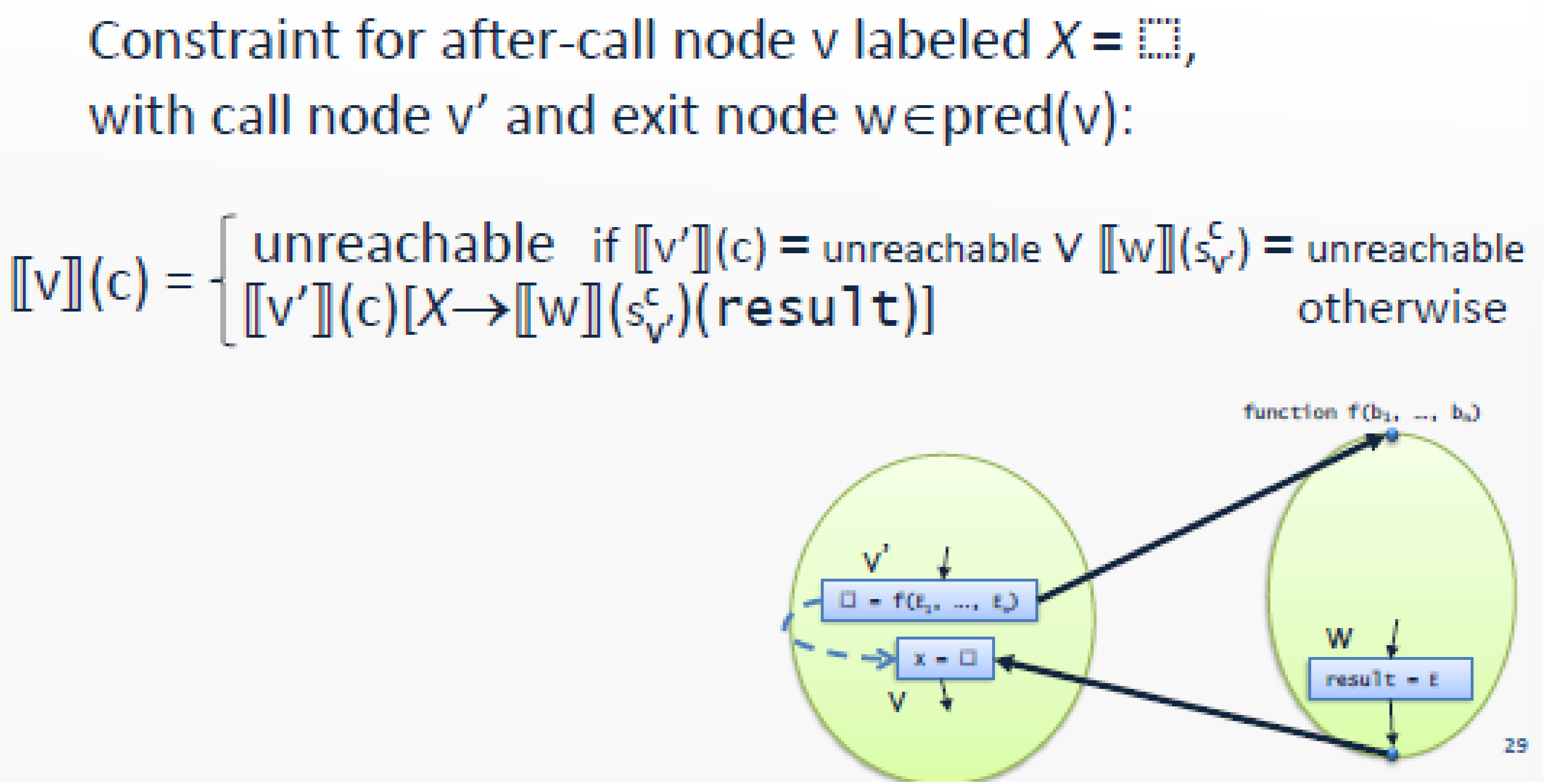
(if not 'main')

$$[\![v]\!](c) = \bigsqcup_{\substack{w \in pred(v) \wedge \\ c = s_w^{c'} \wedge \\ c' \in Contexts}} s_w^{c'}$$

where $s_w^{c'}$ is defined as before

Only consider the call node w if the abstract state from that node matches the context c

Context sensitivity with the functional approach:
after-call nodes



Constraint for after-call node v labeled $X = \square$,
with call node v′ and exit node $w \in pred(v)$:

$$[\![v]\!](c) = \begin{cases} \text{unreachable} & \text{if } [\![v']\!](c) = \text{unreachable} \vee [\![w]\!](s^{c}_{v'}) = \text{unreachable} \\ [\![v']\!](c)[X \rightarrow [\![w]\!](s^{c}_{v'})(\texttt{result})] & \text{otherwise} \end{cases}$$

Choose the Right Context Sensitivity Strategy

- **The call string approach is expensive for k>1**
  - solution: choose k adaptively for each call site
- **The functional approach is expensive if States is large**
  - solution: only consider selected parts of the abstract state as context, for example abstract information about the function parameter values (called *parameter sensitivity*), or, in object-oriented languages, abstract information about the receiver object ‘this’ (called *object sensitivity* or *type sensitivity*)

Thanks