Static Program Analysis

CFL-Reachability and IFDS

Nanjing University

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2020

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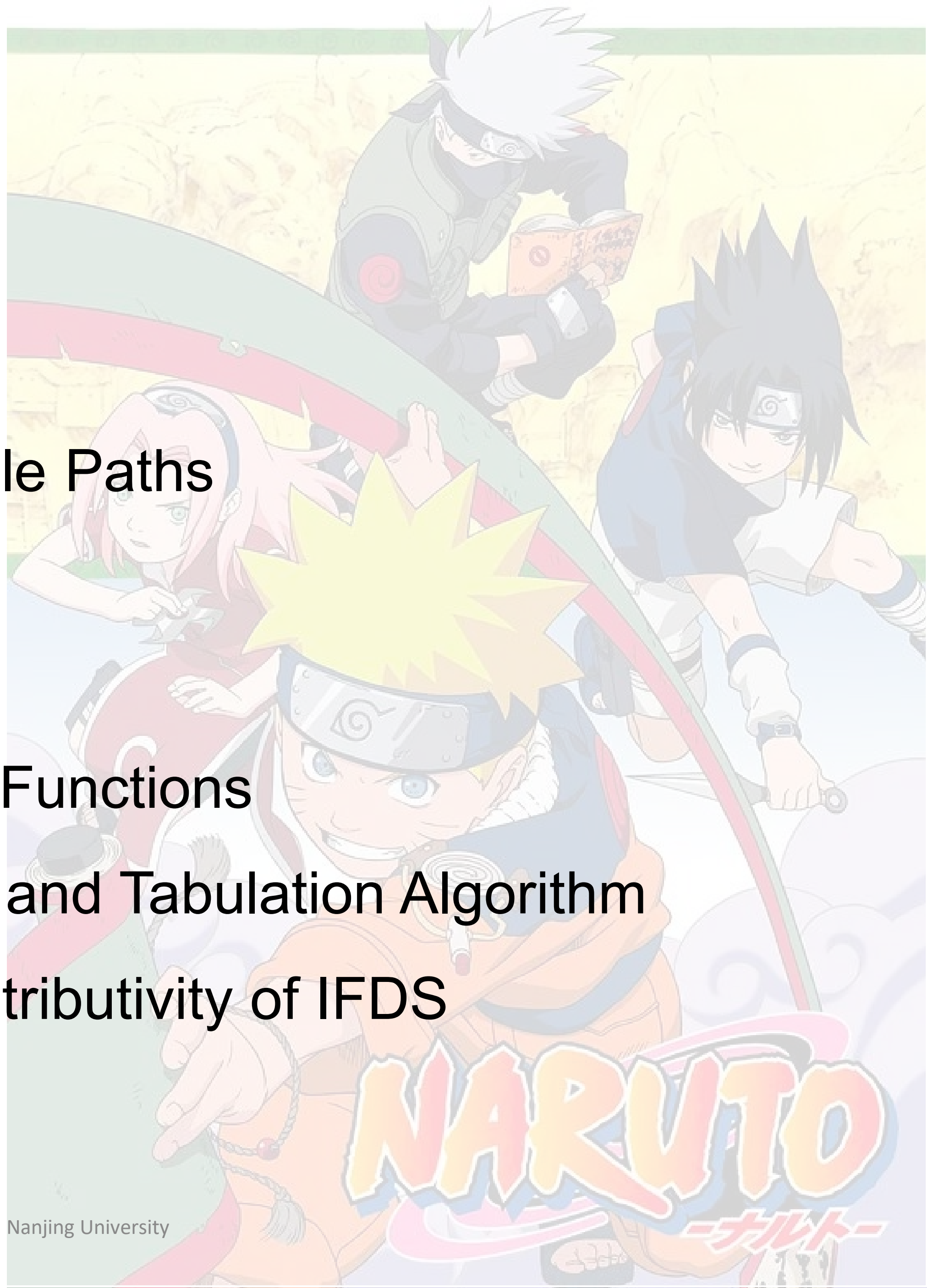
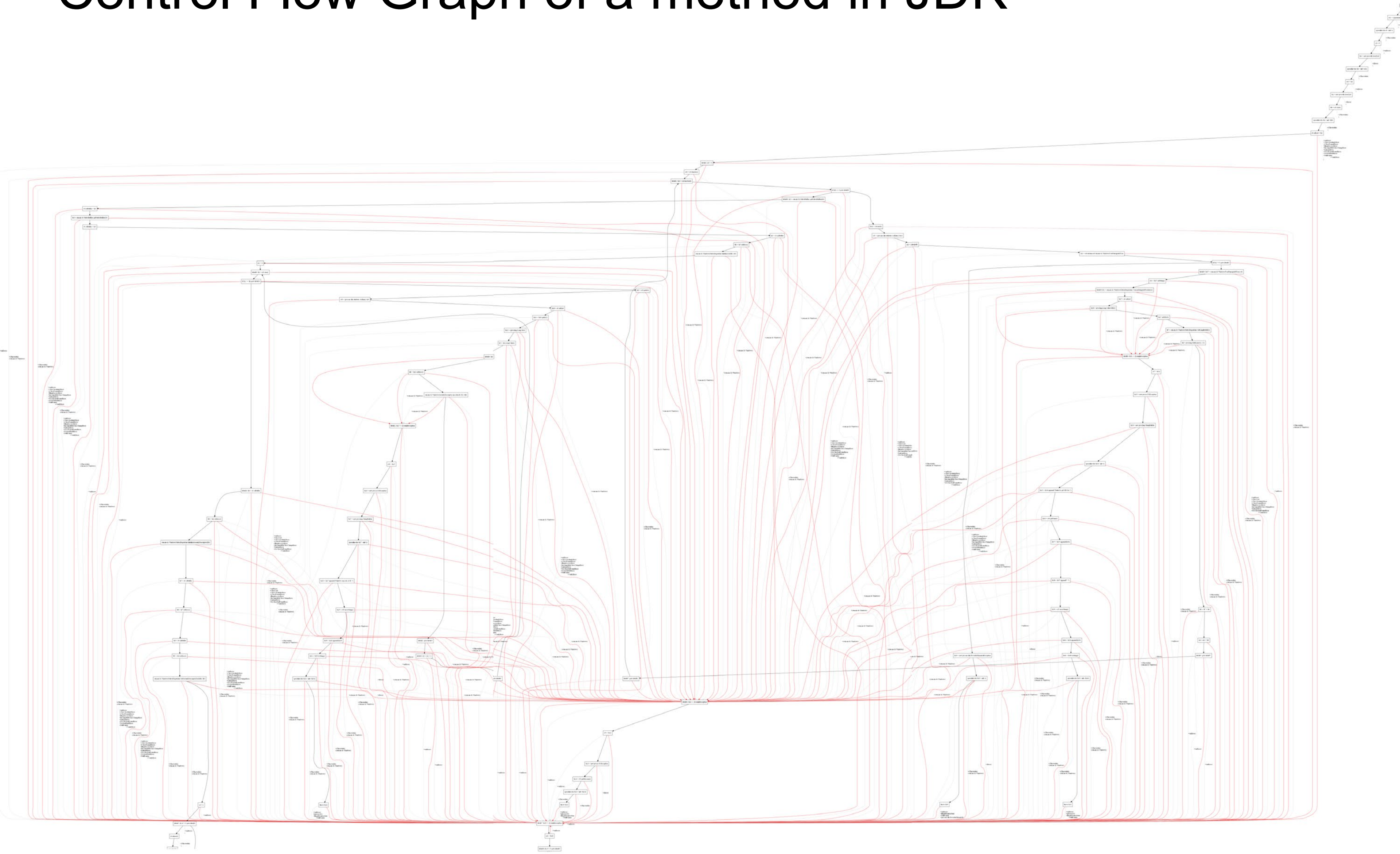


Control Flow Graph of a method in JDK



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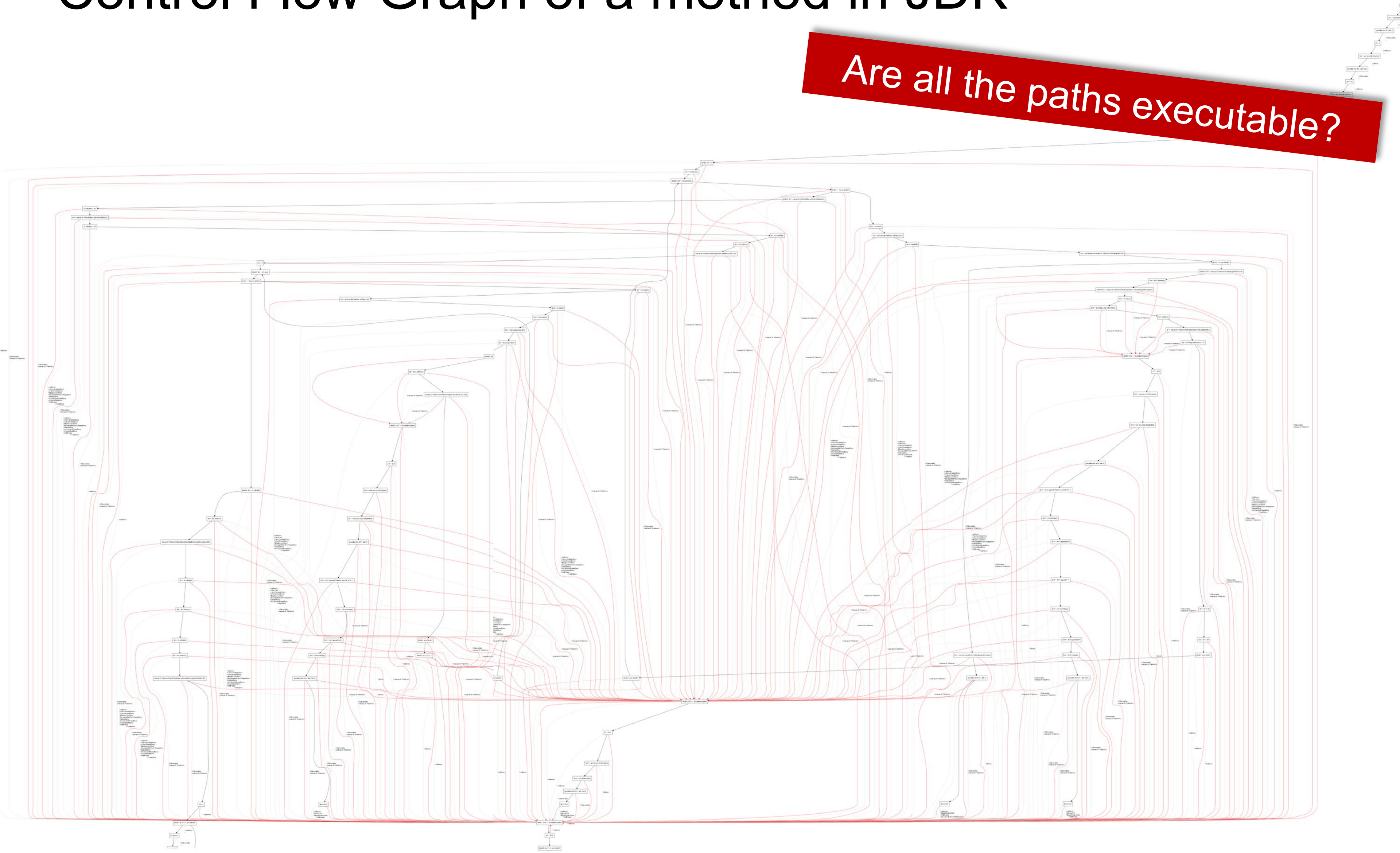

Are all the paths executable?

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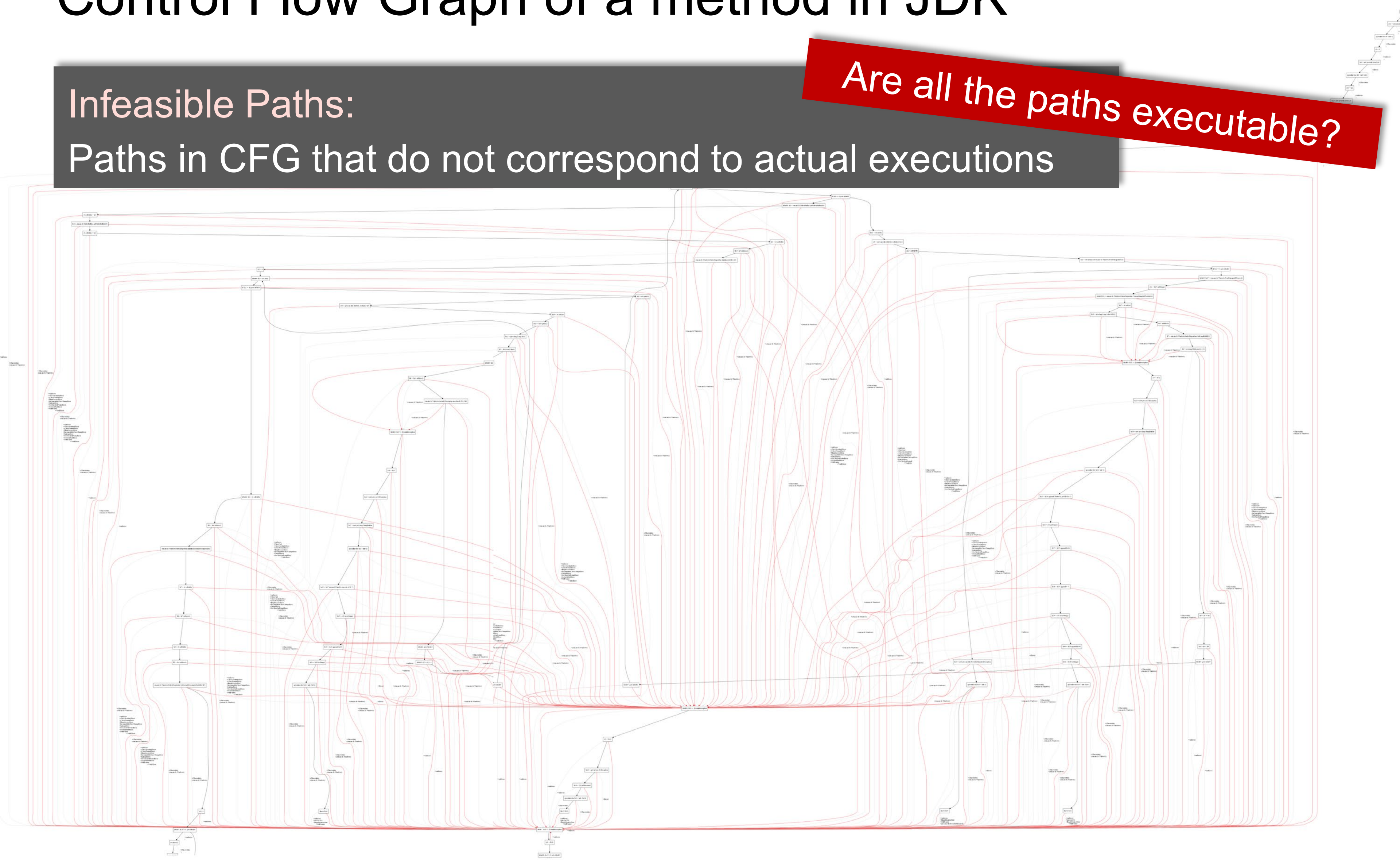

Infeasible Paths:

Paths in CFG that do not correspond to actual executions

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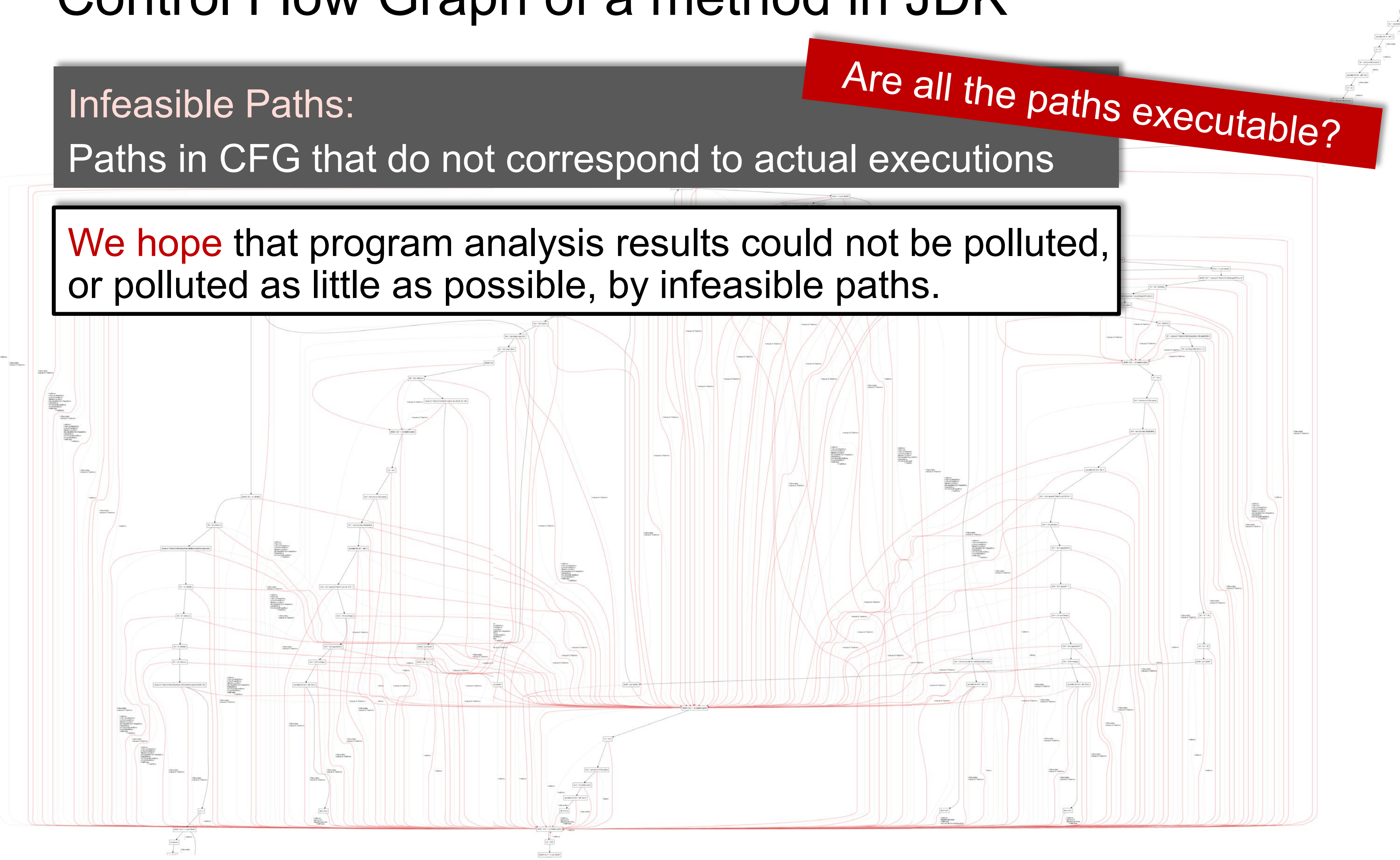

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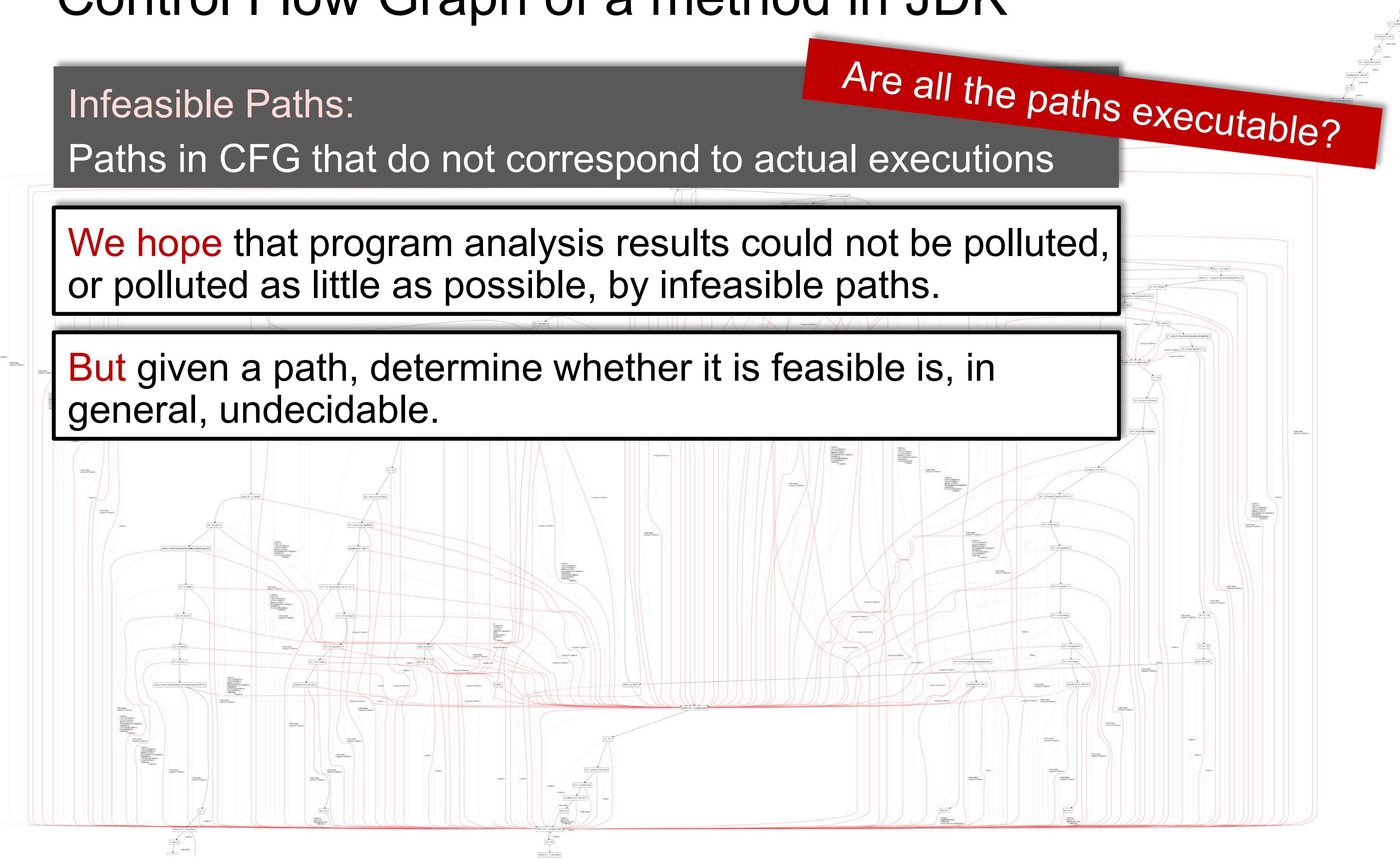

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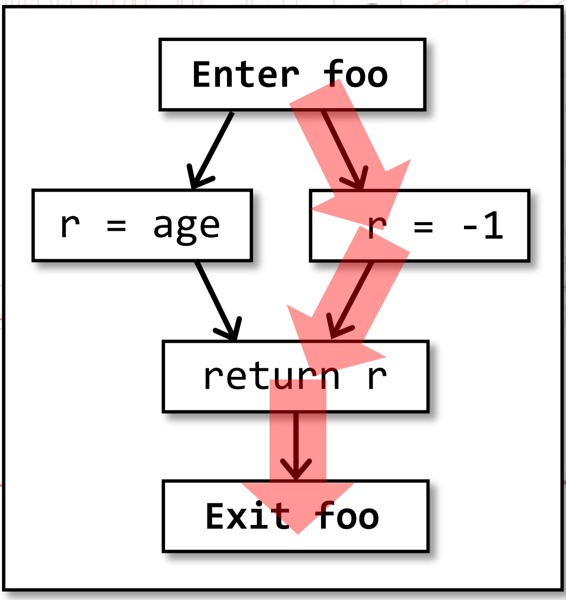

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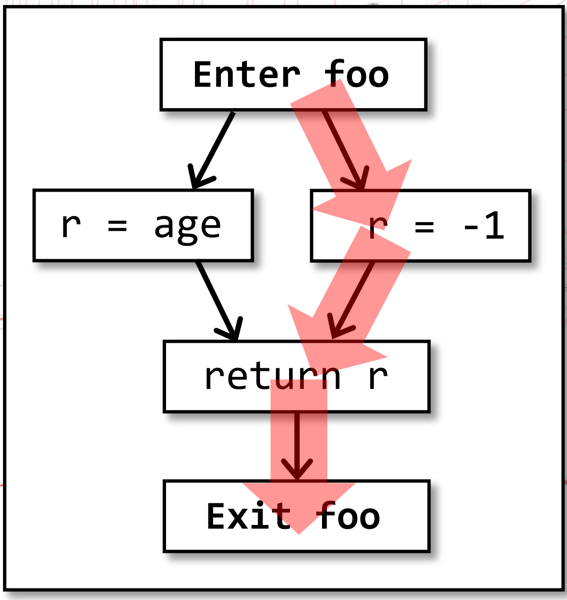

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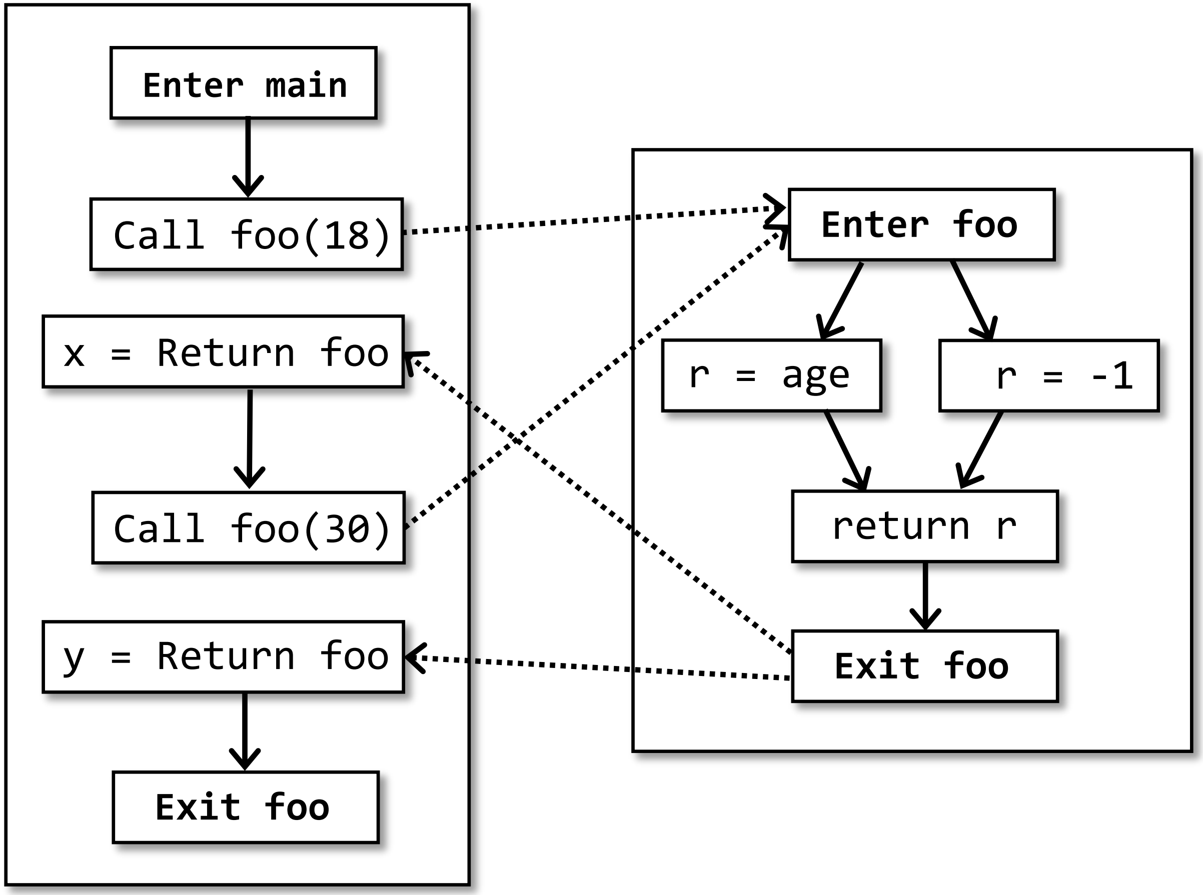

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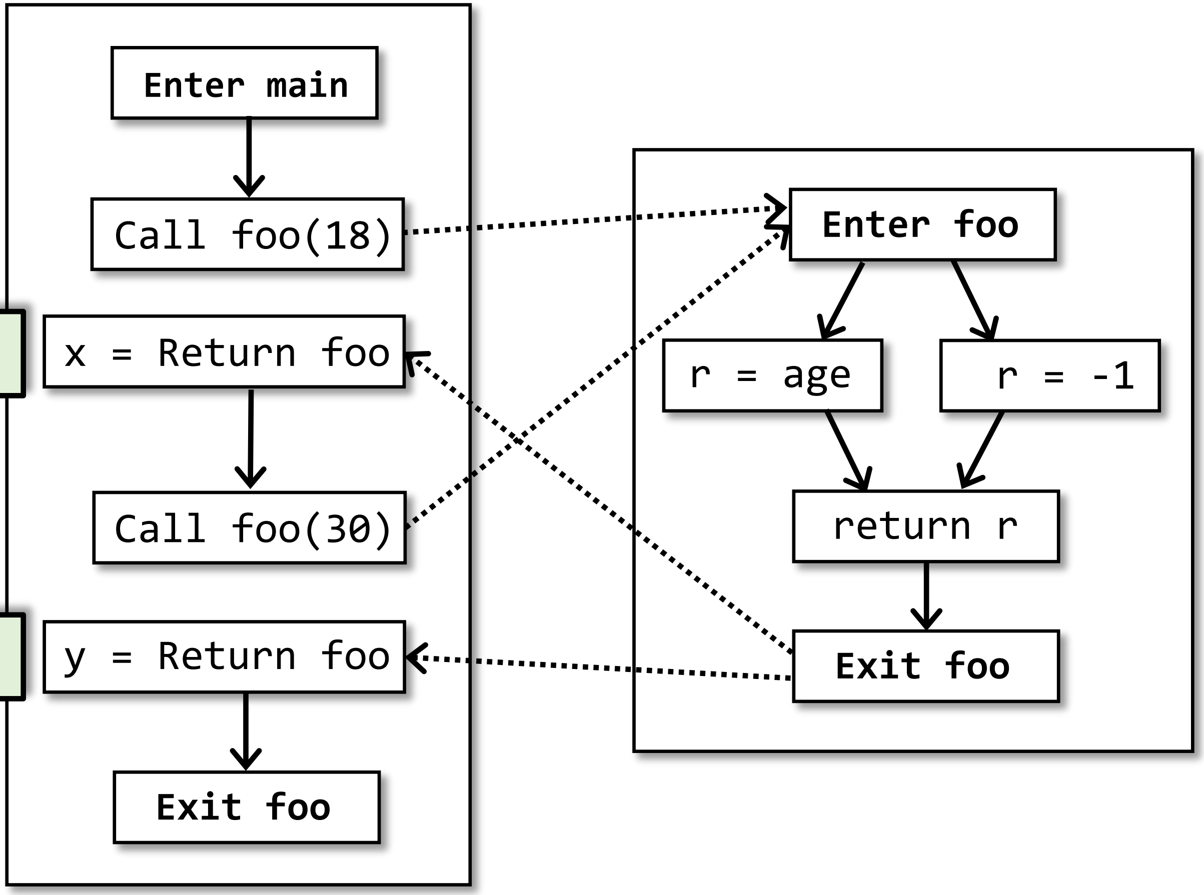

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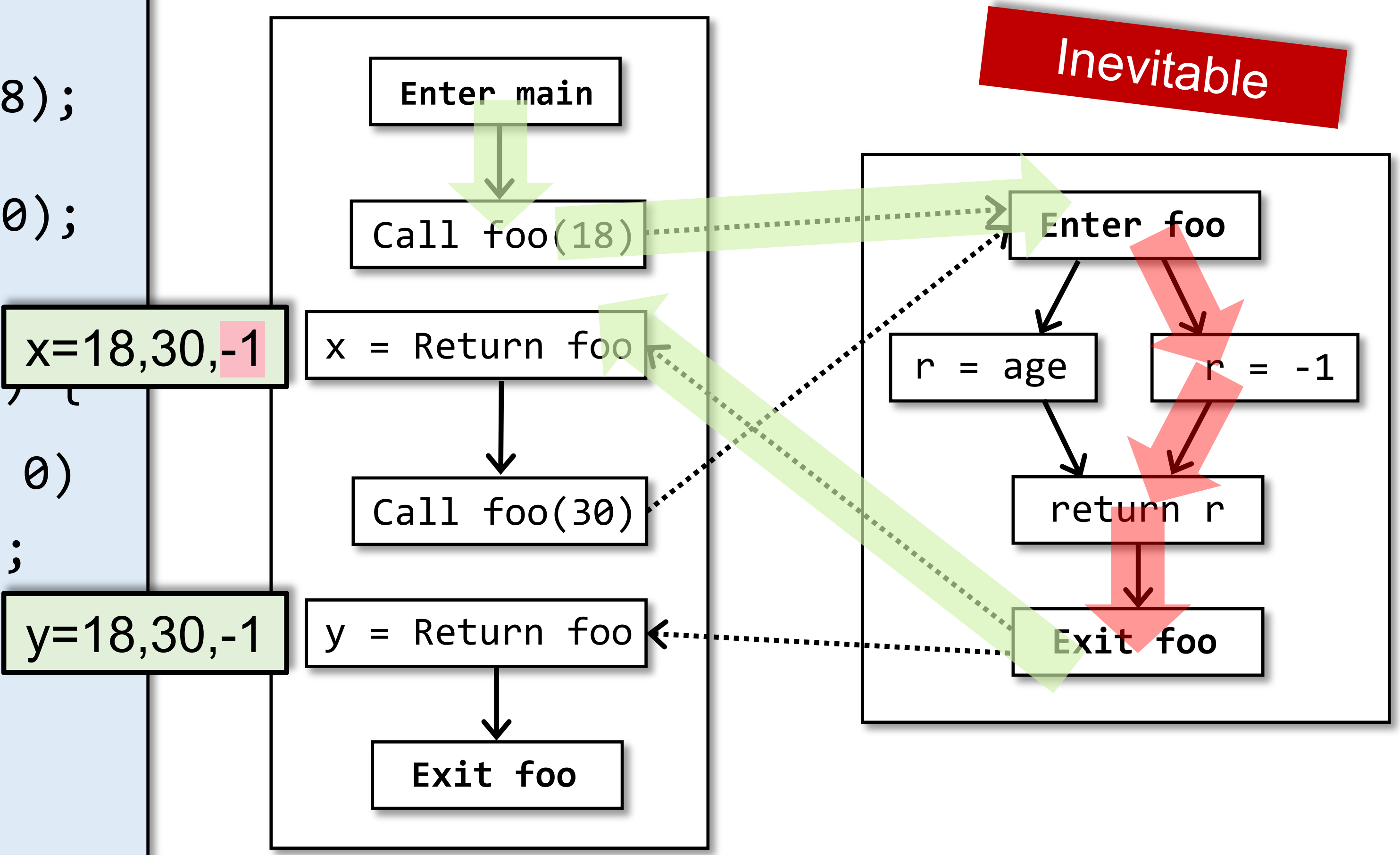

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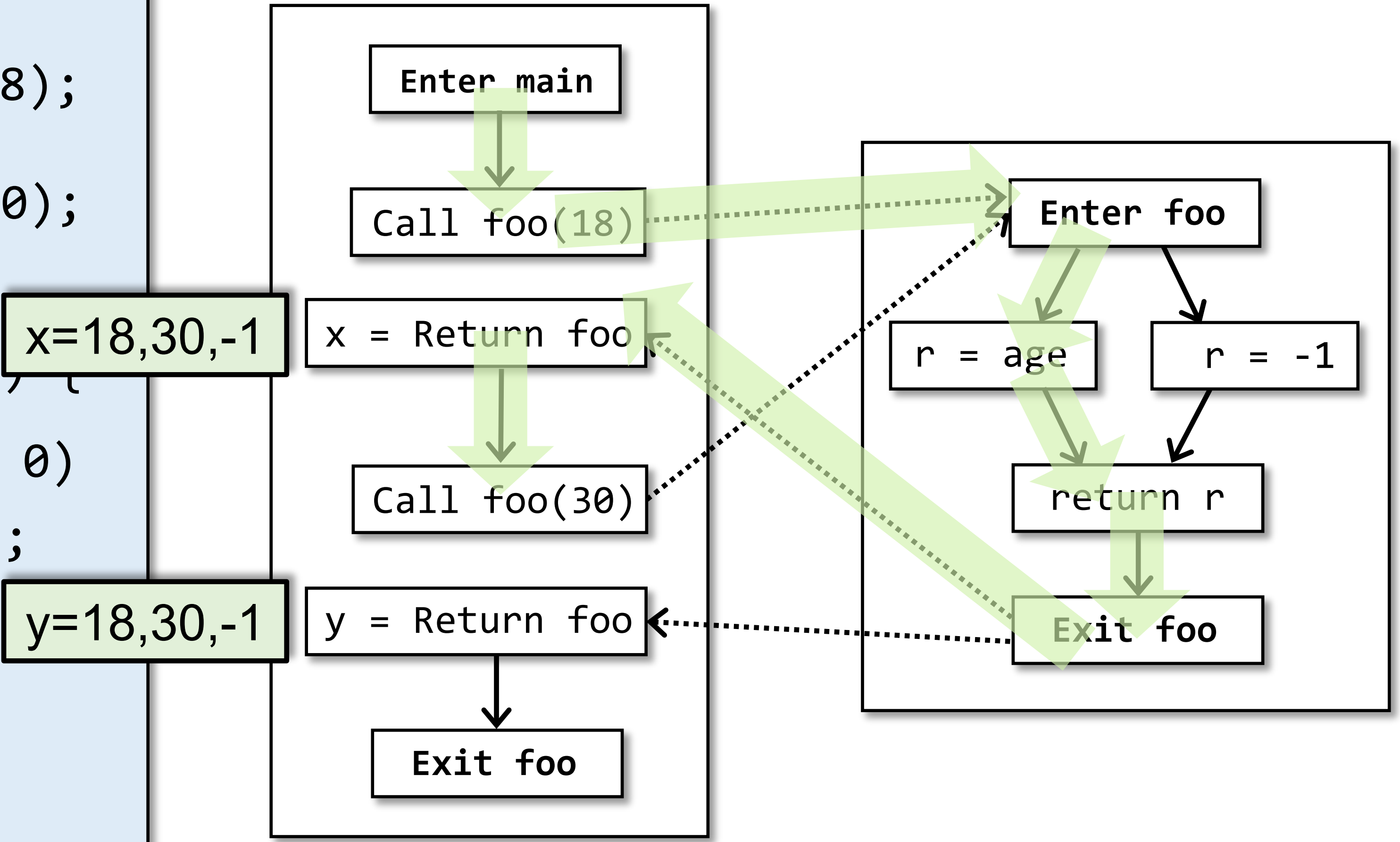

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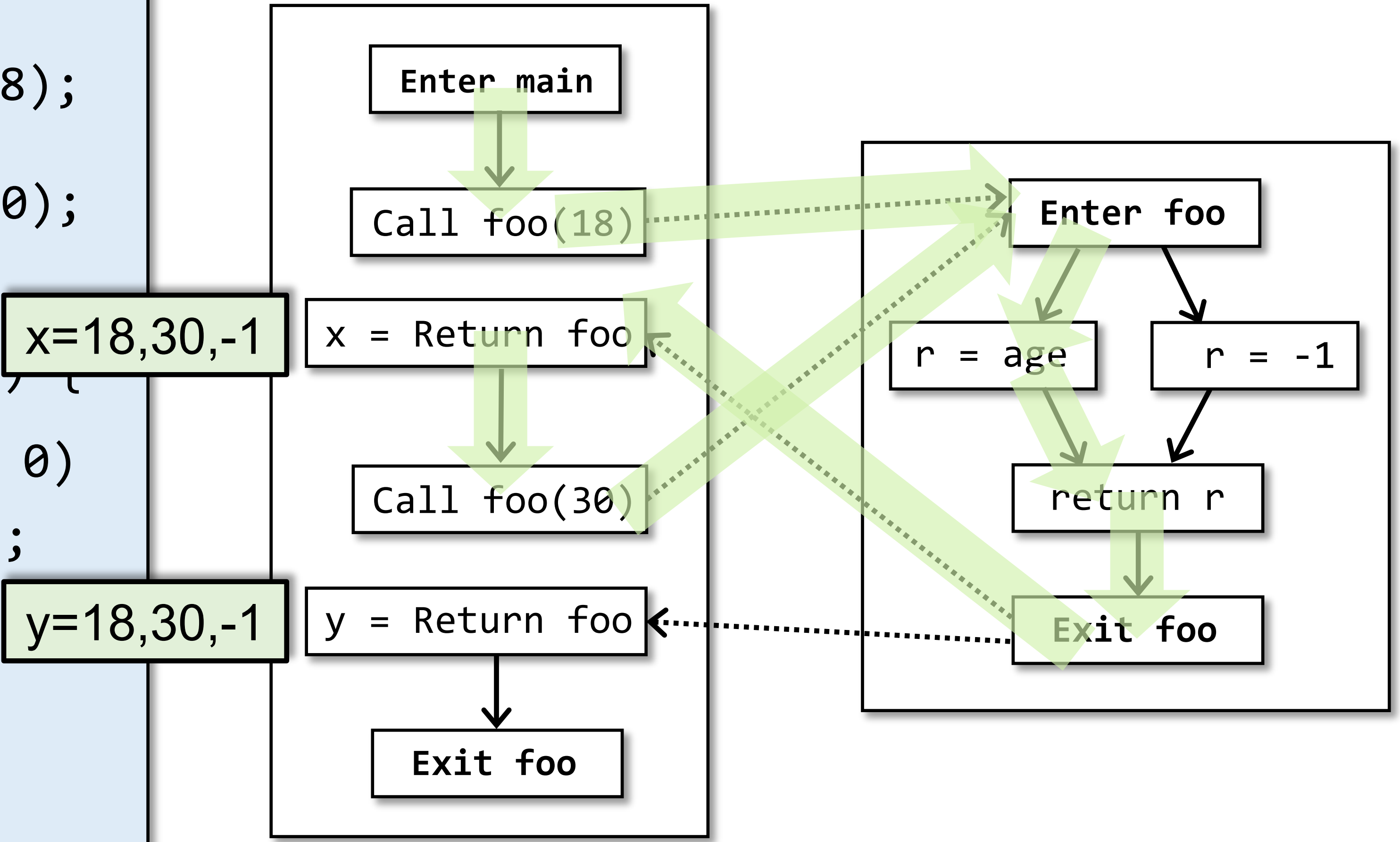

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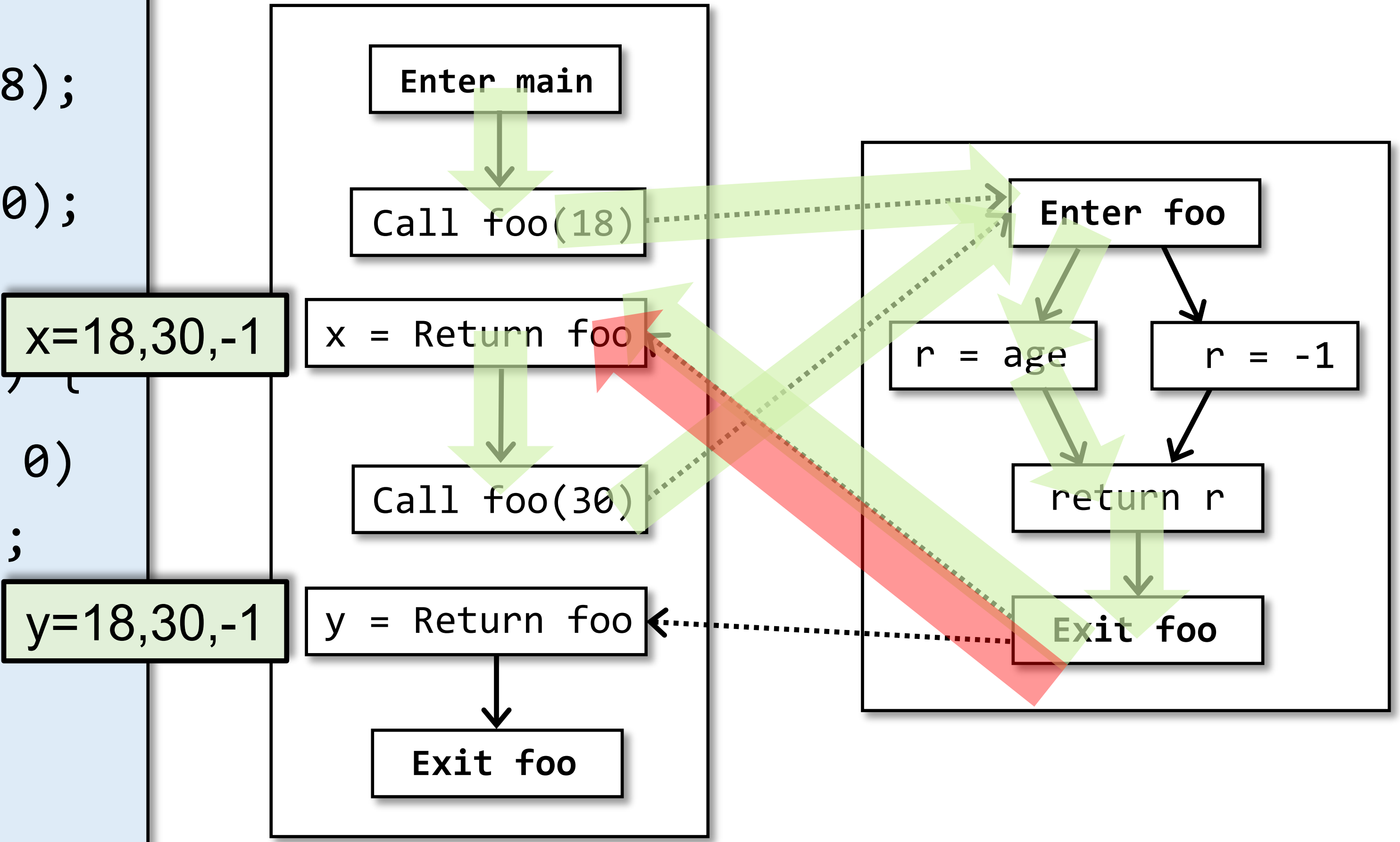

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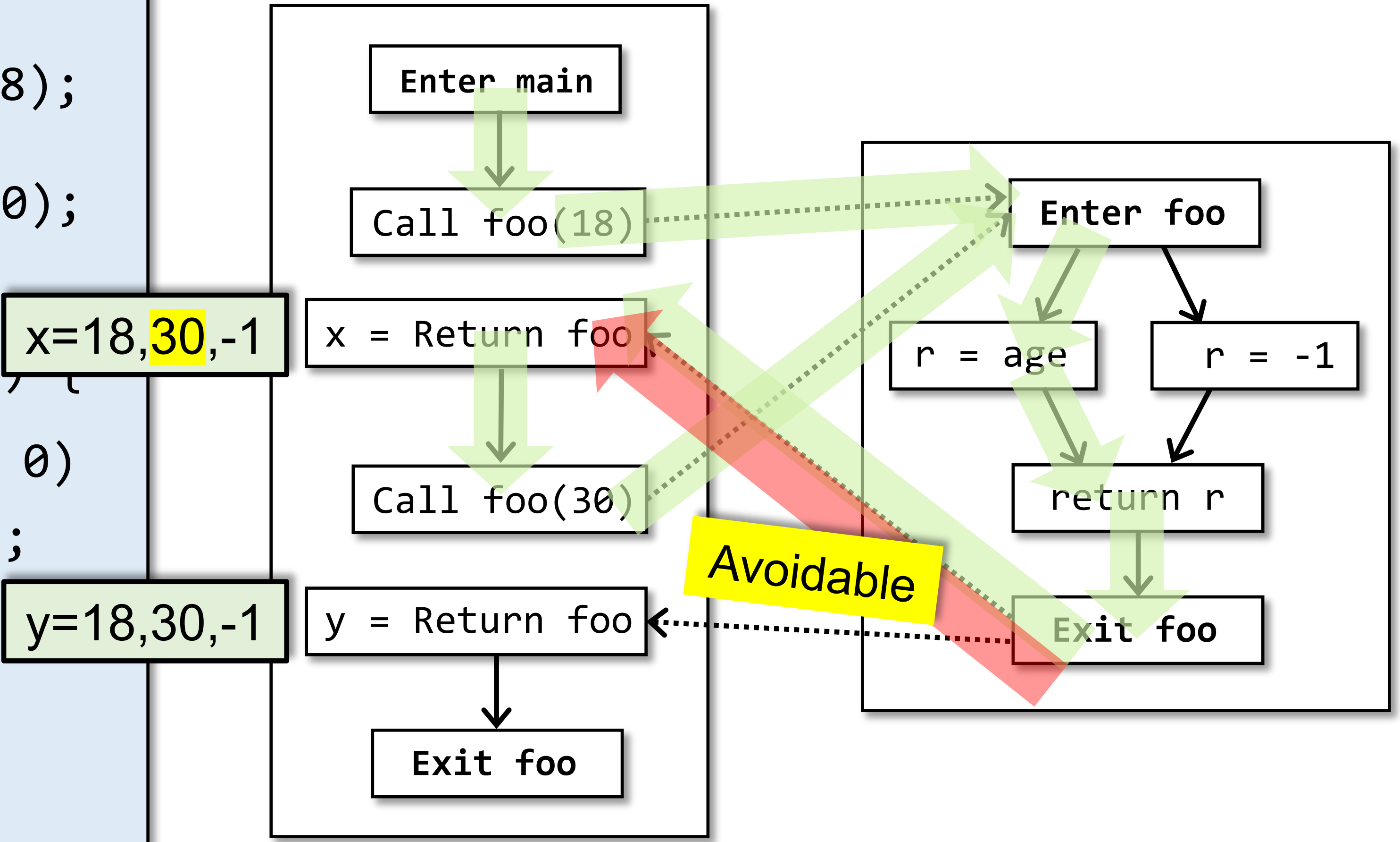

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The paths in which “returns” are matched with corresponding “calls”

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- Our goal is to recognize realizable paths so that we could avoid polluting analysis results along unrealizable paths.

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How?

- O[illegible] is to recognize realizable paths so that we could avoid polluting analysis results along unrealizable paths.

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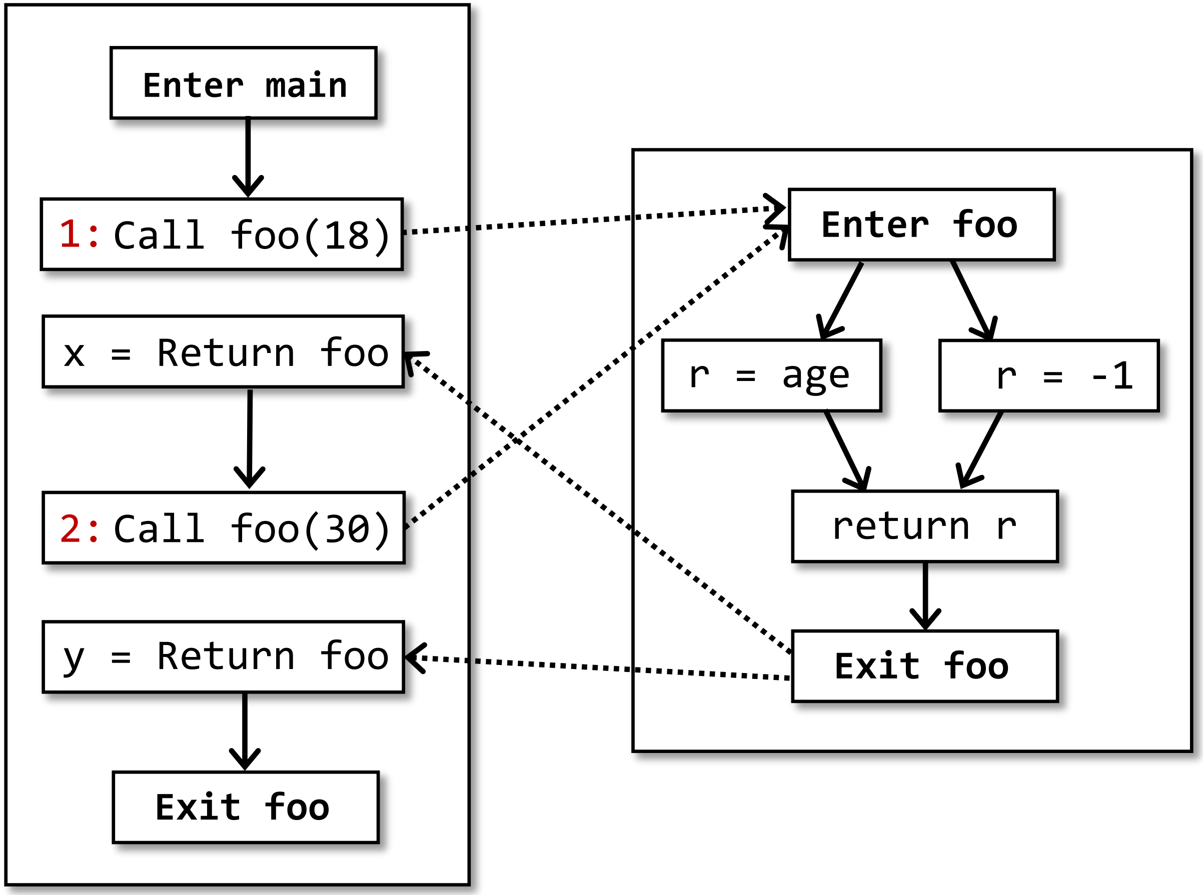

Enter main

1: Call foo(18)

x = Return foo

2: Call foo(30)

y = Return foo

Exit foo

Enter foo

r = age

r = -1

return r

Exit foo

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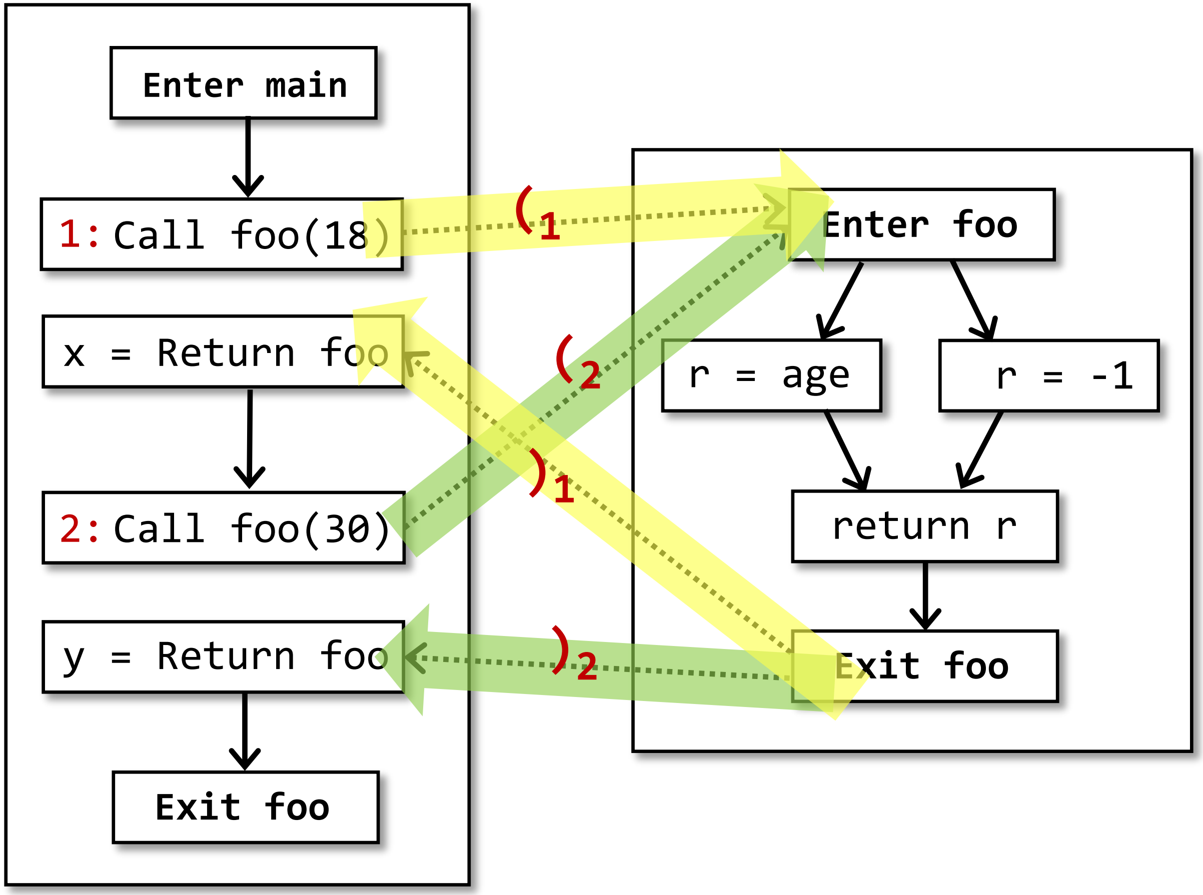

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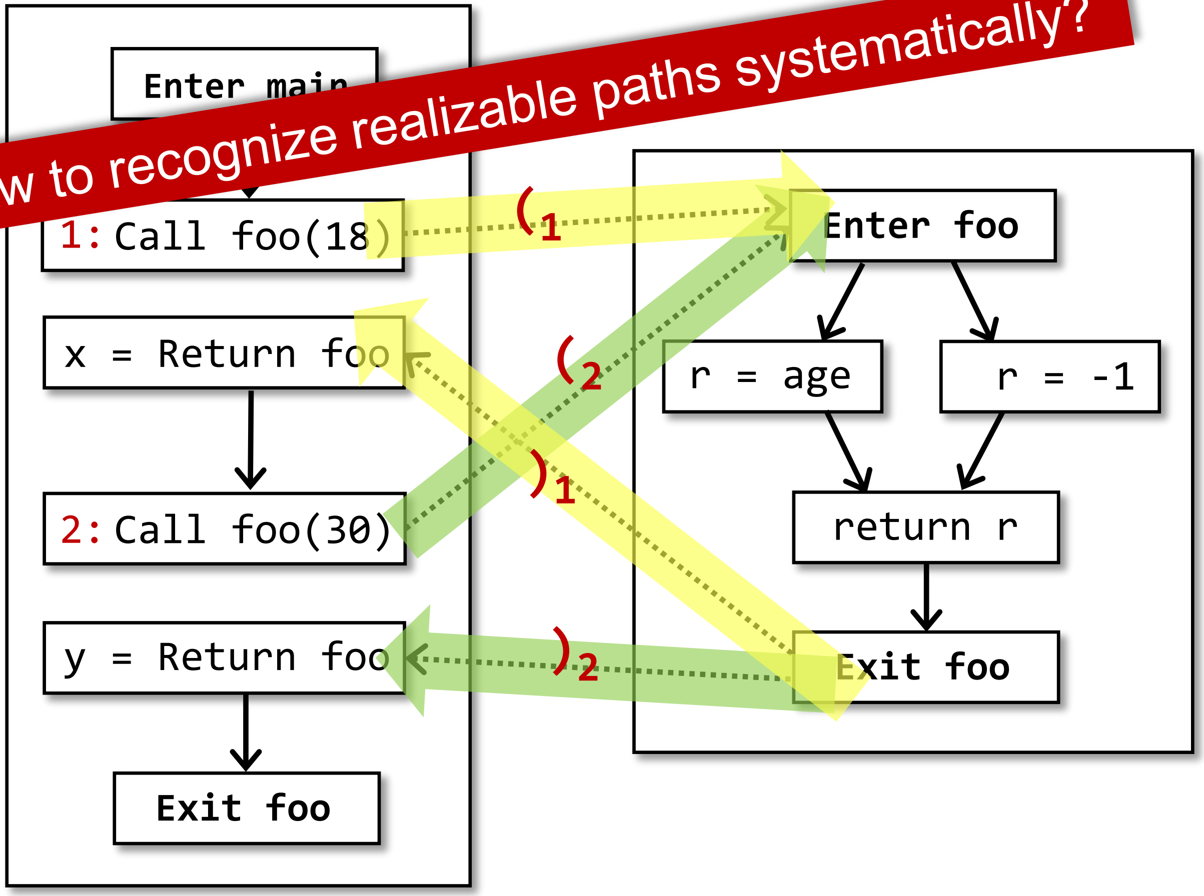

How to recognize realizable paths systematically?

CFL-Reachability

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A path is considered to connect two nodes A and B, or B is reachable from A, only if the concatenation of the labels on the edges of the path is a word in a specified context-free language.

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- A context-free language is a language generated by a context-free grammar (CFG).

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- A context-free language is a language generated by a context-free grammar (CFG).

CFG is a formal grammar in which every production is of the form:

$$S \rightarrow \alpha$$

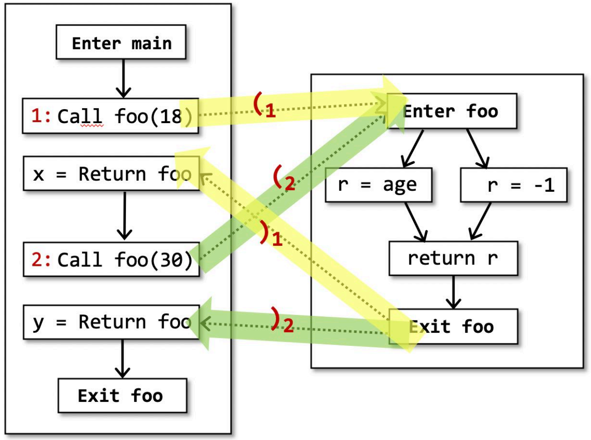
where S is a single nonterminal and α could be a string of terminals and/or nonterminals, or empty.

- S → aSb
- S → ε

Context-free means S could be replaced by aSb/ε anywhere, regardless of where S occurs.

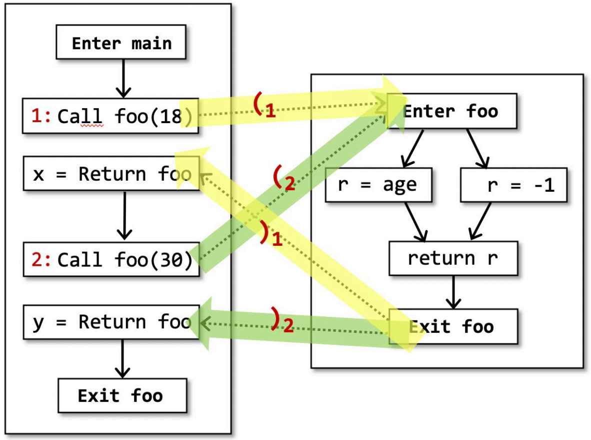
CFL-Reachability

Partially Balanced-Parenthesis Problem via CFL



- Every right parenthesis “$)_i$” is balanced by a preceding left parenthesis “$(_i$”, but the converse needs not hold
- For each call site i, label its call edge “$(_i$” and return edge “$)_i$”
- Label all other edges with symbol “e”

CFL-Reachability



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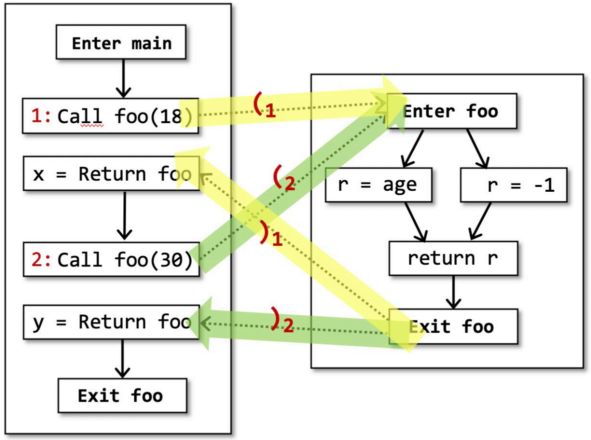

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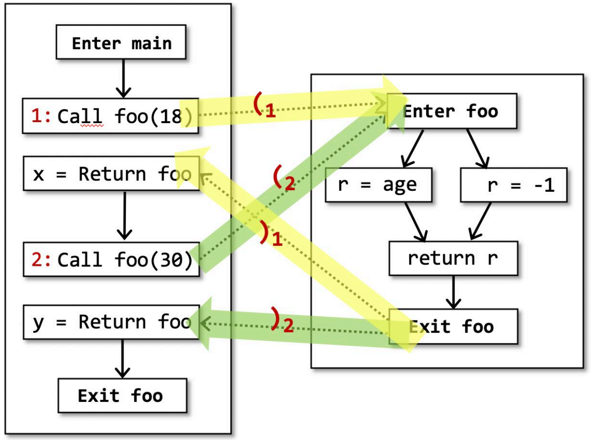

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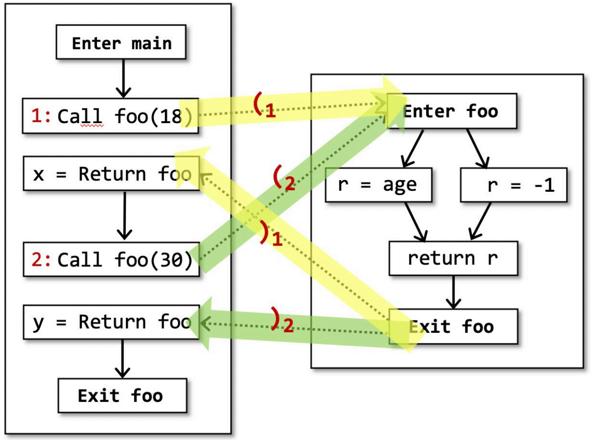

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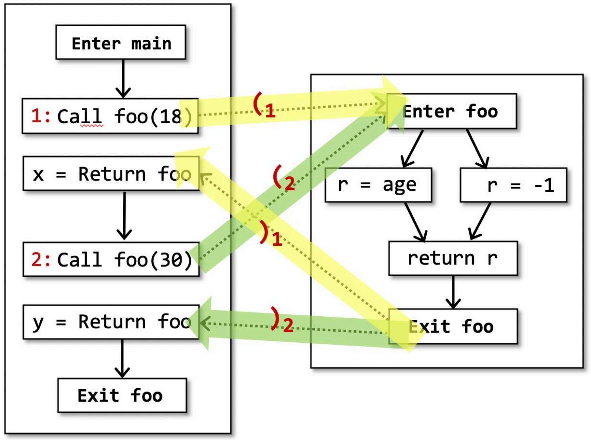

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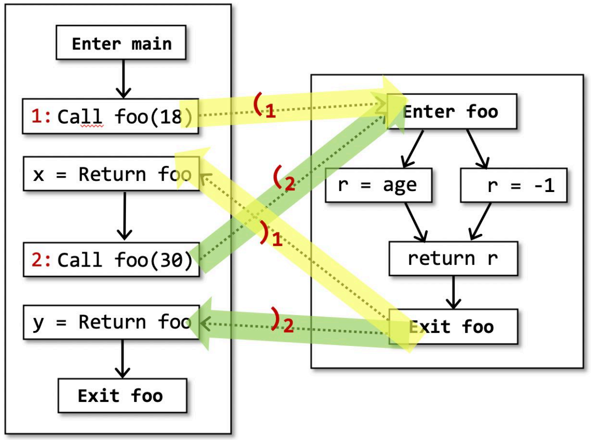

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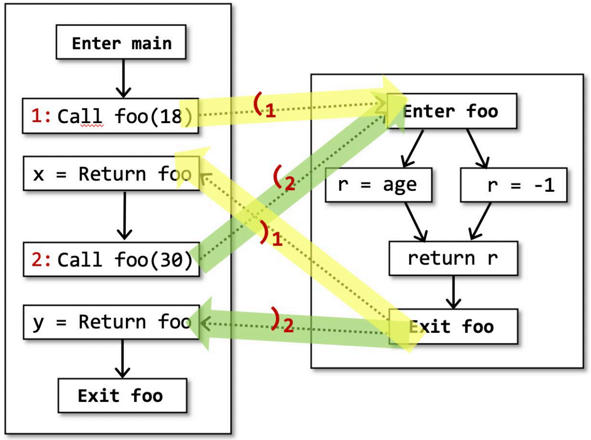

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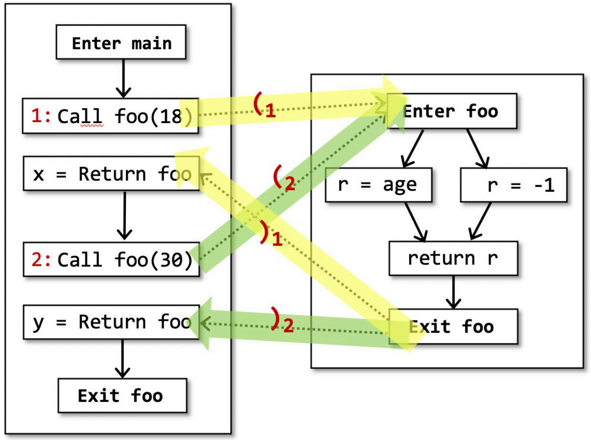

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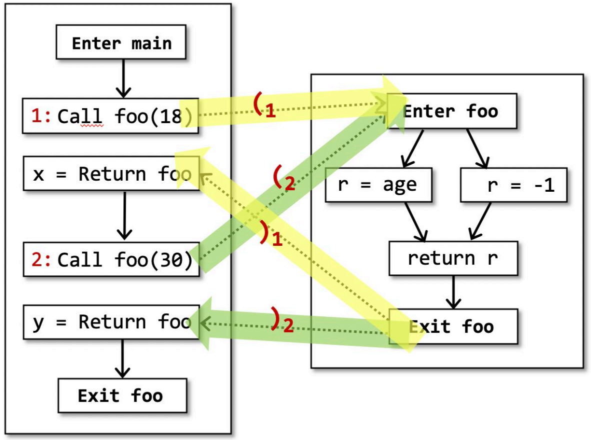

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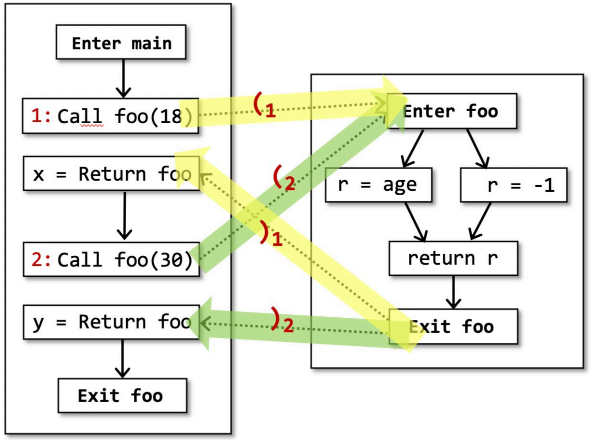

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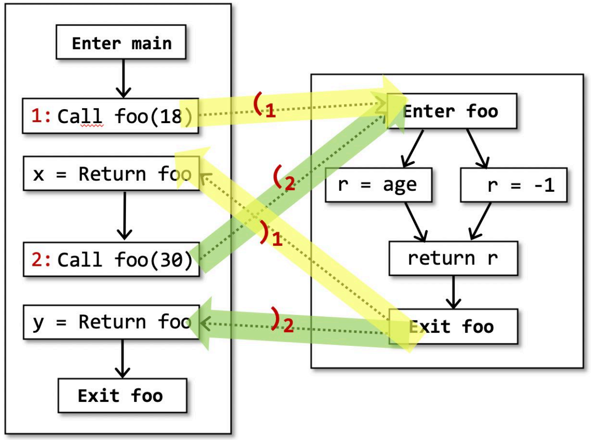

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→ e
→ ε
→ *matched matched*

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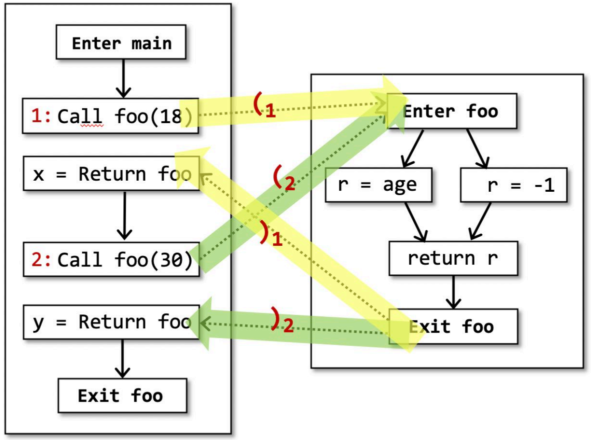

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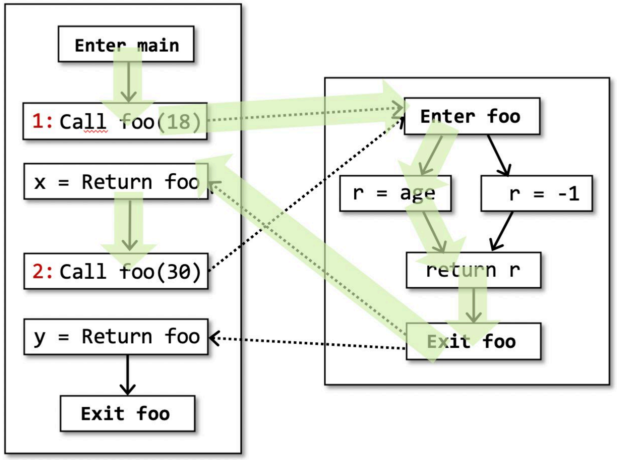

L(realizable):

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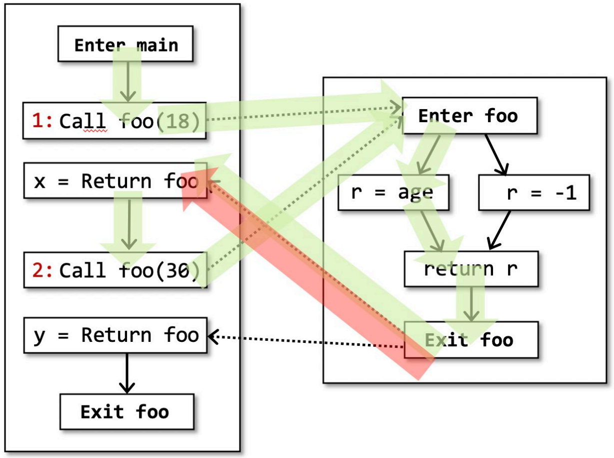
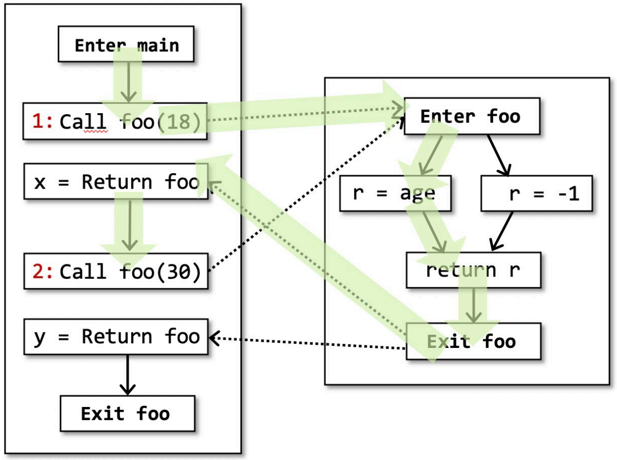
\mathit{matched} &\rightarrow (_{i}\ \mathit{matched}\ )_{i}\\
&\rightarrow e\\
&\rightarrow \varepsilon\\
&\rightarrow \mathit{matched}\ \mathit{matched}
\end{aligned}
$$





$e(_1eee)_1e \in L(realizable)$

L(realizable):

realizable → *matched realizable*

→ $(_i$ *realizable*

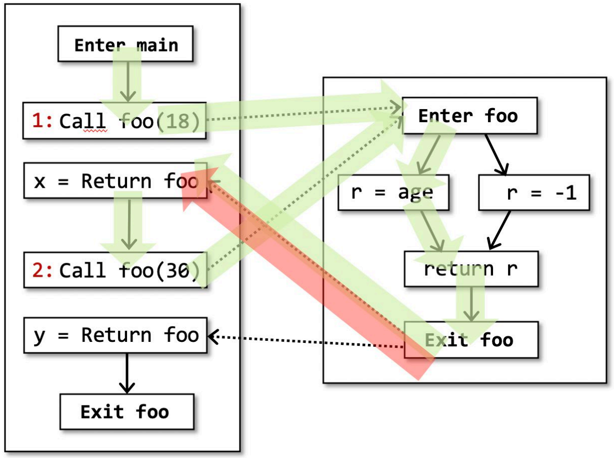
→ ε

matched → $(_i$ *matched* $)_i$

→ e

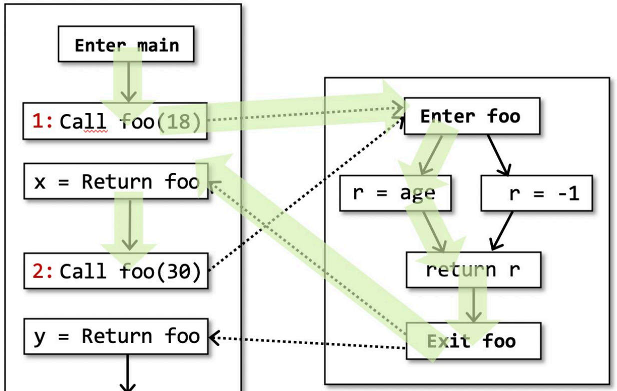
→ ε

→ *matched matched*



L(realizable):

$$\begin{aligned}
\textit{realizable} &\rightarrow \textit{matched}\ \ \textit{realizable} \\
&\rightarrow (_i\ \ \textit{realizable} \\
&\rightarrow \varepsilon \\
\textit{matched} &\rightarrow (_i\ \textit{matched}\ )_i \\
&\rightarrow e \\
&\rightarrow \varepsilon \\
&\rightarrow \textit{matched}\ \textit{matched}
\end{aligned}$$



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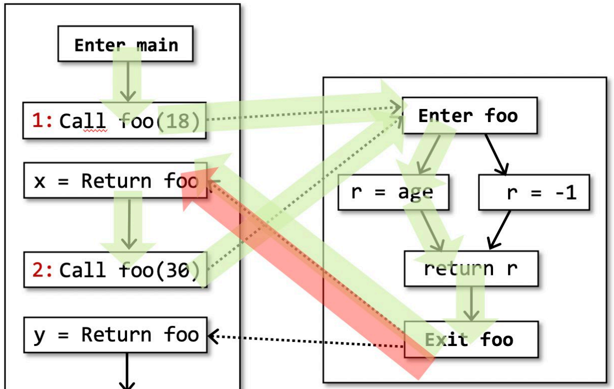
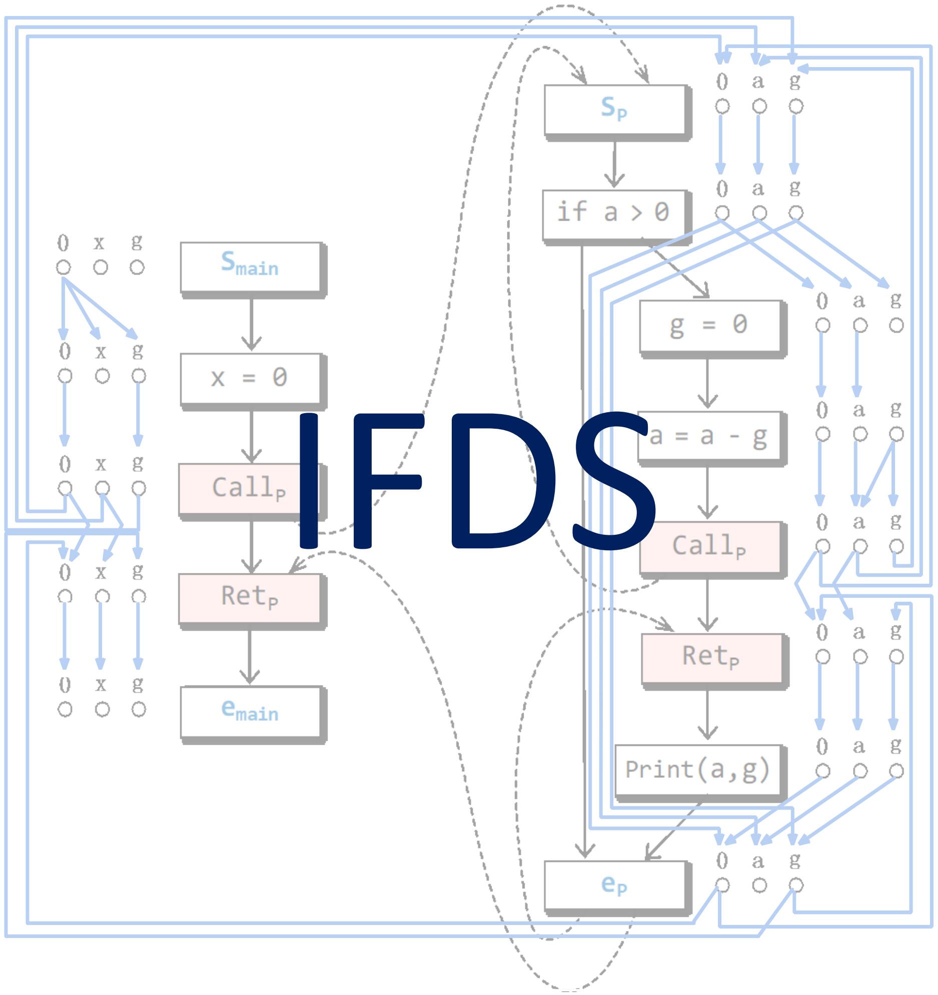


$e(_1eee)_1e(_2eee)_1$

$\notin L(\textit{realizable})$

IFDS



A Program Analysis Framework via Graph Reachability

Yue Li @ Nanjing University

IFDS

“Precise Interprocedural Dataflow Analysis via Graph Reachability”

Thomas Reps, Susan Horwitz, and Mooly Sagiv, POPL’95

IFDS (Interprocedural, Finite, Distributive, Subset Problem)

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IFDS is for interprocedural data flow analysis
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Provide meet-over-all-realizable-paths (MRP) solution.

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Path function for path *p*, denoted as pf_p, is a composition of flow functions for all edges (sometimes nodes) on *p*.

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$$\boxed{pf_p = f_n \circ \ldots \circ f_2 \circ f_1}$$

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For each node n, MOP_n provides a "meet-over-all-paths" solution where $\mathrm{Paths}(start, n)$ denotes the set of paths in CFG from the start node to n.

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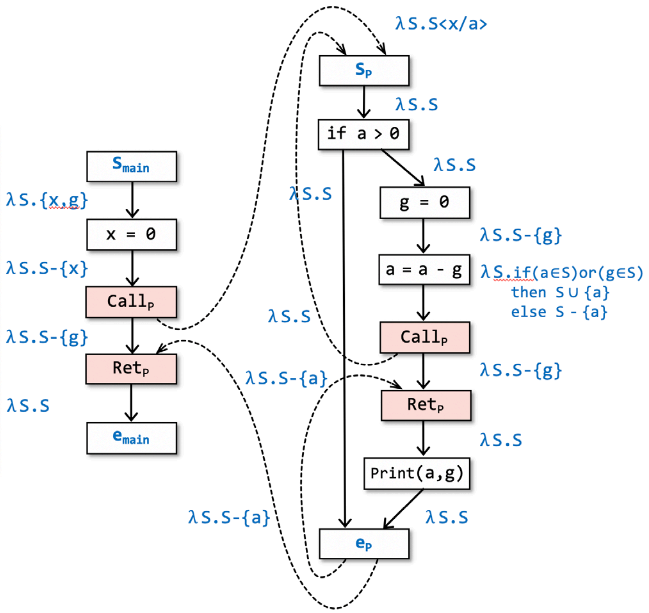

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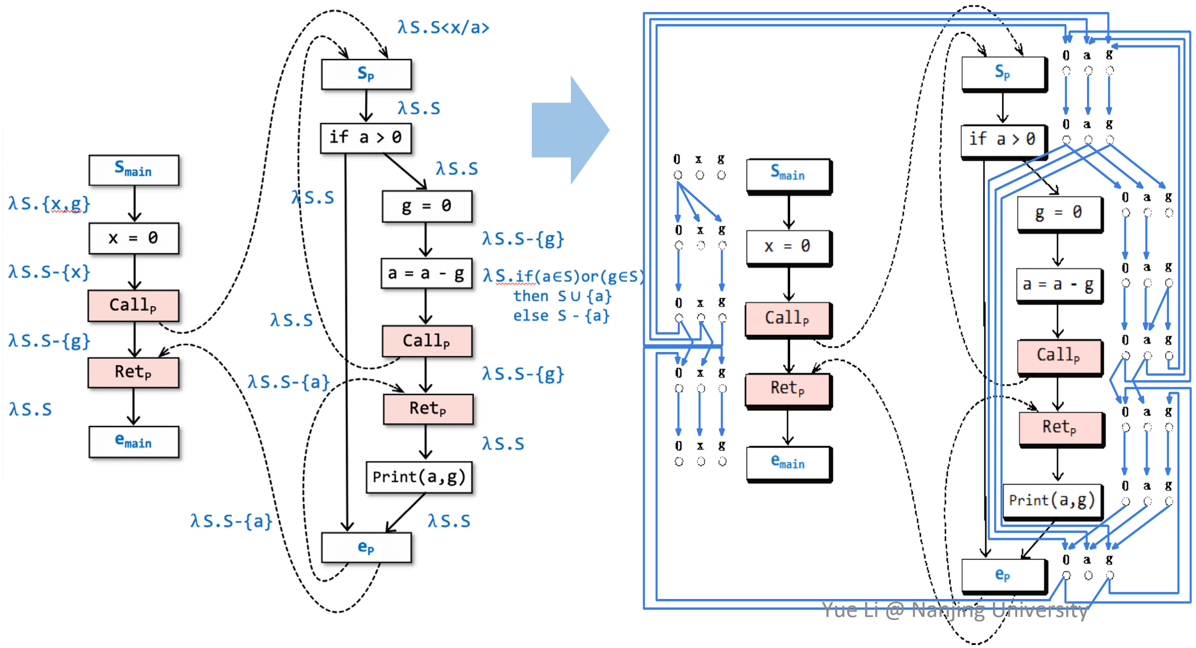

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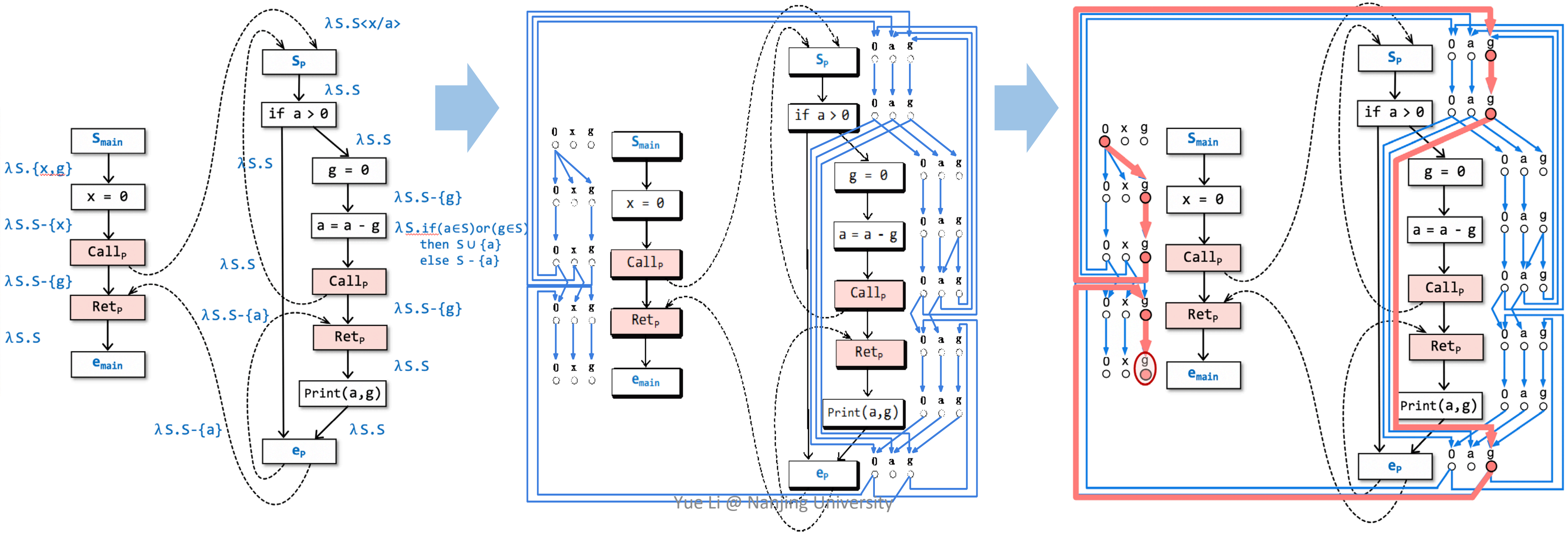

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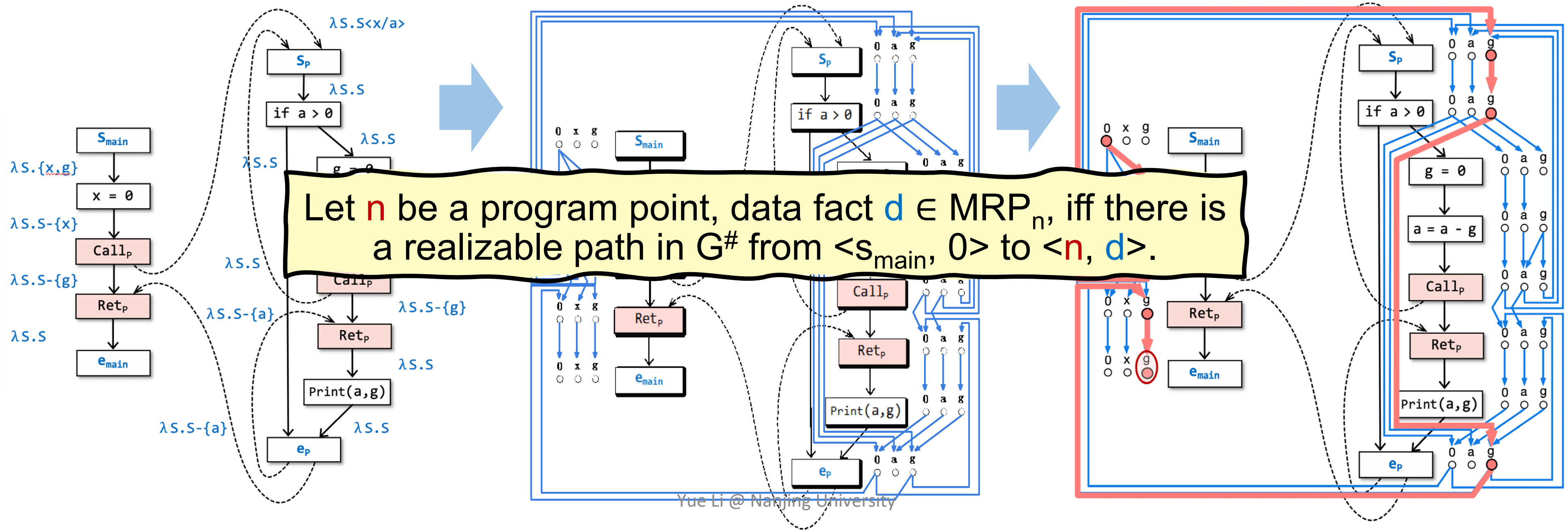

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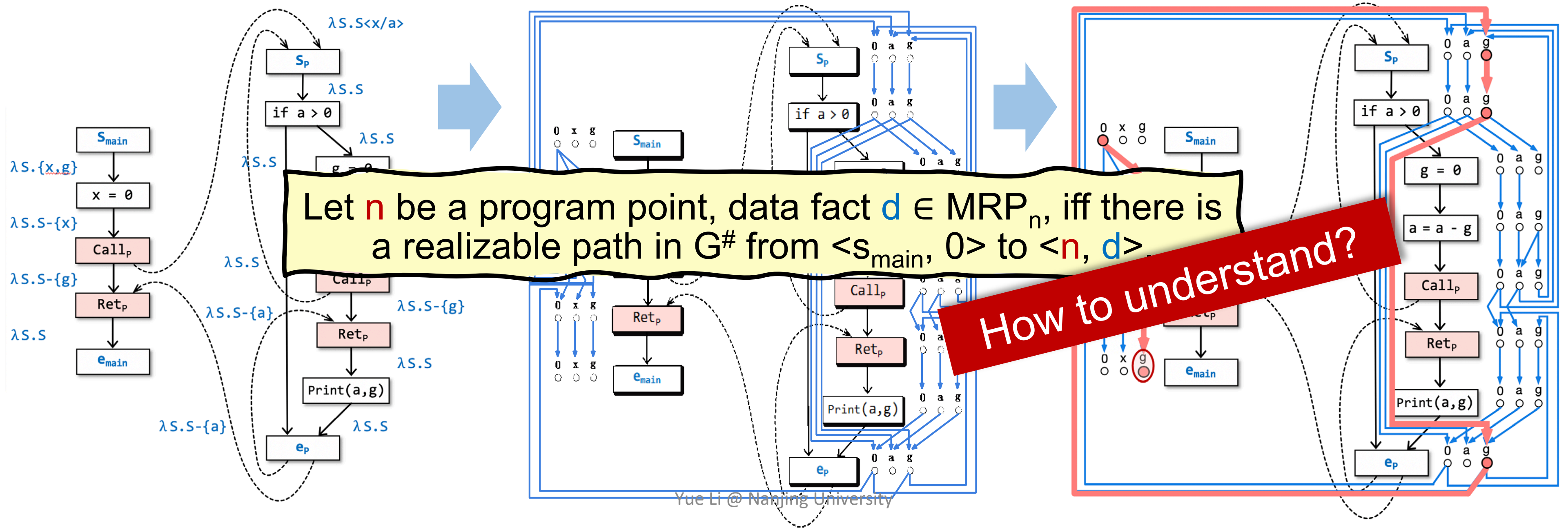

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How to understand?

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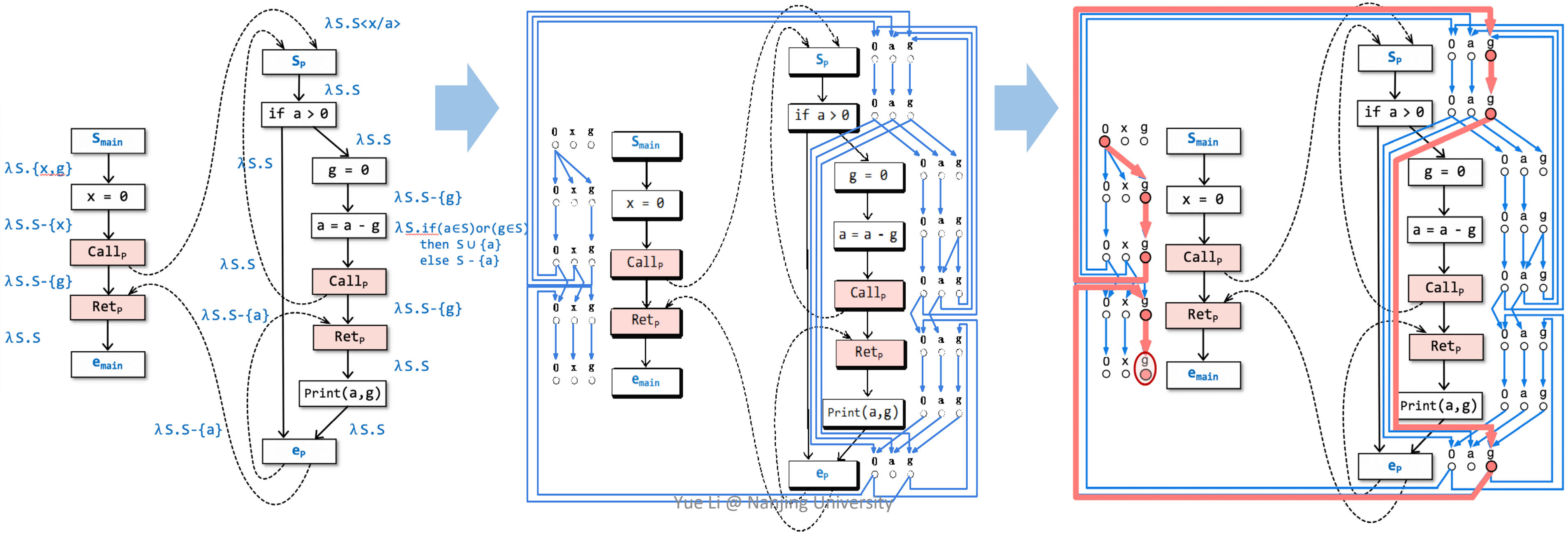

Supergraph

In IFDS, a program is represented by G* = (N*, E*) called a supergraph.

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int g;
main(){
  int x;
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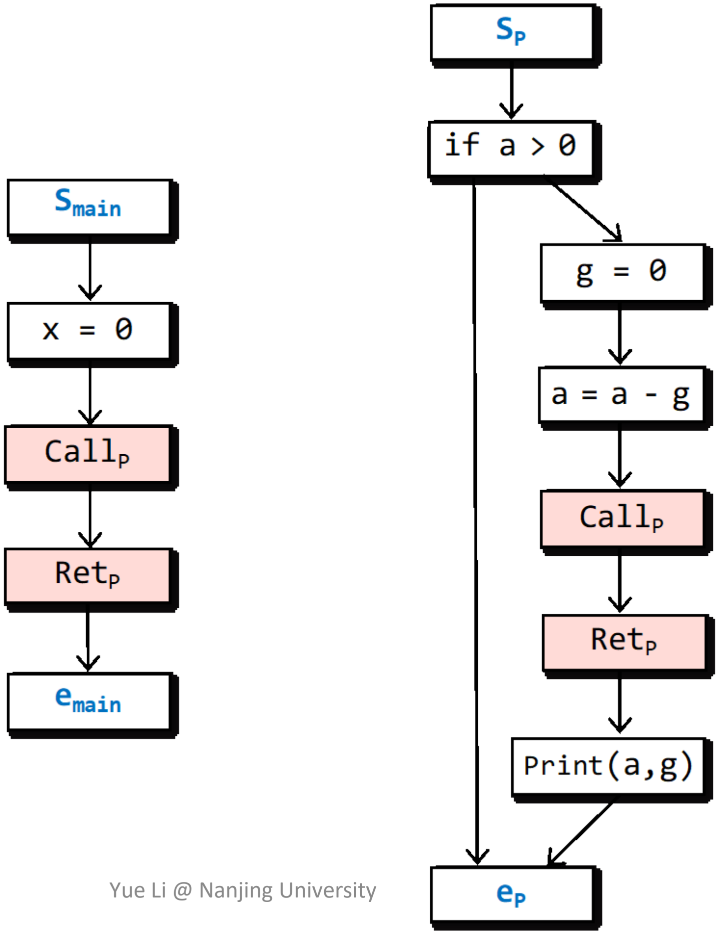
  P(x);
}
P(int a){
  if(a > 0){
    g = 0;
    a = a - g;
    P(a);
    Print(a,g);
  }
}
```



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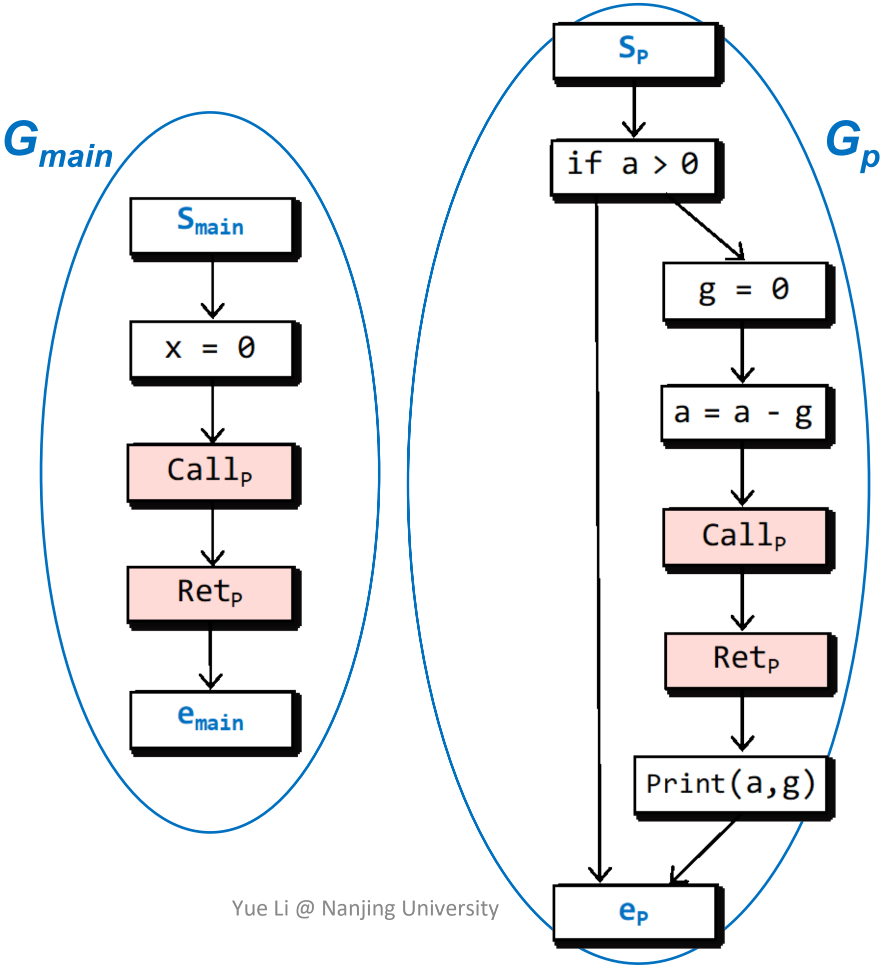

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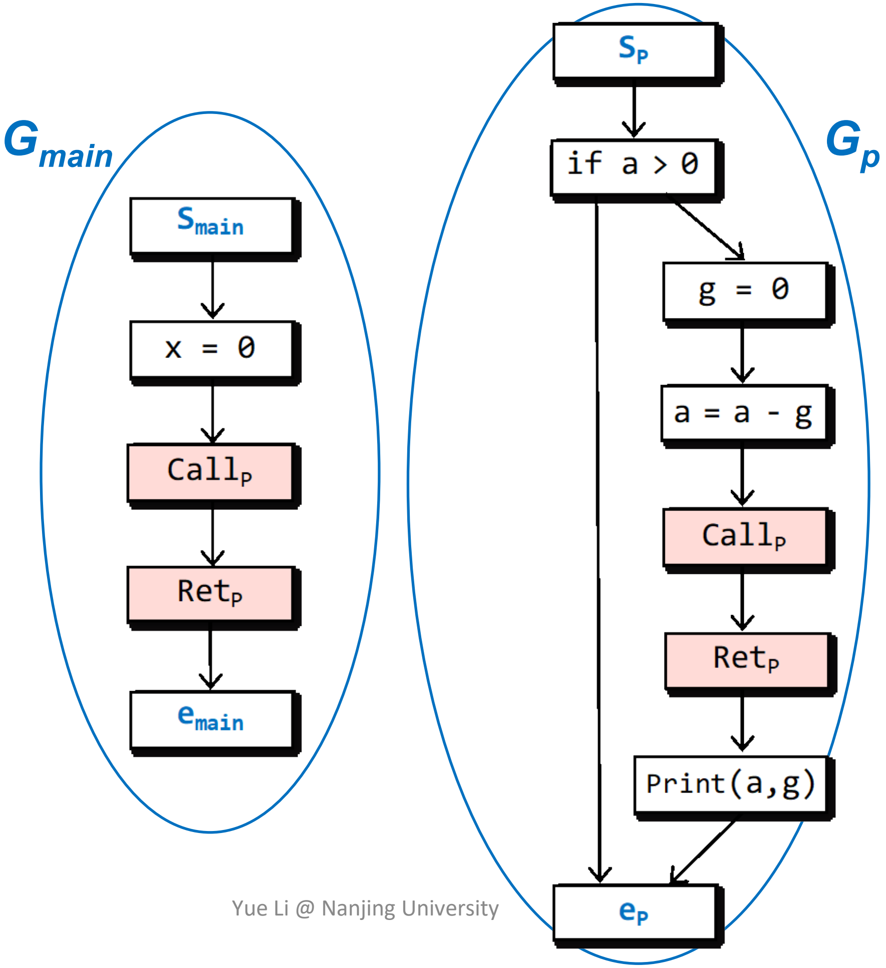

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- *Each flowgraph G_p has a unique start node s_p, and a unique exit node e_p*
- *A procedure call is represented by a call node $Call_p$, and a return-site node Ret_p*

```
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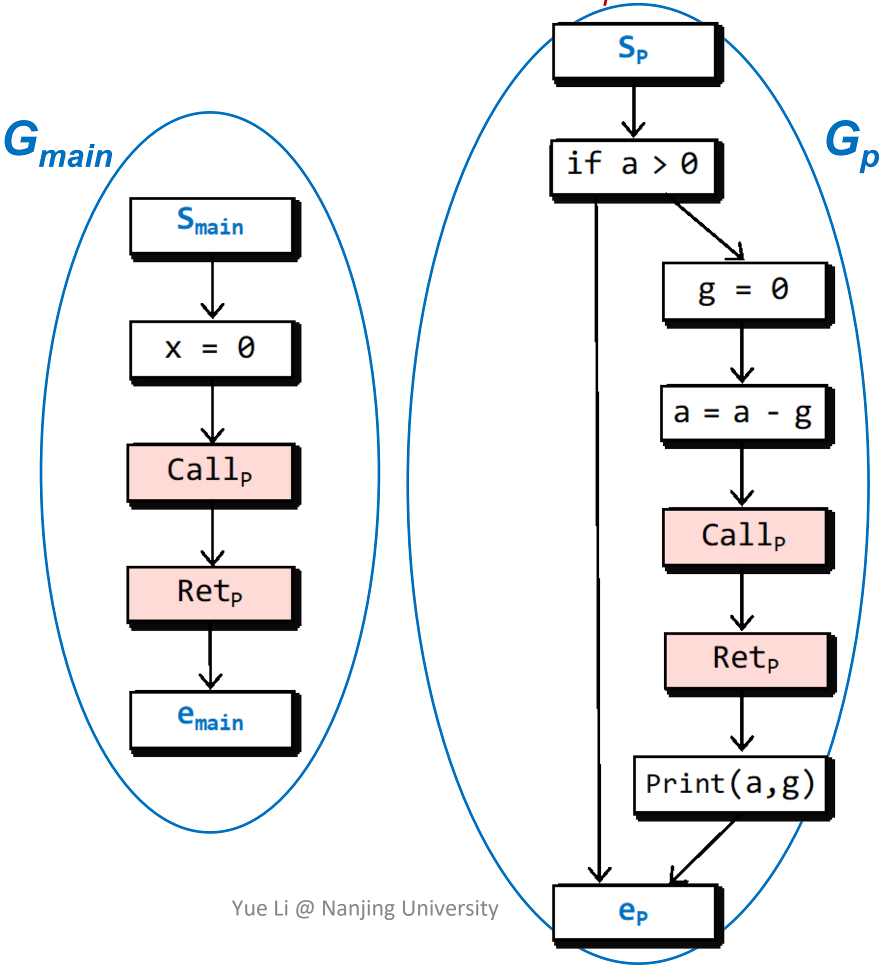

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G has three edges for each procedure call:*

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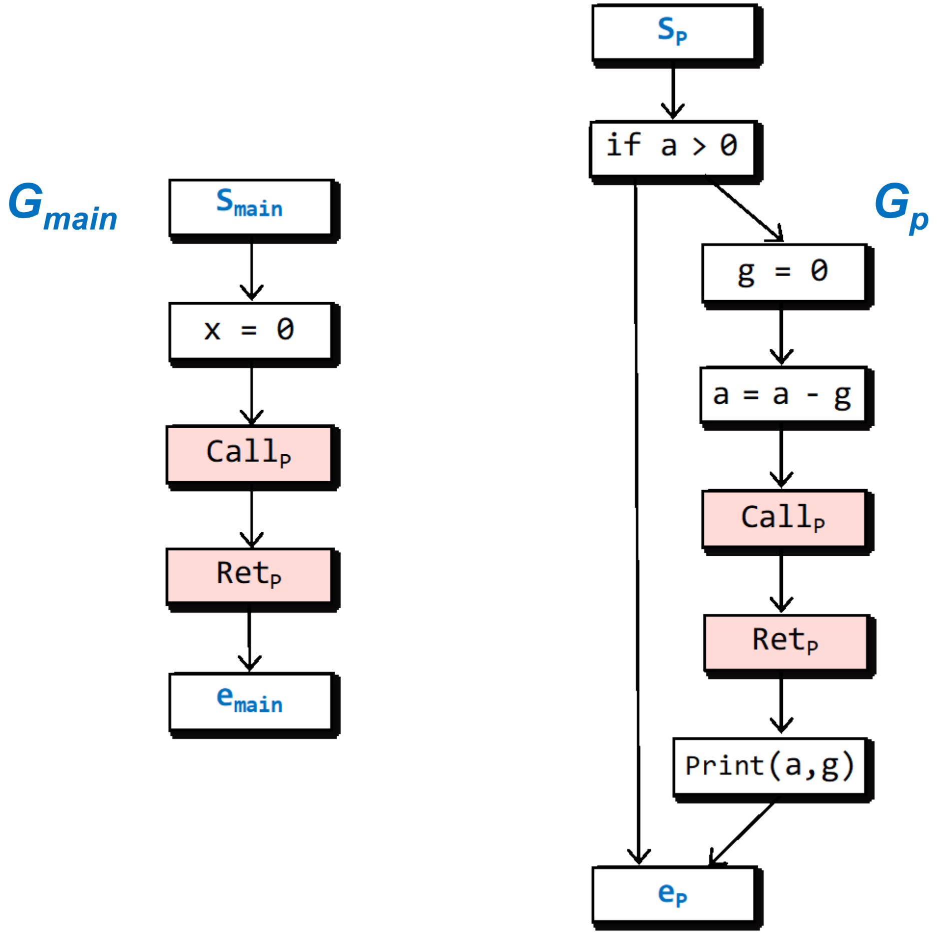

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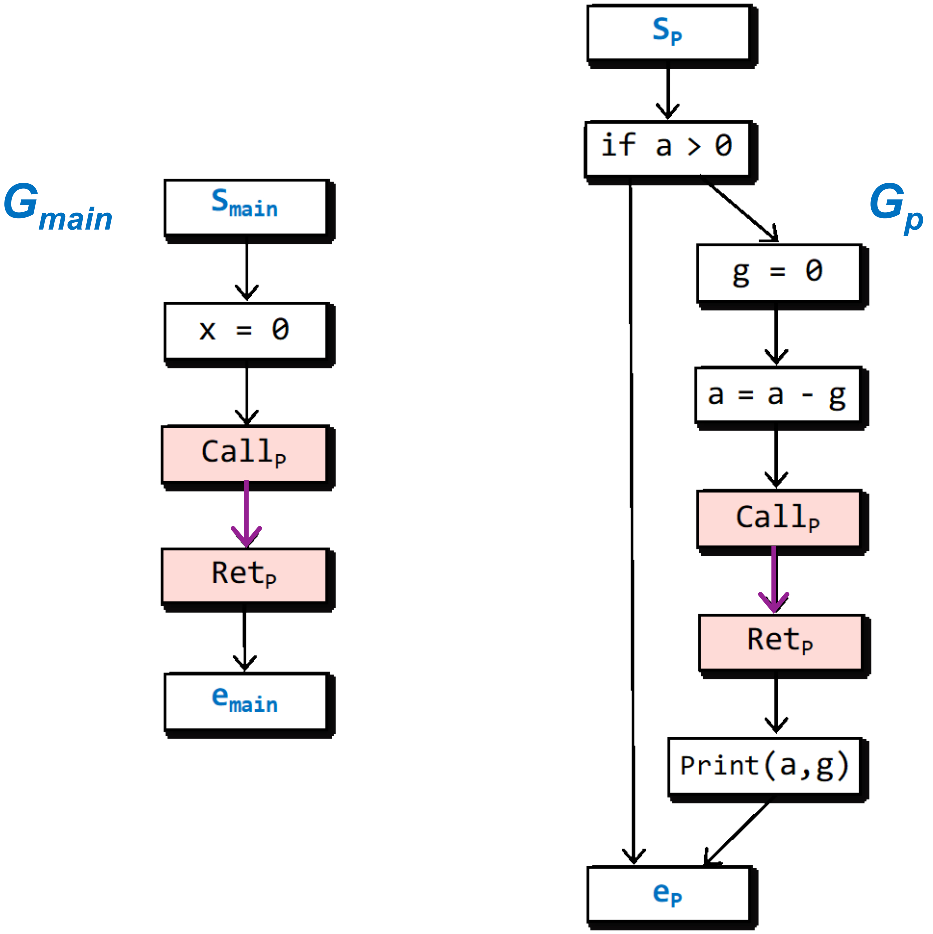

Supergraph

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- *An interprocedural call-to-start edge from Call$_p$ to s$_p$ of the called procedure*

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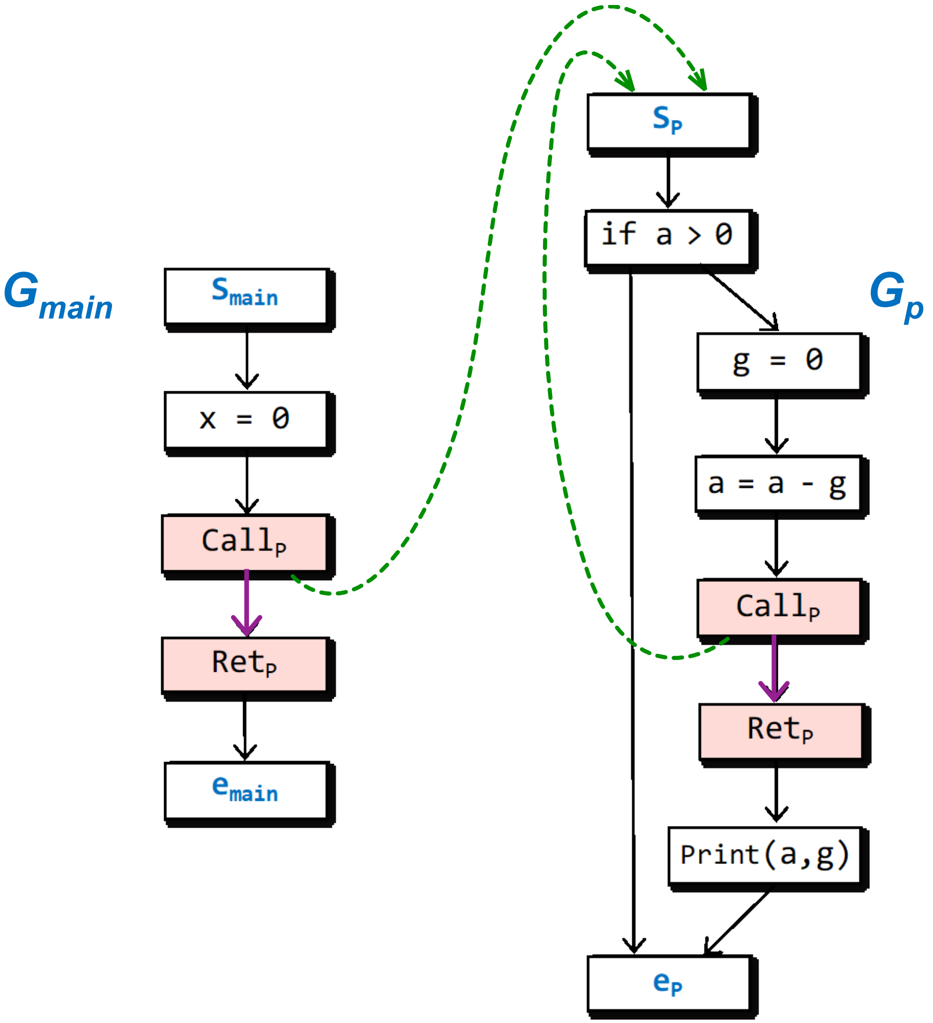

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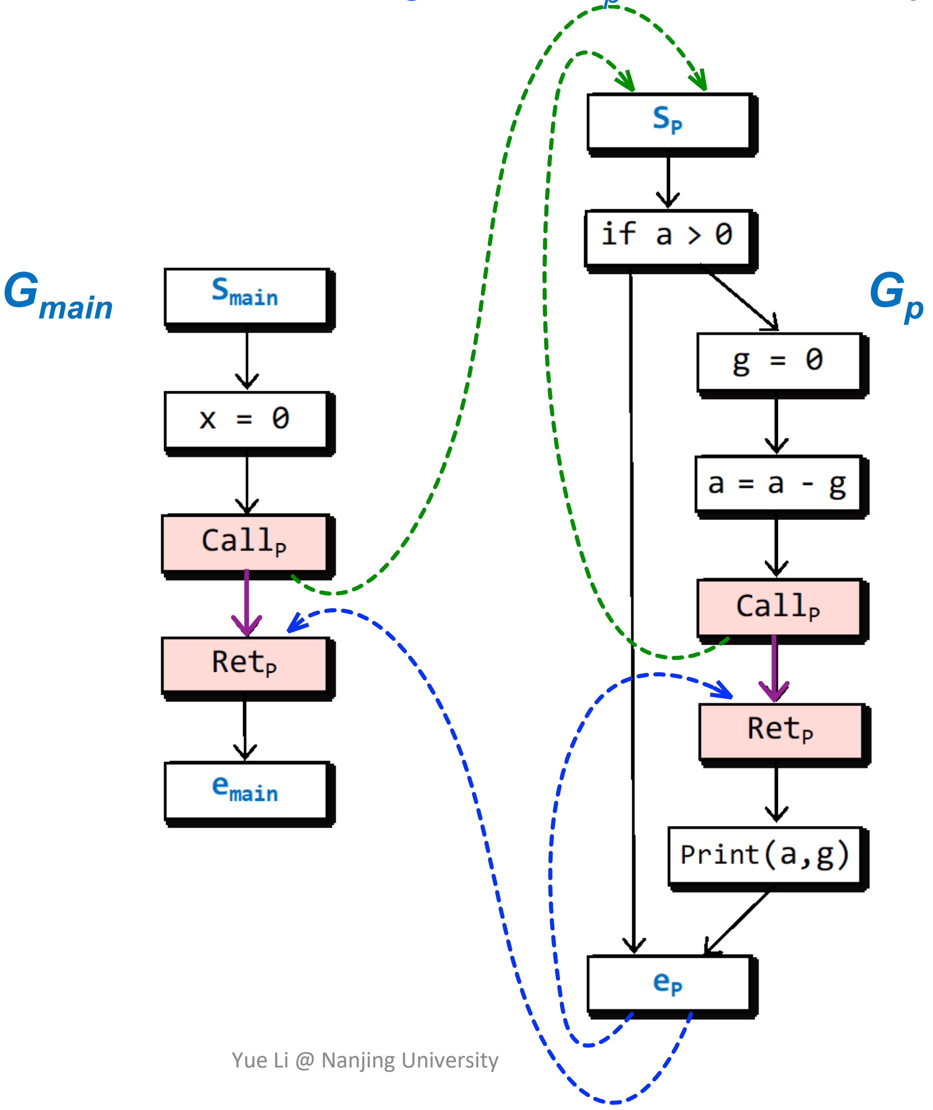

Design Flow Functions

“Possibly-uninitialized variables”: for each node n ∈ N*, determine the set of variables that may be uninitialized before execution reaches n.

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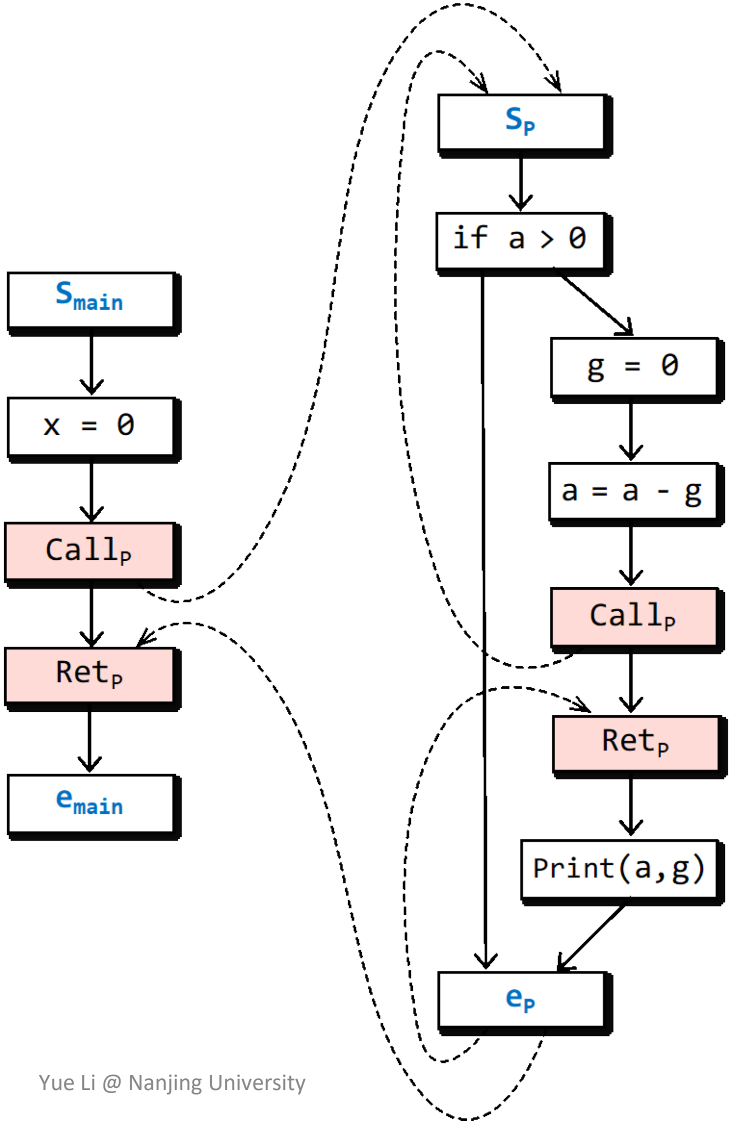

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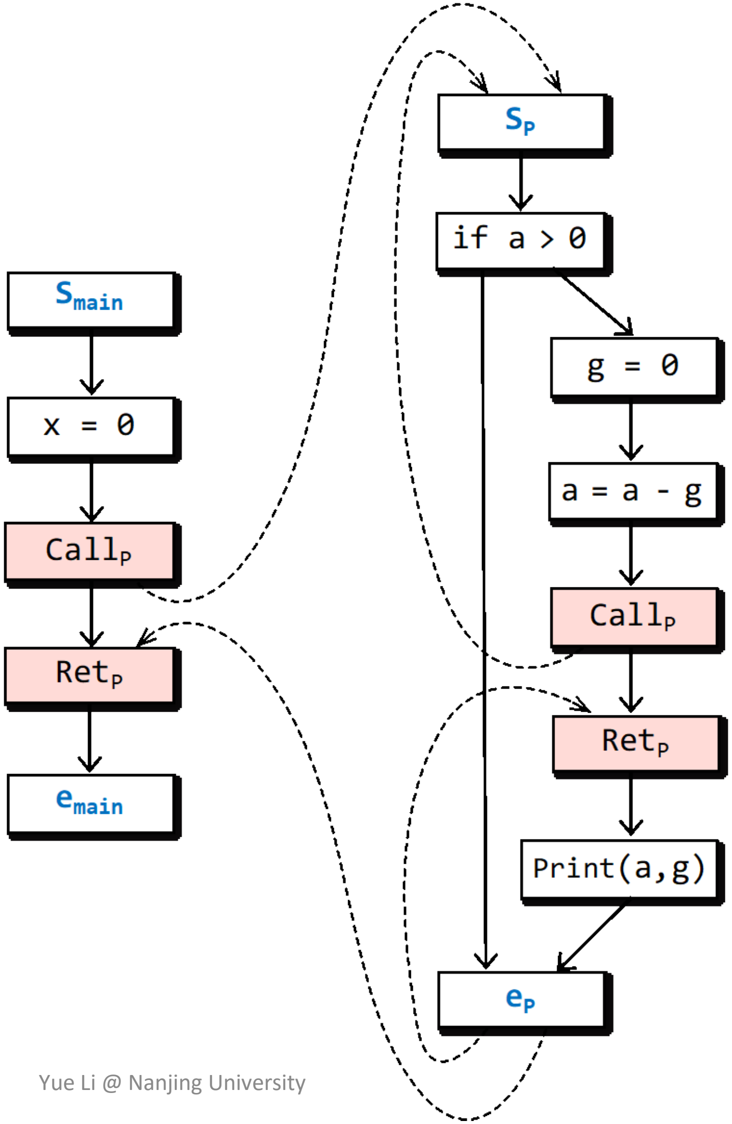
$\lambda\, e_{param} .\, e_{body}$



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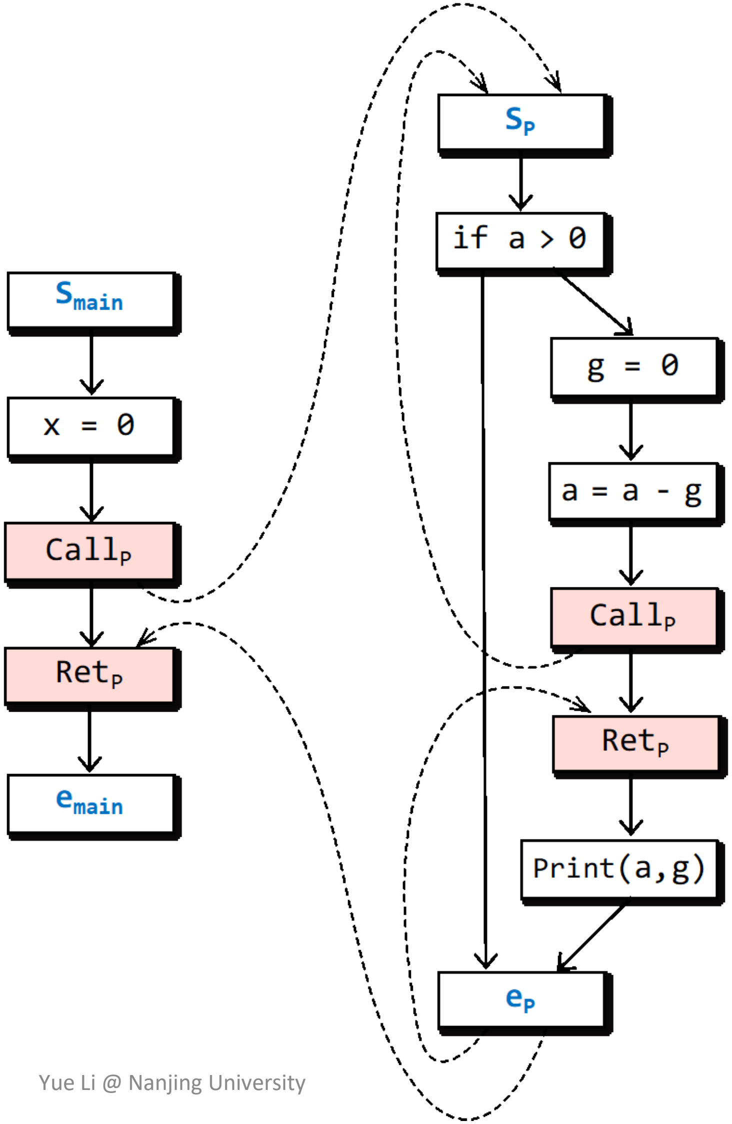
e.g., $\lambda\, x . x+1$



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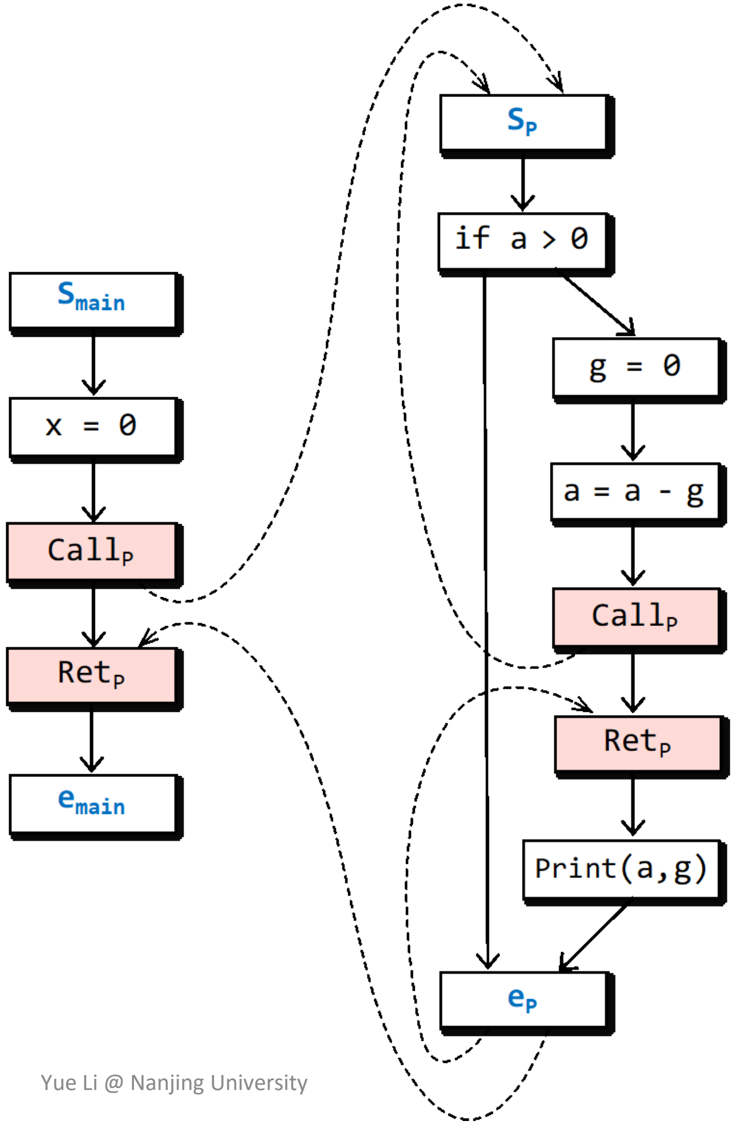

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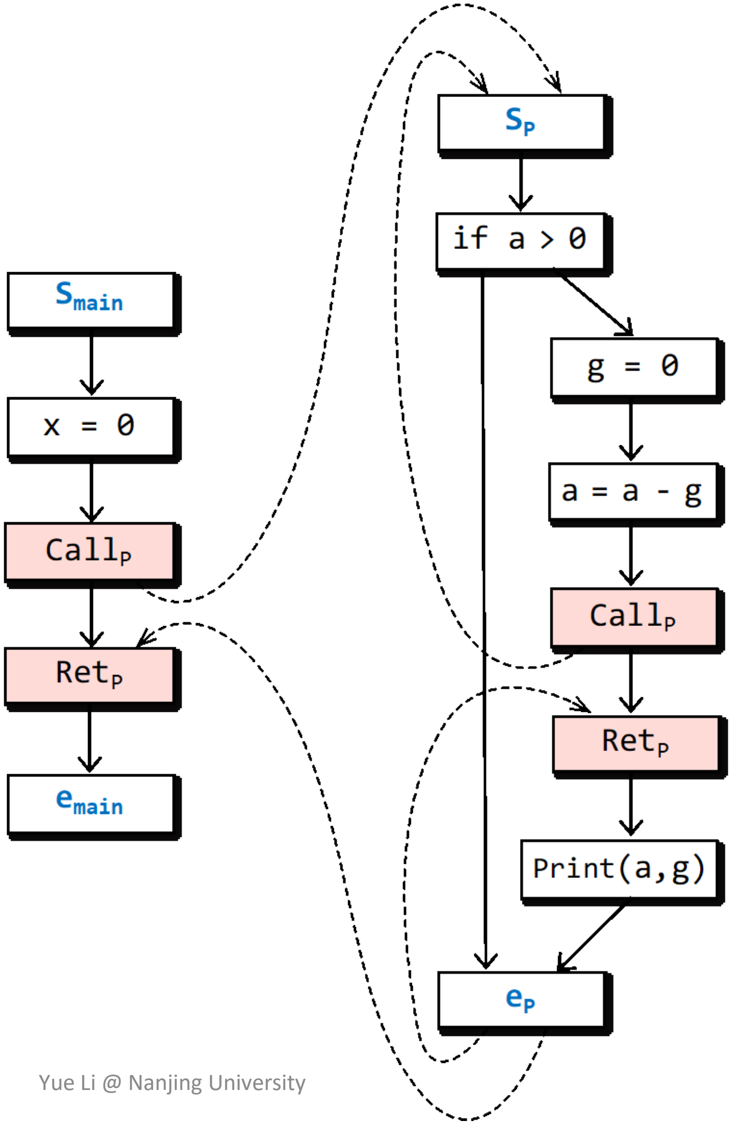
$(\lambda\, x . x+1) 3$

$\Rightarrow 3+1$

$\Rightarrow 4$



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  }
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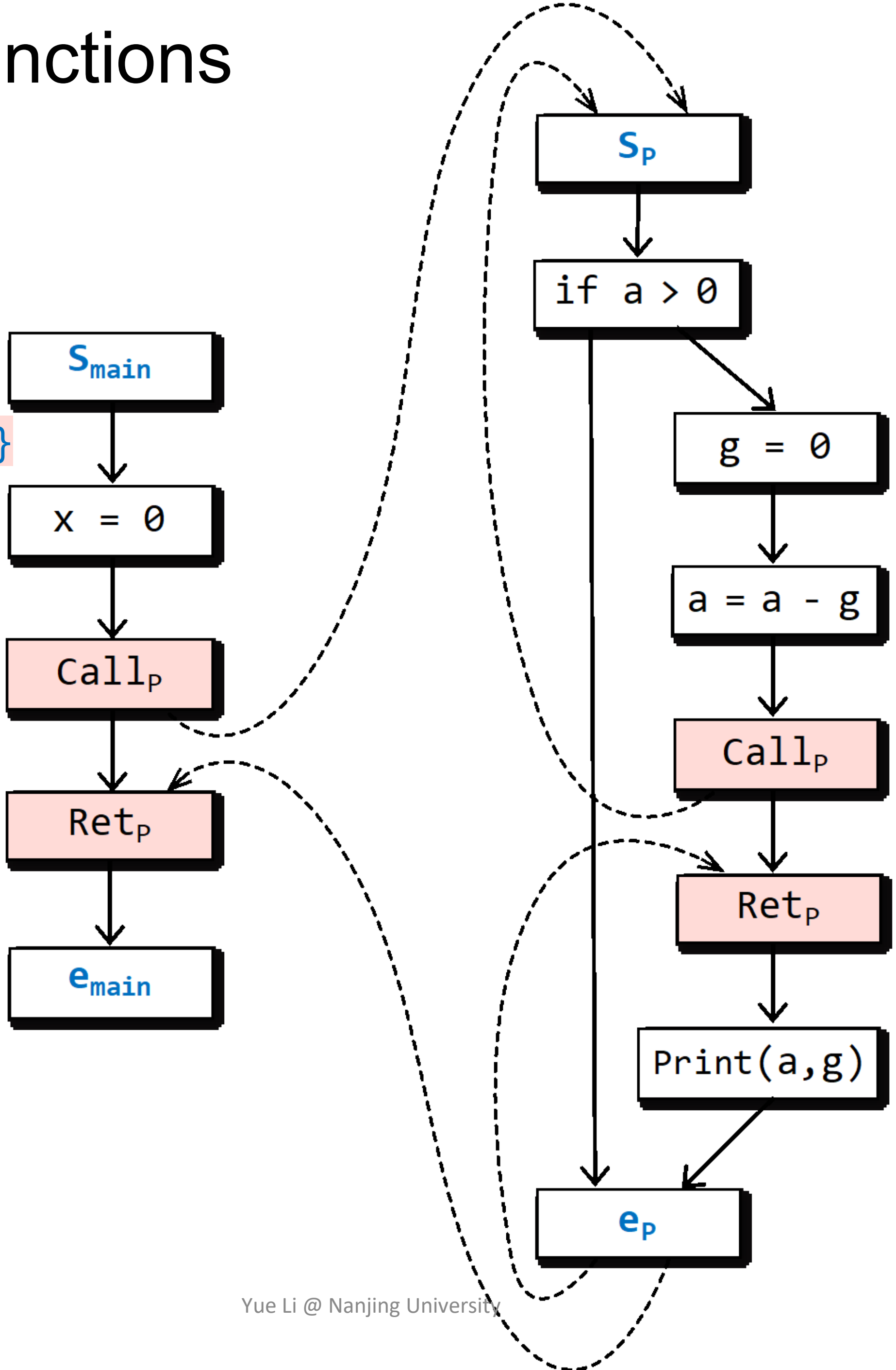
```

$\lambda S.\{x,g\}$



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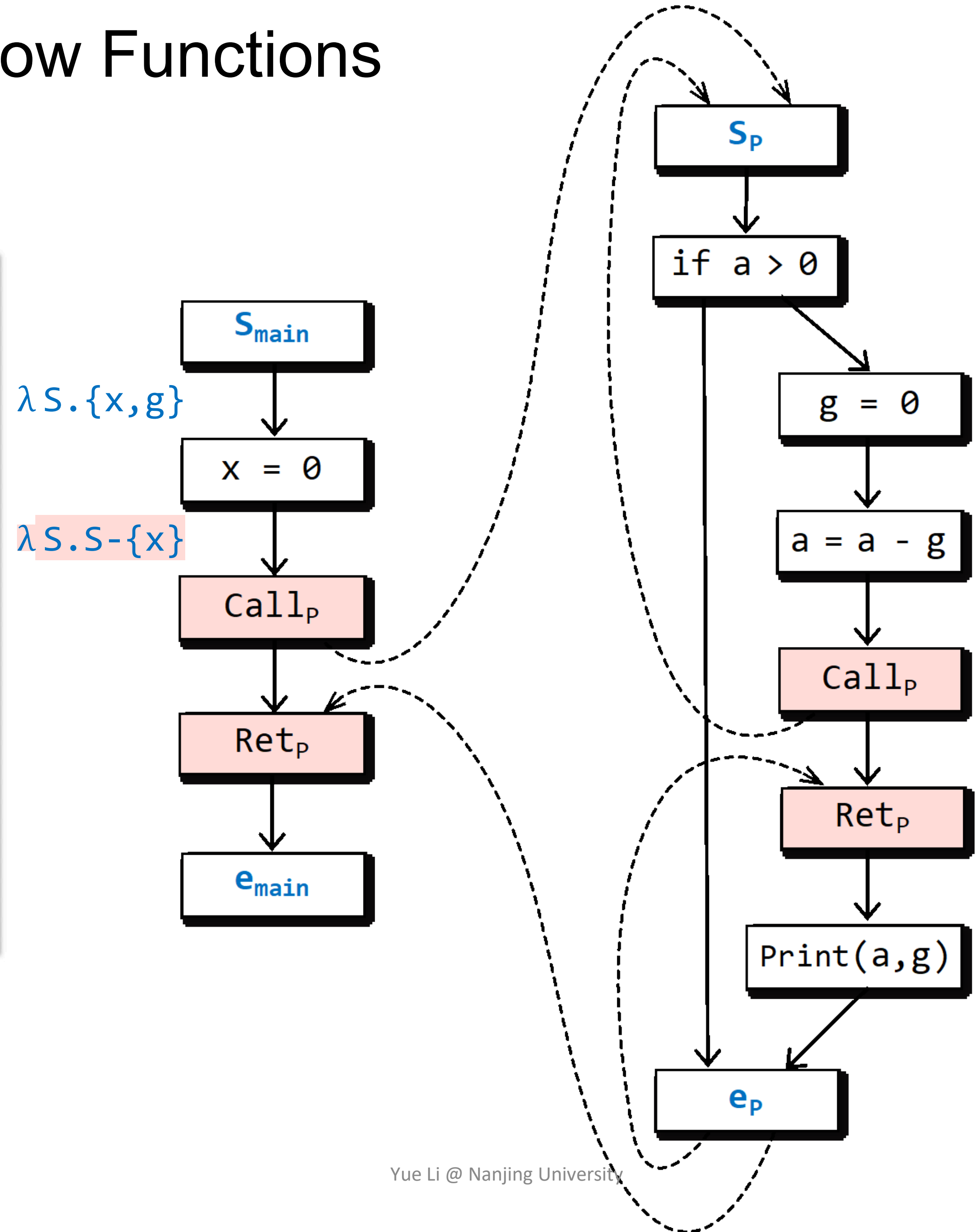

λS.{x,g}

λS.S-{x}

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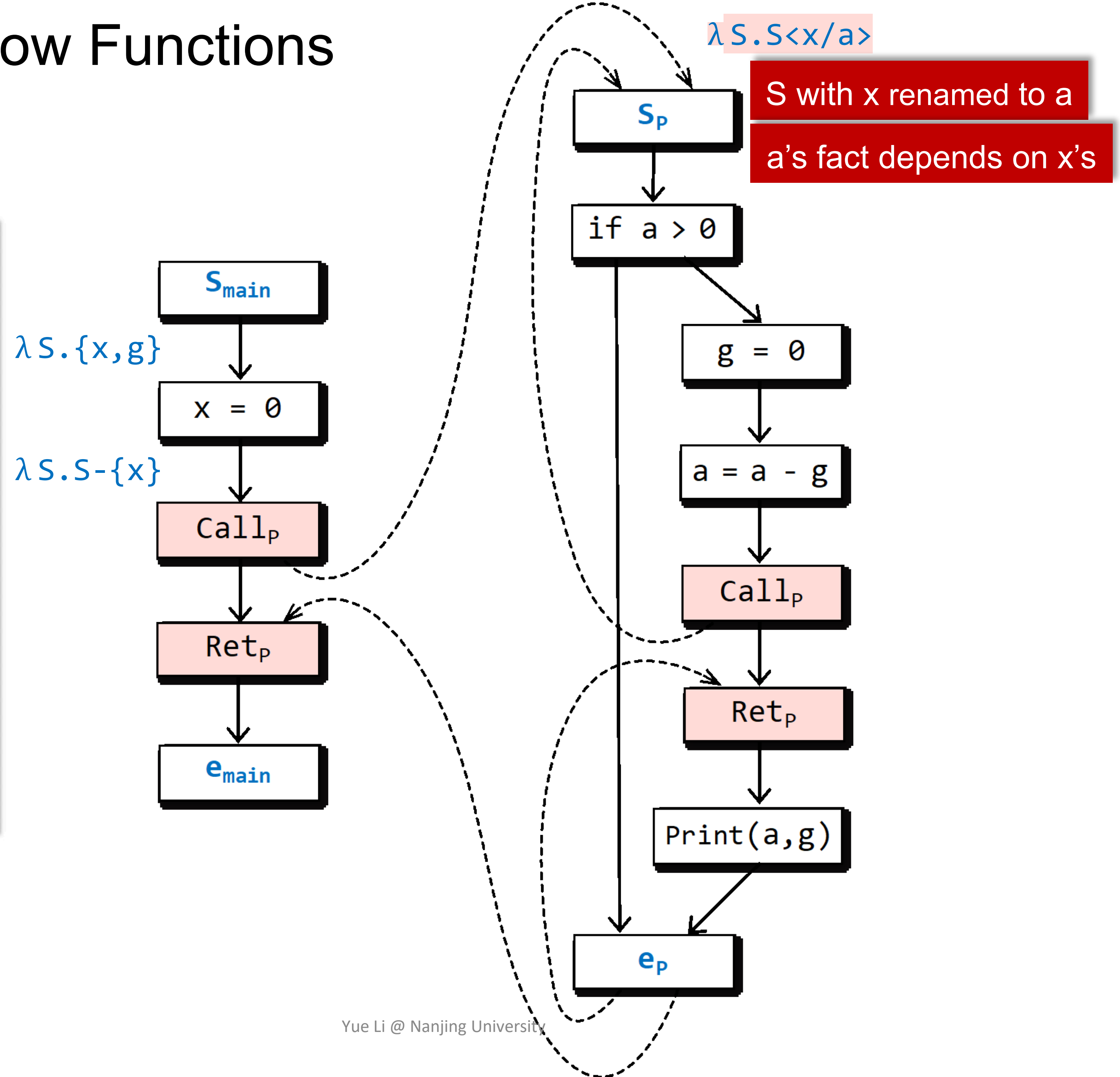

S_{main}

x = 0

$Call_P$

Ret_P

e_{main}

λS.{x,g}

λS.S-{x}

S_P

if a > 0

g = 0

a = a - g

$Call_P$

Ret_P

Print(a,g)

e_P

λS.S<x/a>

S with x renamed to a

a's fact depends on x's

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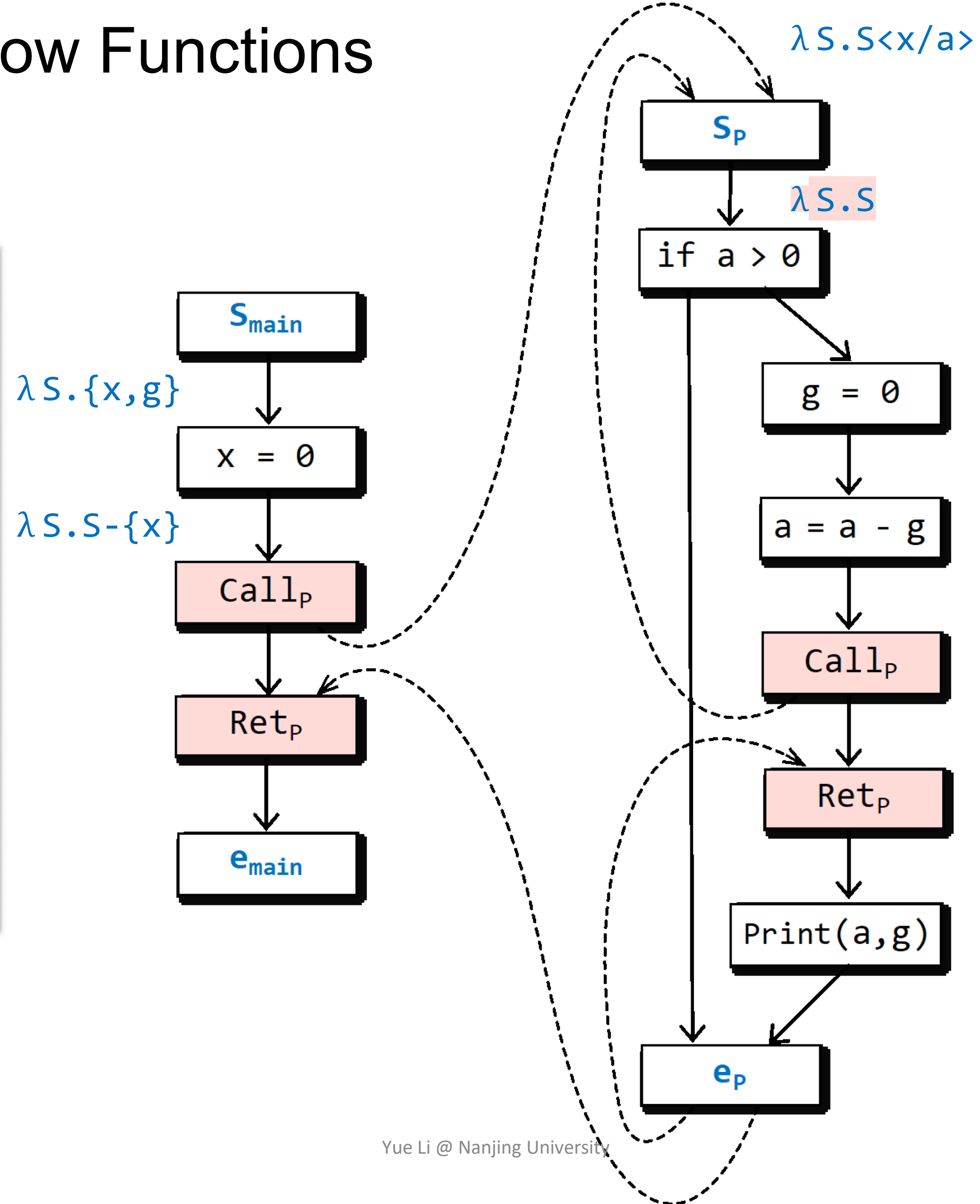

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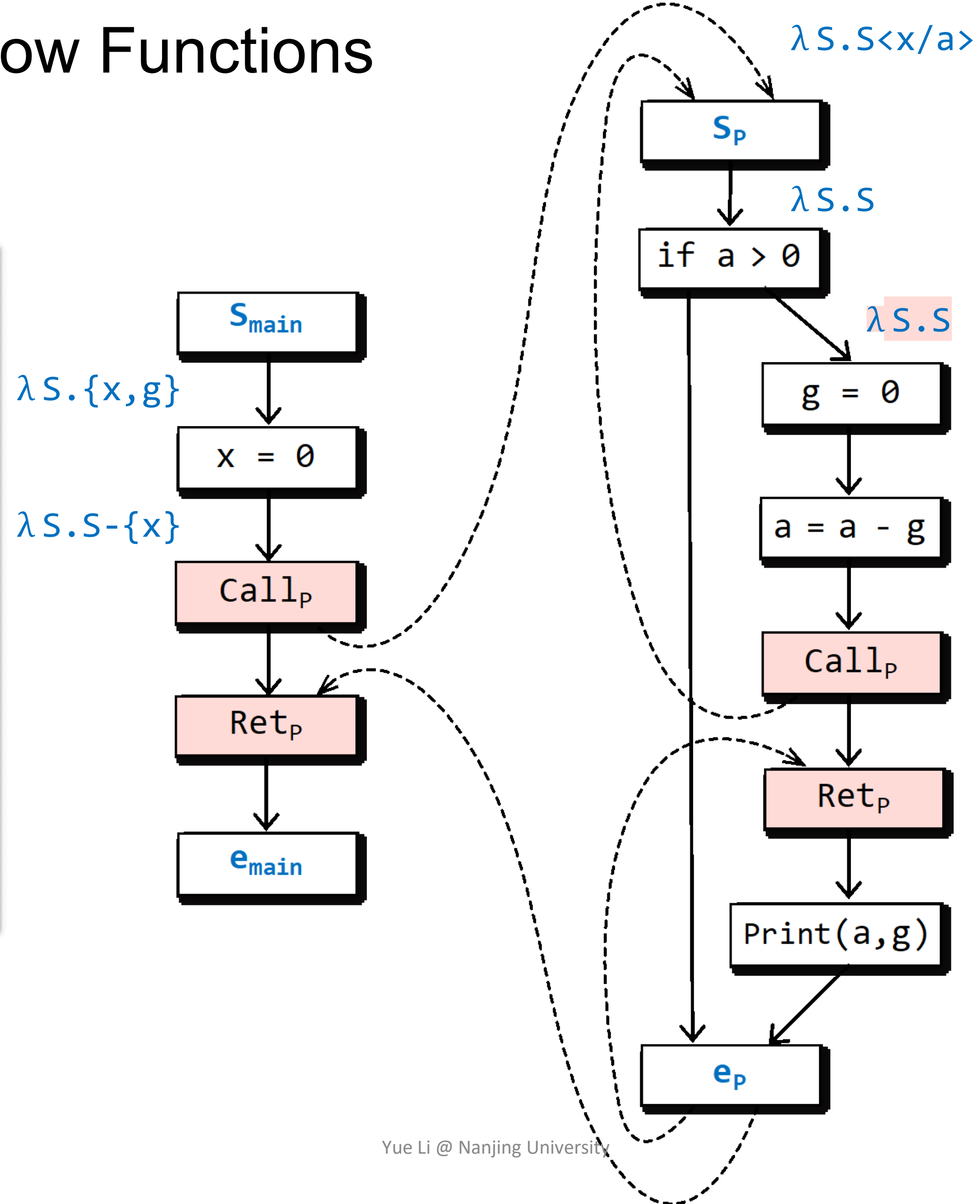

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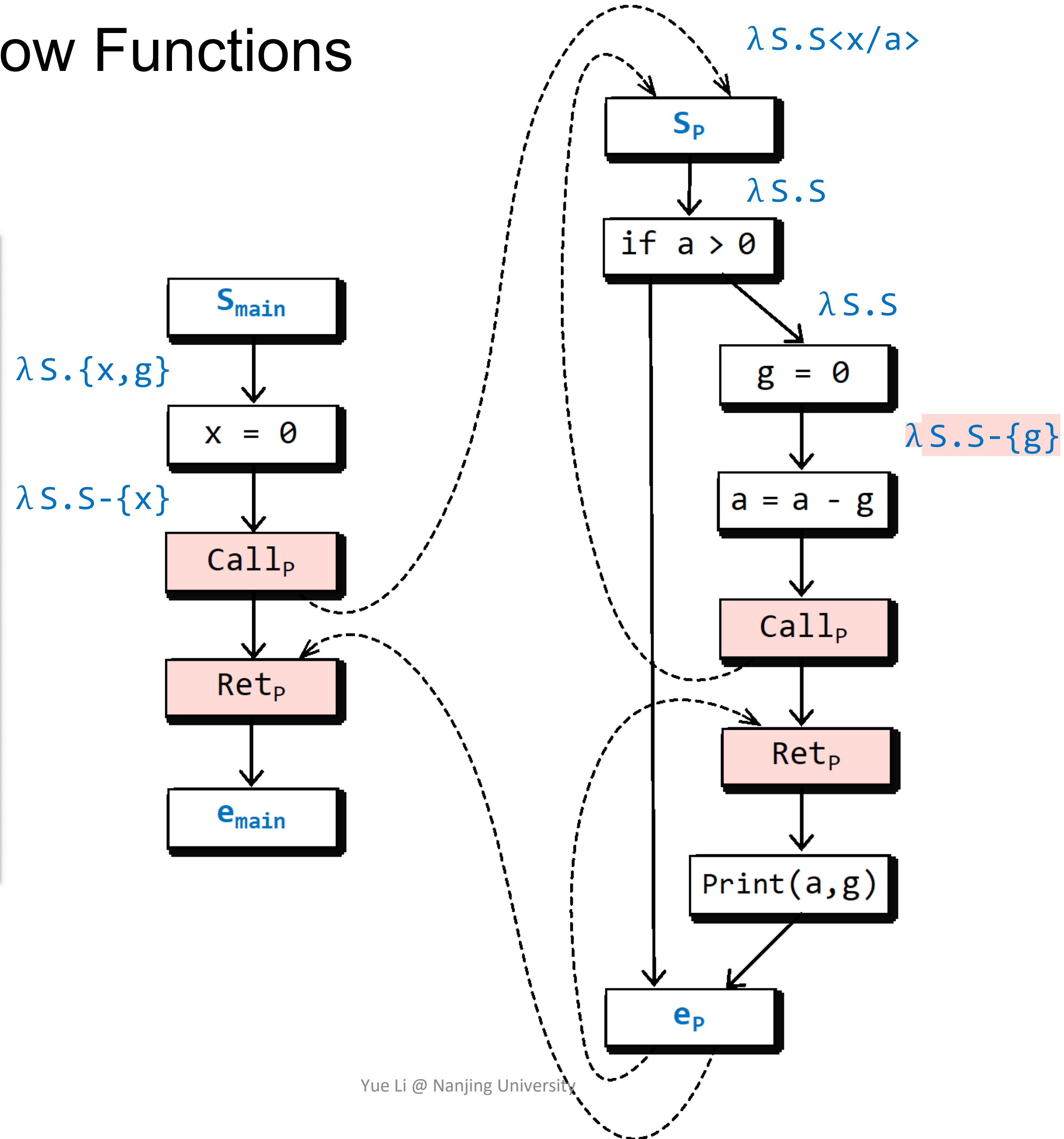

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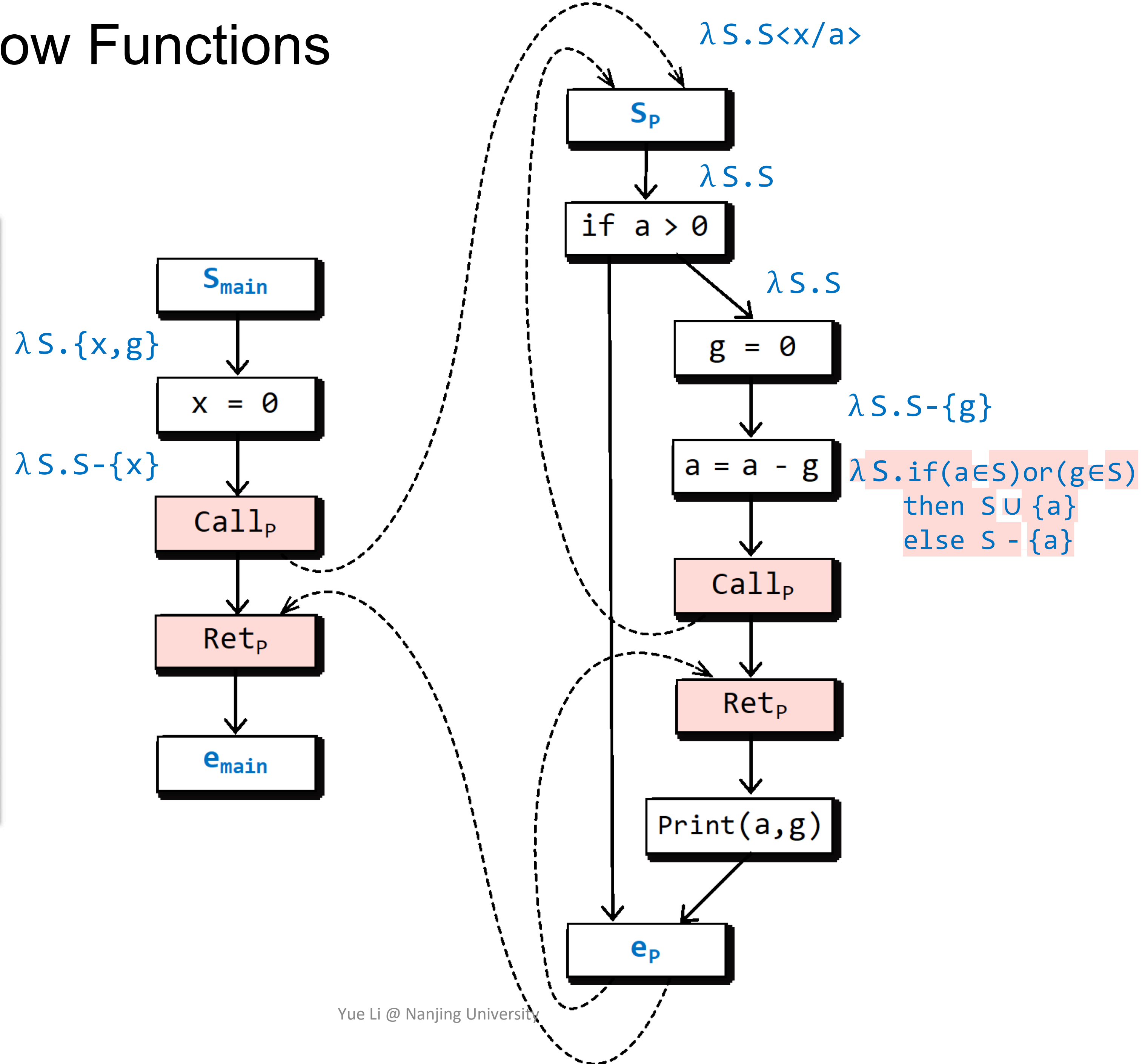

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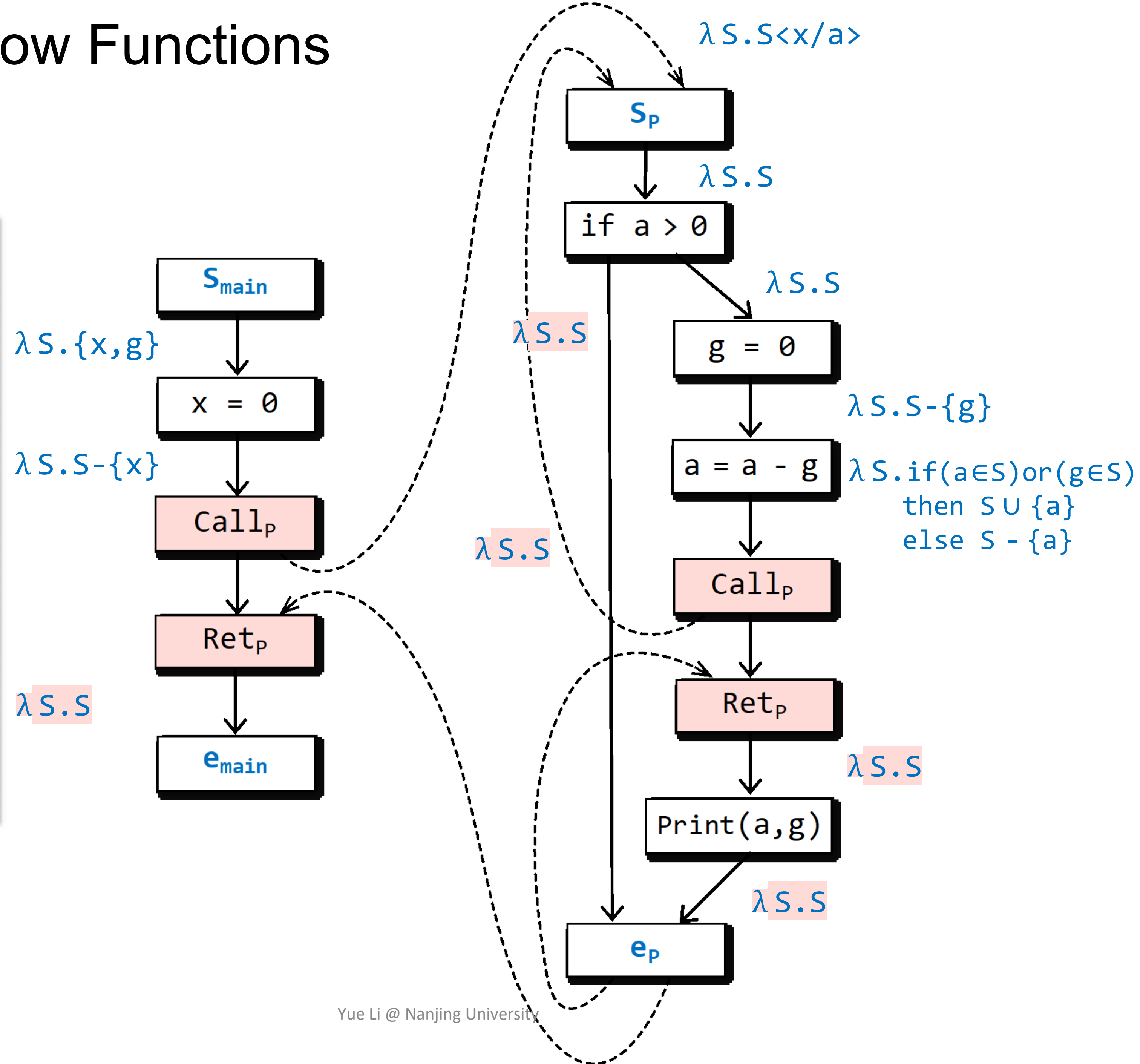

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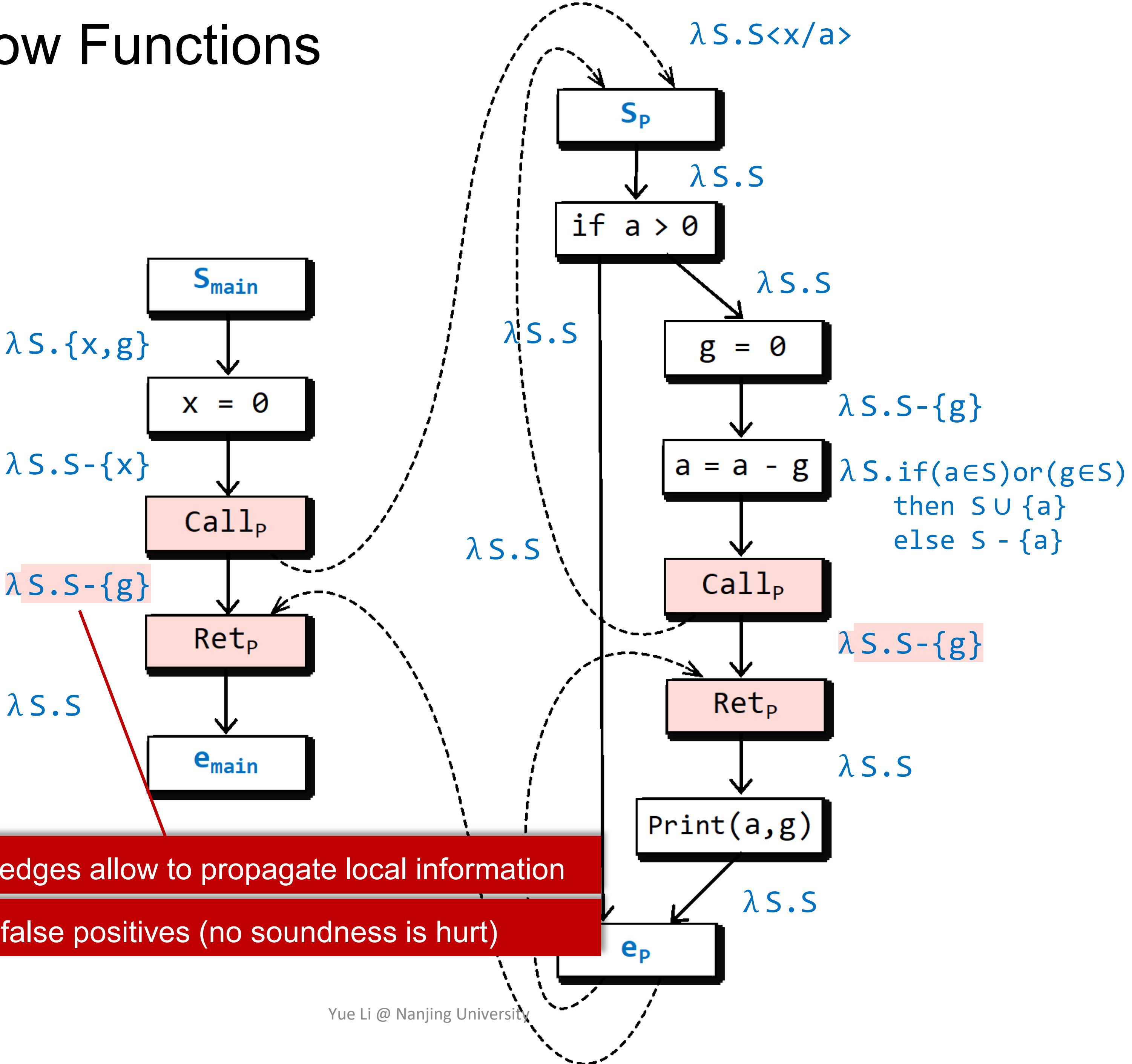


s_{main}

λS.{x,g}

x = 0

λS.S-{x}

$Call_P$

λS.S-{g}

Ret_P

λS.S

e_{main}

λS.S<x/a>

s_P

λS.S

if a > 0

λS.S

λS.S

g = 0

λS.S-{g}

a = a - g

λS.if(a∈S)or(g∈S)
then S∪{a}
else S-{a}

$Call_P$

λS.S

λS.S-{g}

Ret_P

λS.S

Print(a,g)

λS.S

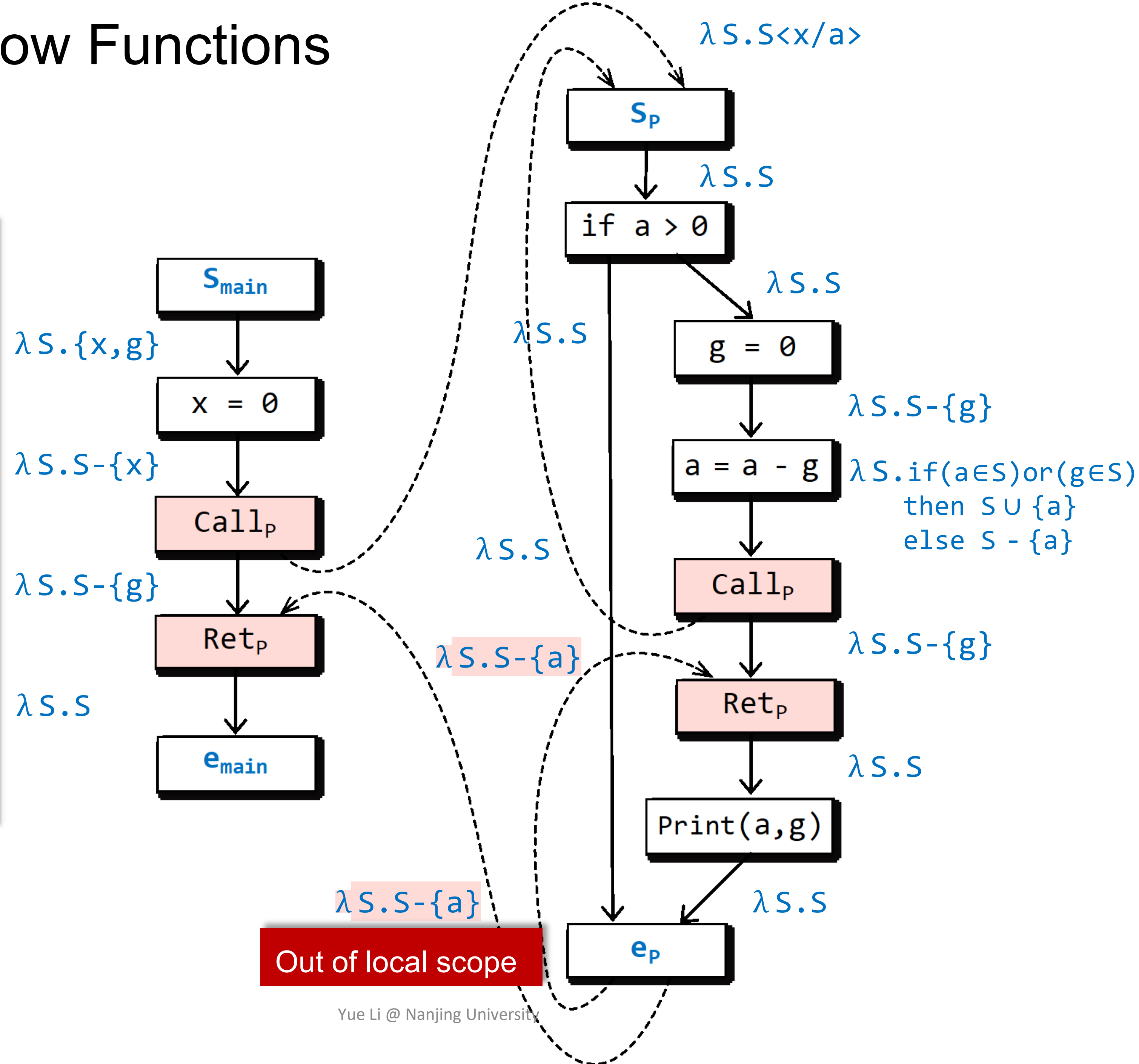
e_P

“call-to-return-site” edges allow to propagate local information

S-{g} helps reduce false positives (no soundness is hurt)

Design Flow Functions

```
int g;
main(){
  int x;
  x = 0;
  P(x);
}
P(int a){
  if(a > 0){
    g = 0;
    a = a - g;
    P(a);
    Print(a,g);
  }
}
```



Design Flow Functions

Done

```
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main(){
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  P(x);
}
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    a = a - g;
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    Print(a,g);
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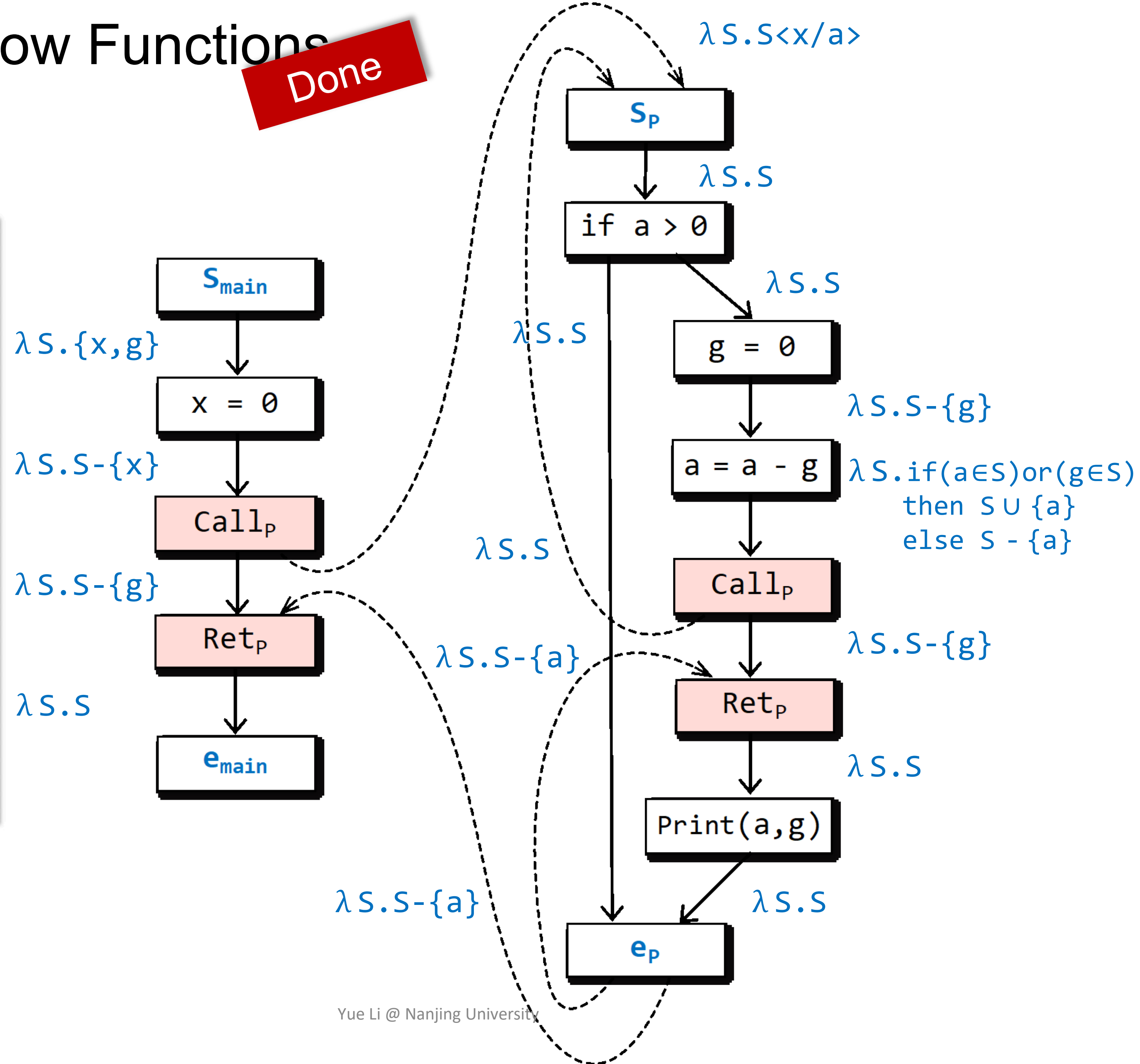


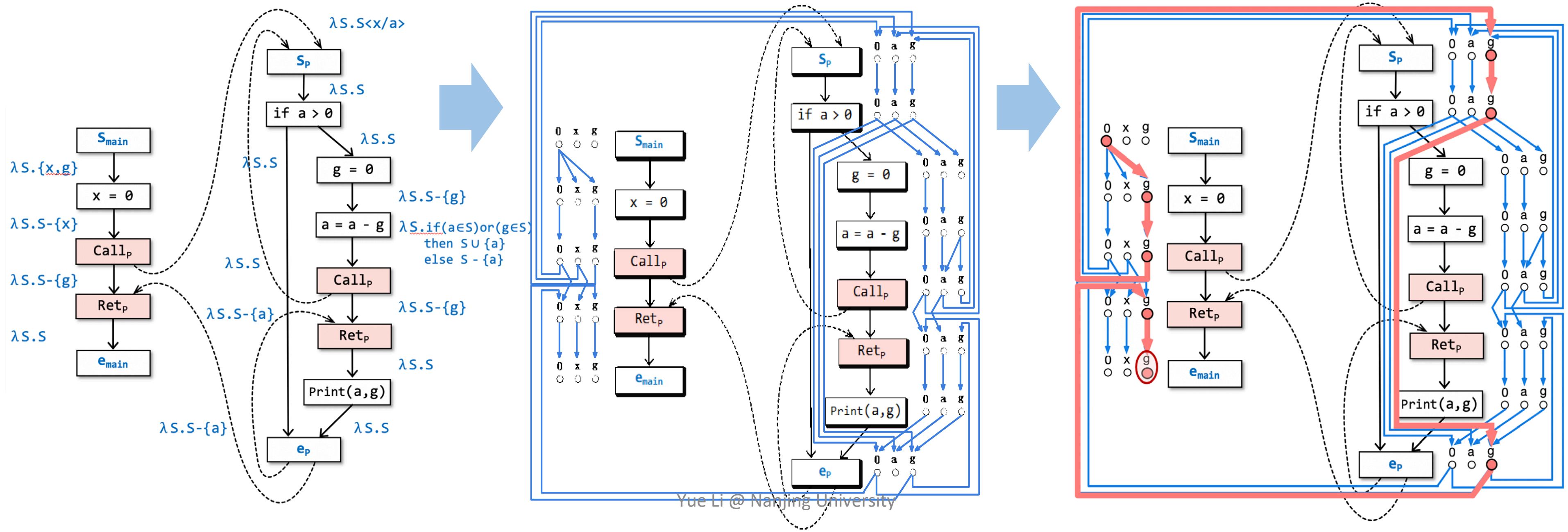
Overview of IFDS

Given a program P, and a dataflow-analysis problem Q

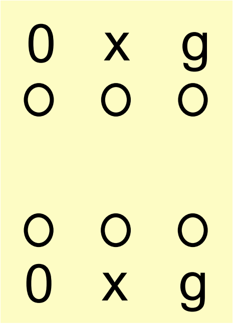
- Build a supergraph G* for P and
  define flow functions for edges in G* based on Q

- Build exploded supergraph $G^{\#}$ for P by transforming
  flow functions to representation relations (graphs)

- Q can be solved as graph reachability problems (find out MRP solutions)
  via applying Tabulation algorithm on $G^{\#}$

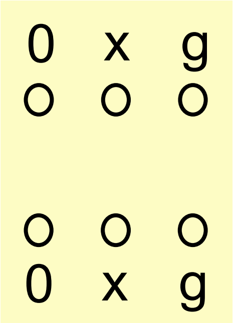


Build Exploded Supergraph



- Build exploded supergraph $G^{\#}$ for a program by transforming flow functions to representation relations (graphs)
- Each flow function can be represented as a graph with 2(D+1) nodes (at most $(D+1)^2$ edges), where D is a finite set of dataflow facts

Build Exploded Supergraph



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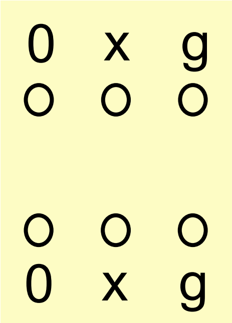

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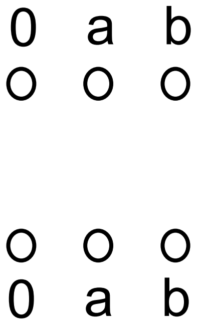
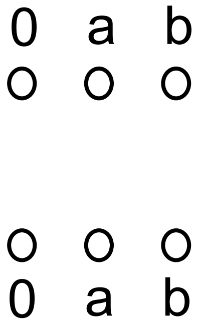
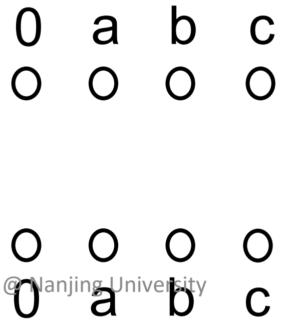
λS.S



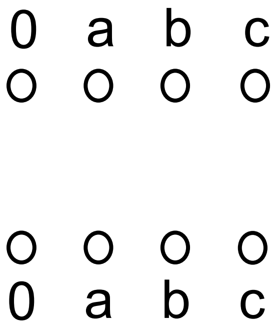
λS.{a}



λS.(S-{a})∪{b}



λS.if a ∈ S
then S ∪ {b}
else S - {b}



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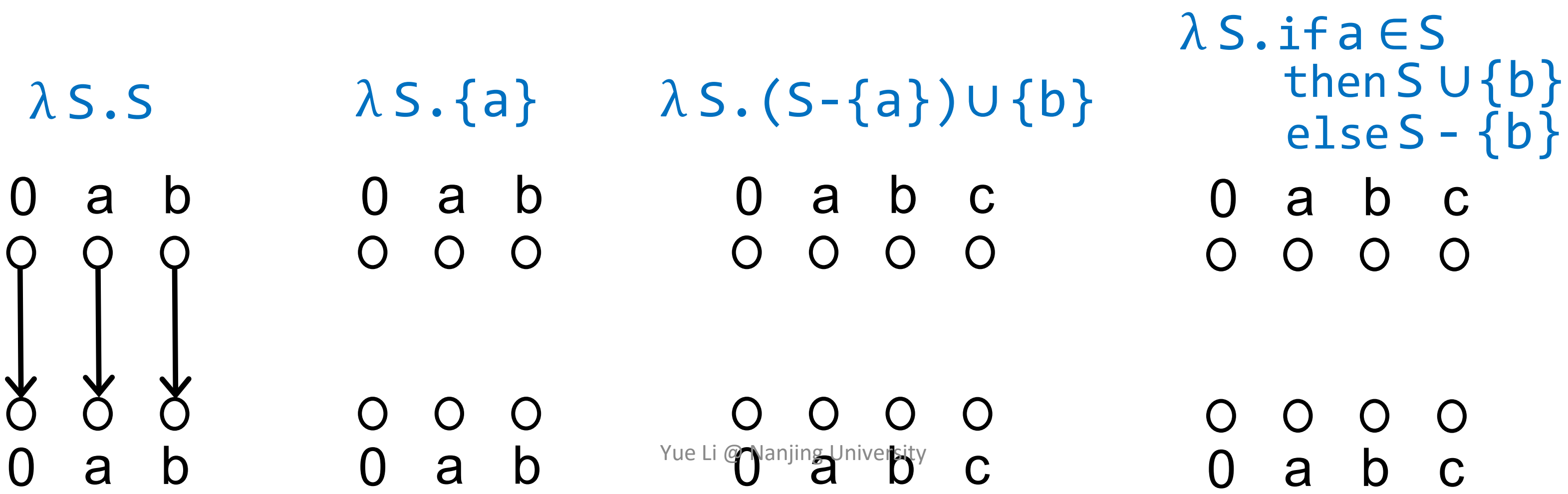

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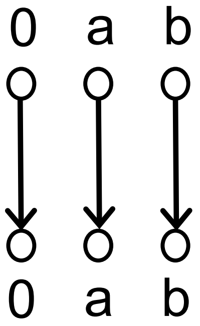

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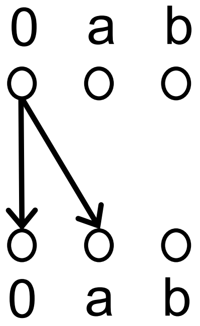
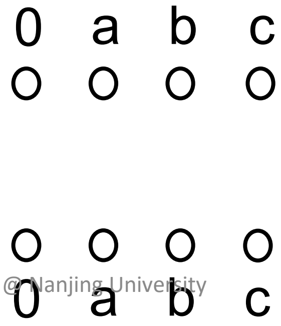


λS.(S-{a})∪{b}



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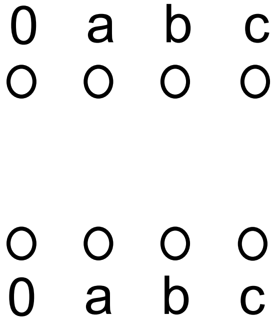

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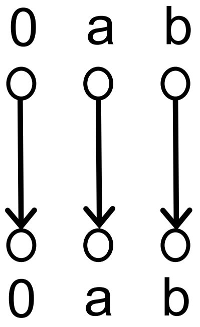

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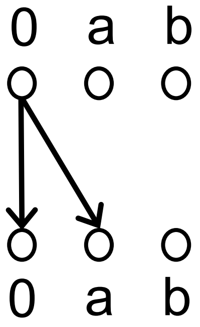

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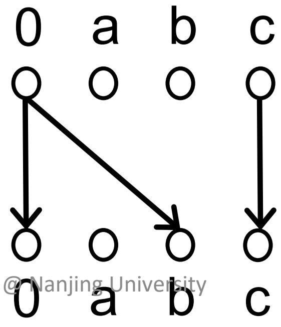

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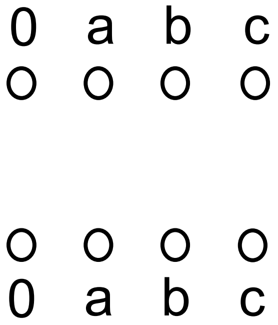

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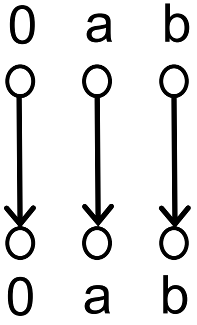

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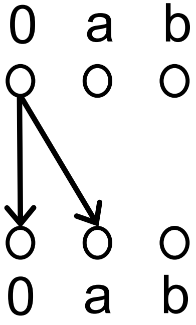

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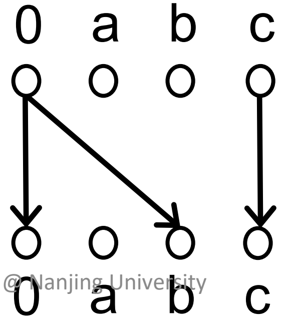

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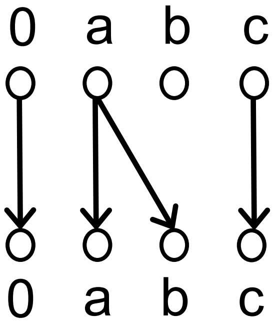

Build Exploded Supergraph

Exploded Supergraph $G^{\#}$:

Each node n in supergraph G^* is “exploded” into D+1 nodes in $G^{\#}$, and each edge $n_1 \longrightarrow n_2$ in G^* is “exploded” into the representation relation of the flow function associated with $n_1 \longrightarrow n_2$ in $G^{\#}$

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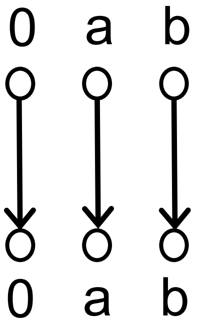

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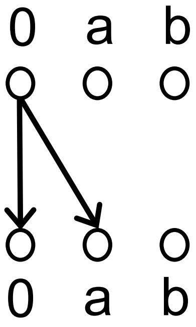

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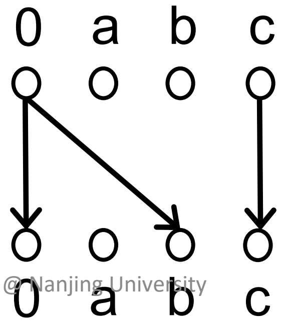

```
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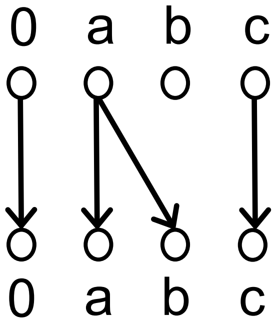

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Why we need $0 \longrightarrow 0$ edges?

λS.S

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λS.(S-{a})∪{b}

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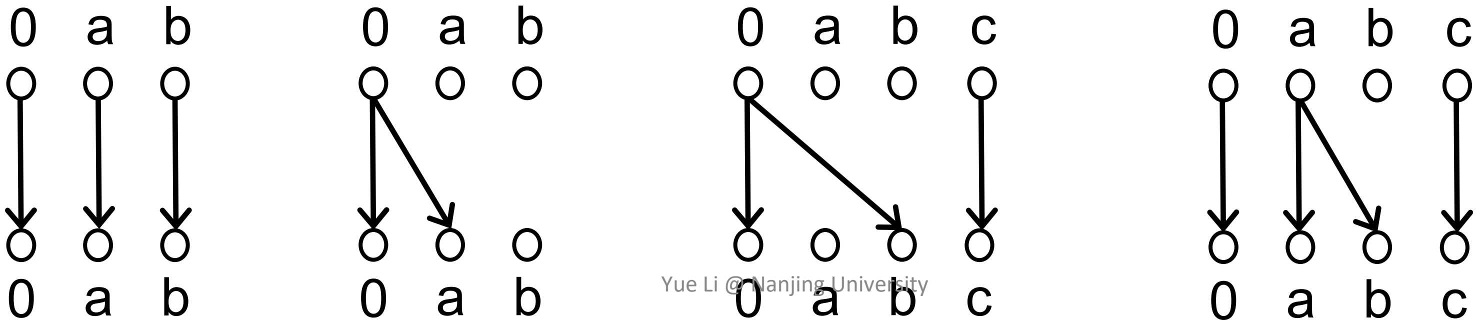
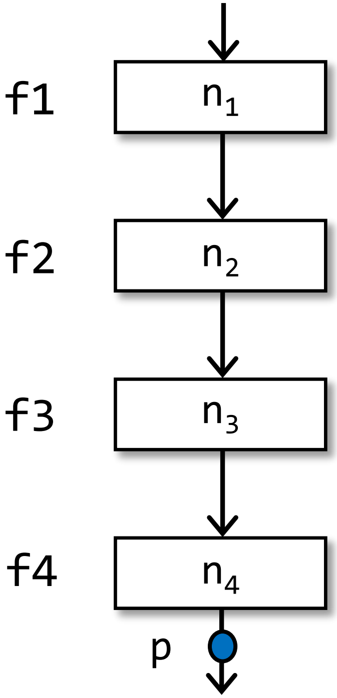


Why We Need Edge 0 ⟶ 0?

In traditional data flow analysis, to see whether data fact a holds at program point p, we check if a is in OUT[n_4] after the analysis finishes

$$OUT[n_4] = f4 \circ f3 \circ f2 \circ f1(IN[n1])$$



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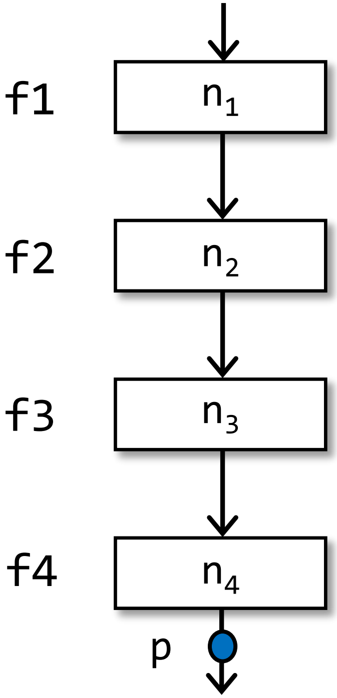
Data facts are propagated via the composition of flow functions. In this case, the "reachability" is directly retrieved from the final result in OUT[n_4] .



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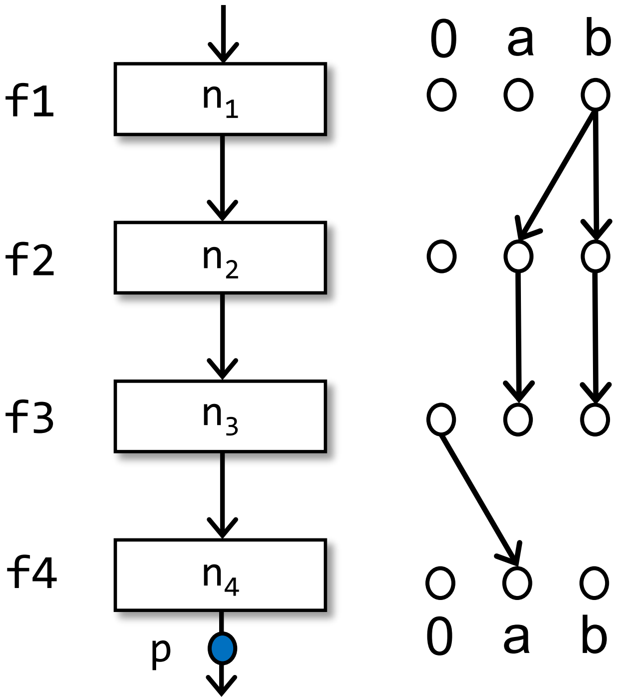

For the same case, in IFDS, whether data fact a holds at p depends on if there is a path from <s_{main}, 0> to <n_4,a>, and the "reachability" is retrieved by connecting the edges (finding out a path) on the "pasted" representation relations

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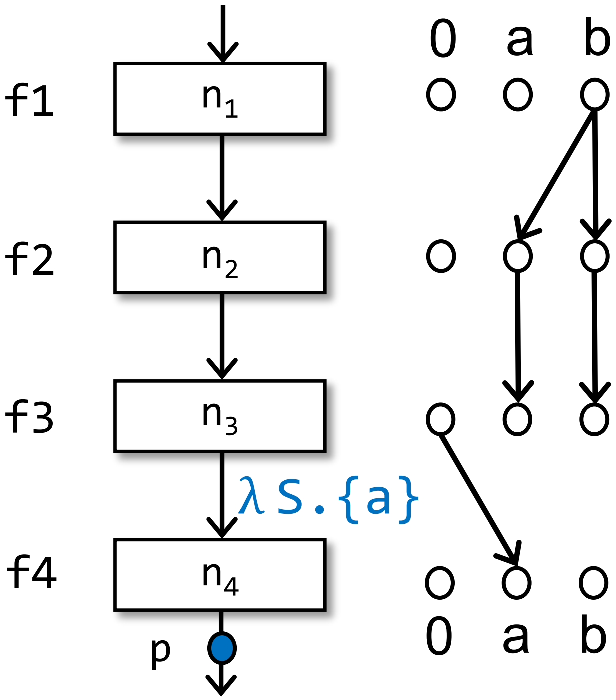

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λS.{a} says a holds at p regardless of input S; however, *without edge 0⟶0,*

the representation relation for each edge cannot be connected or “pasted” together, like flow functions cannot be composed together in traditional data flow analysis.

Thus IFDS cannot produce correct solutions via such disconnected representation relations.

So We Need the "Glue Edge" 0 ⟶ 0!

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```
OUT[n4] = f4 ∘ f3 ∘ f2 ∘ f1(IN[n1])
```

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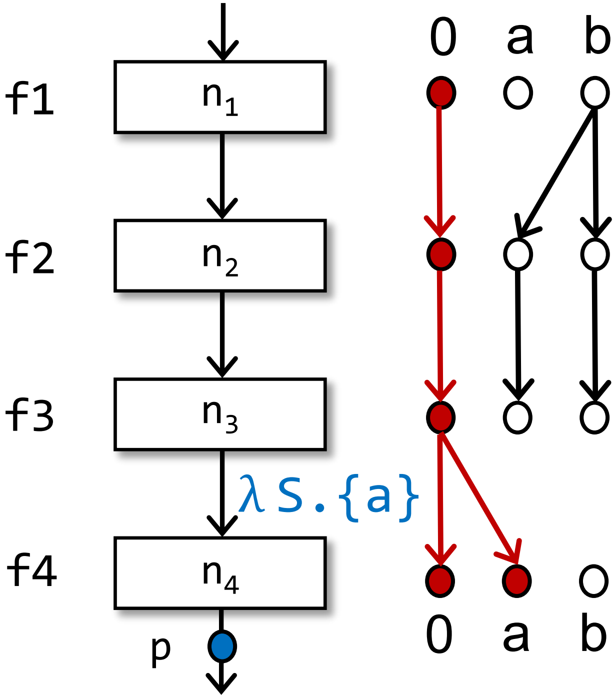

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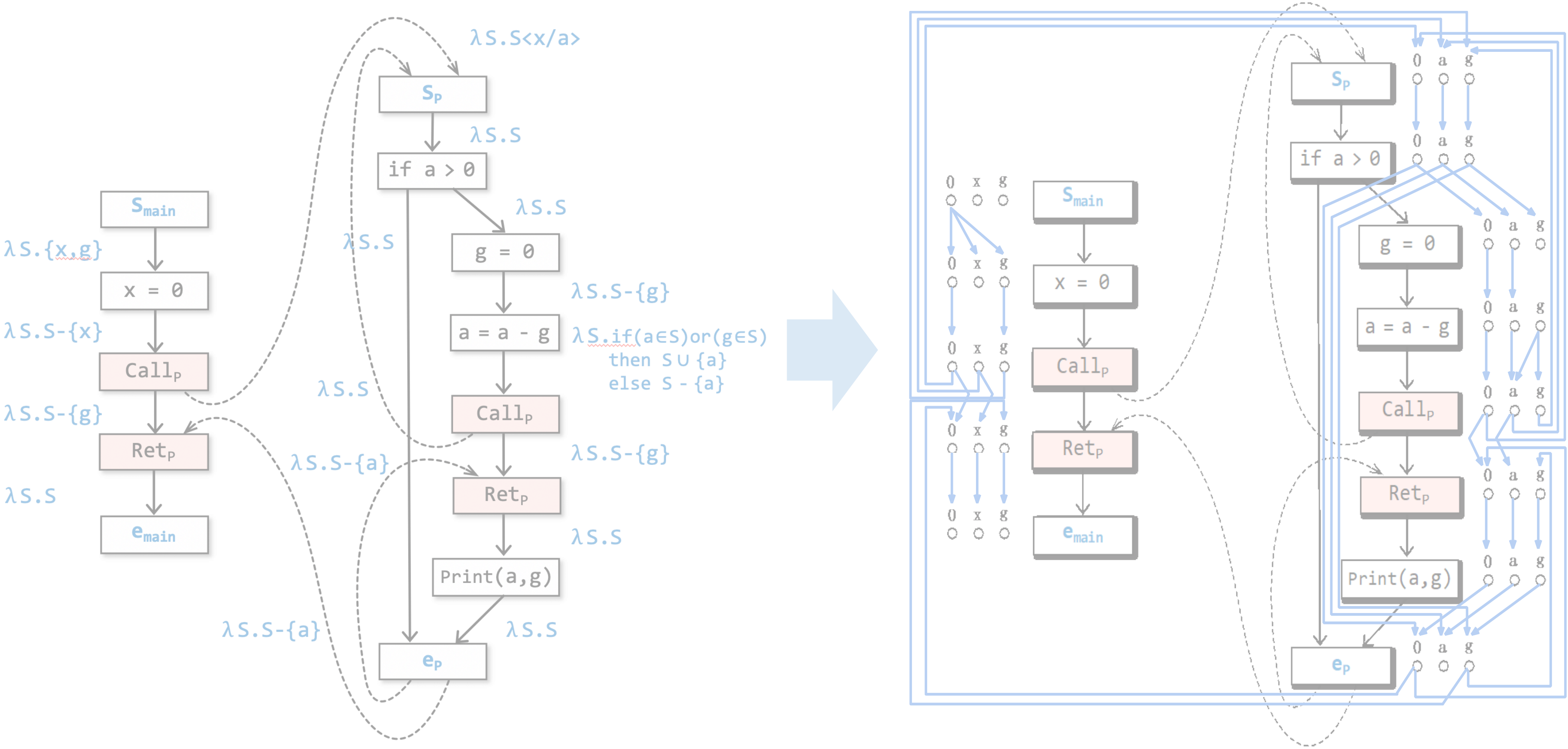
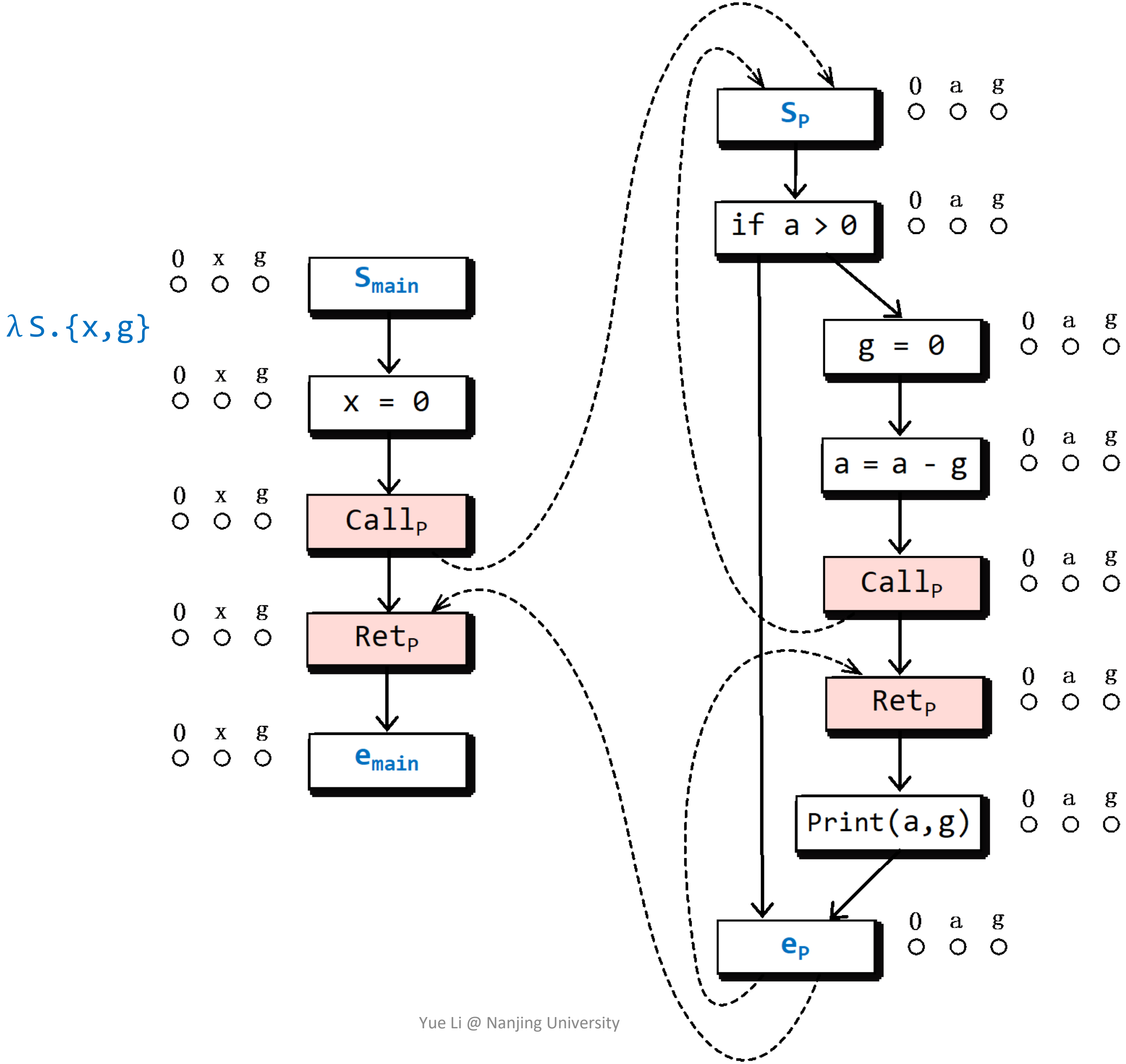
Now, let’s build an exploded supergraph



Yue Li @ Nanjing University



λS.{x,g}

s_{main}

x = 0

$Call_p$

Ret_p

e_{main}

s_p

if a > 0

g = 0

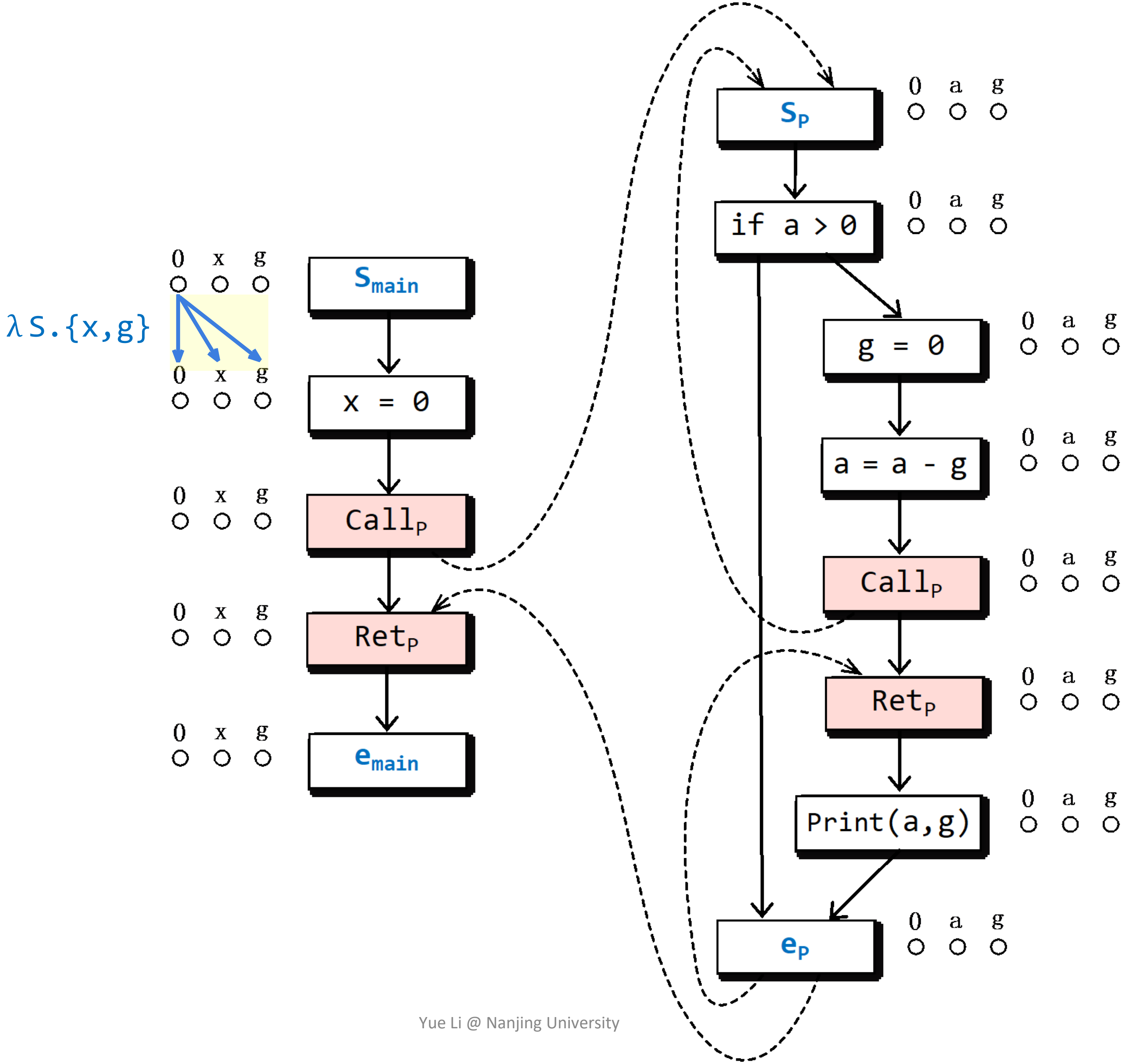
a = a - g

$Call_p$

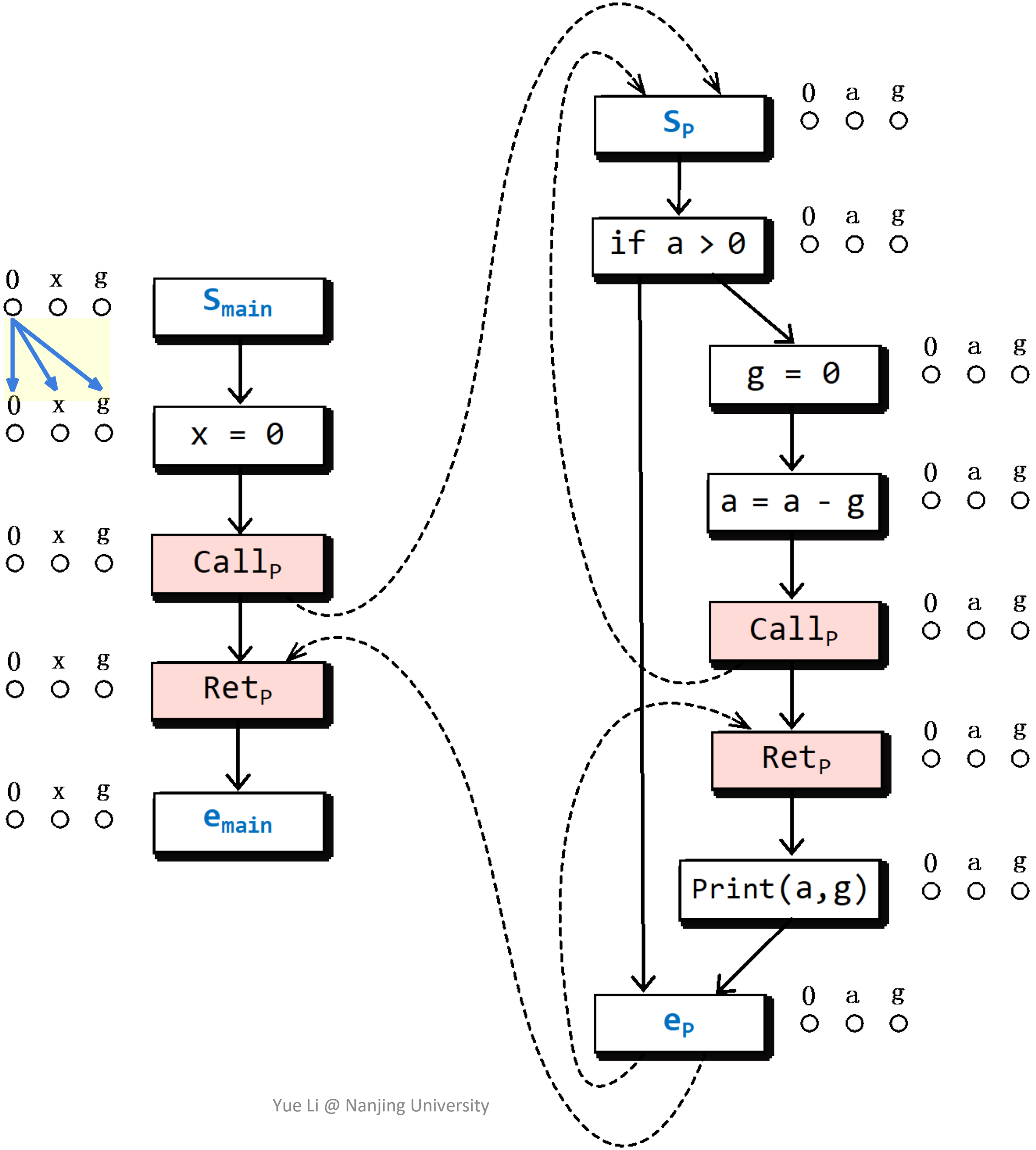
Ret_p

Print(a,g)

e_p


λS.{x,g}
0 x g
Smain
x = 0
Callp
Retp
emain
0 a g
Sp
if a > 0
g = 0
a = a - g
Callp
Retp
Print(a,g)
ep

λS.S-{x}



0 x g
S_main
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Call_P
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Call_P
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Print(a,g)
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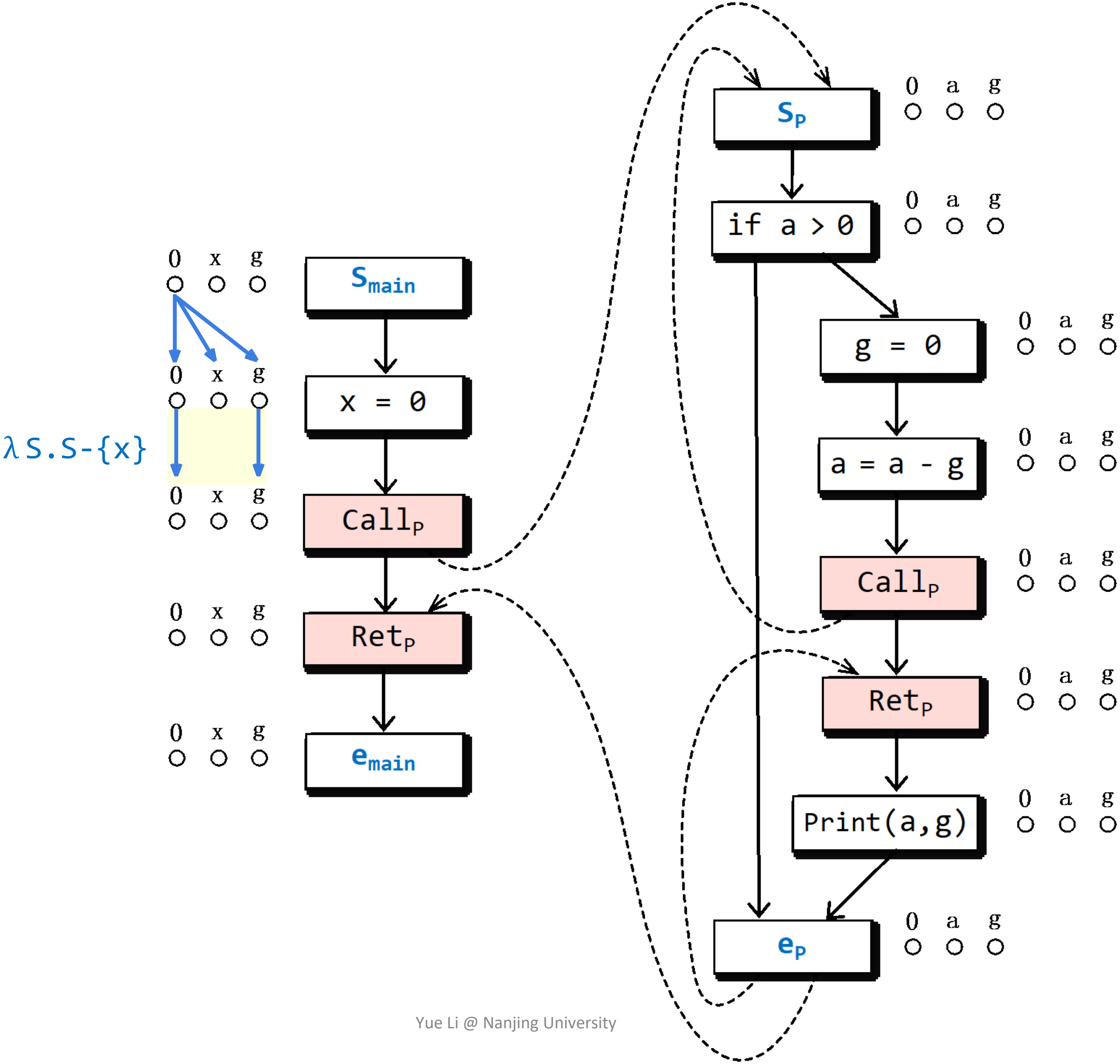
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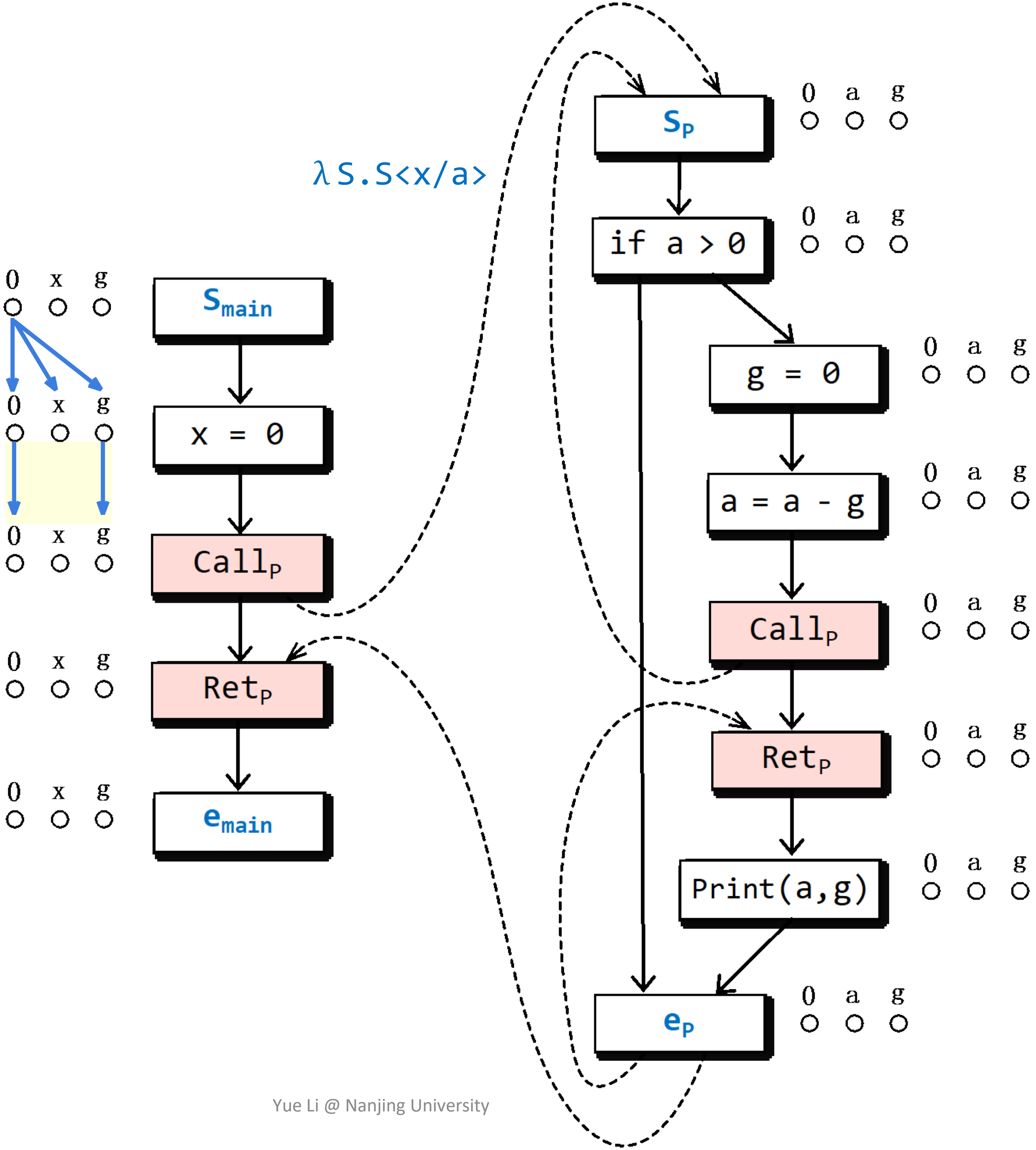
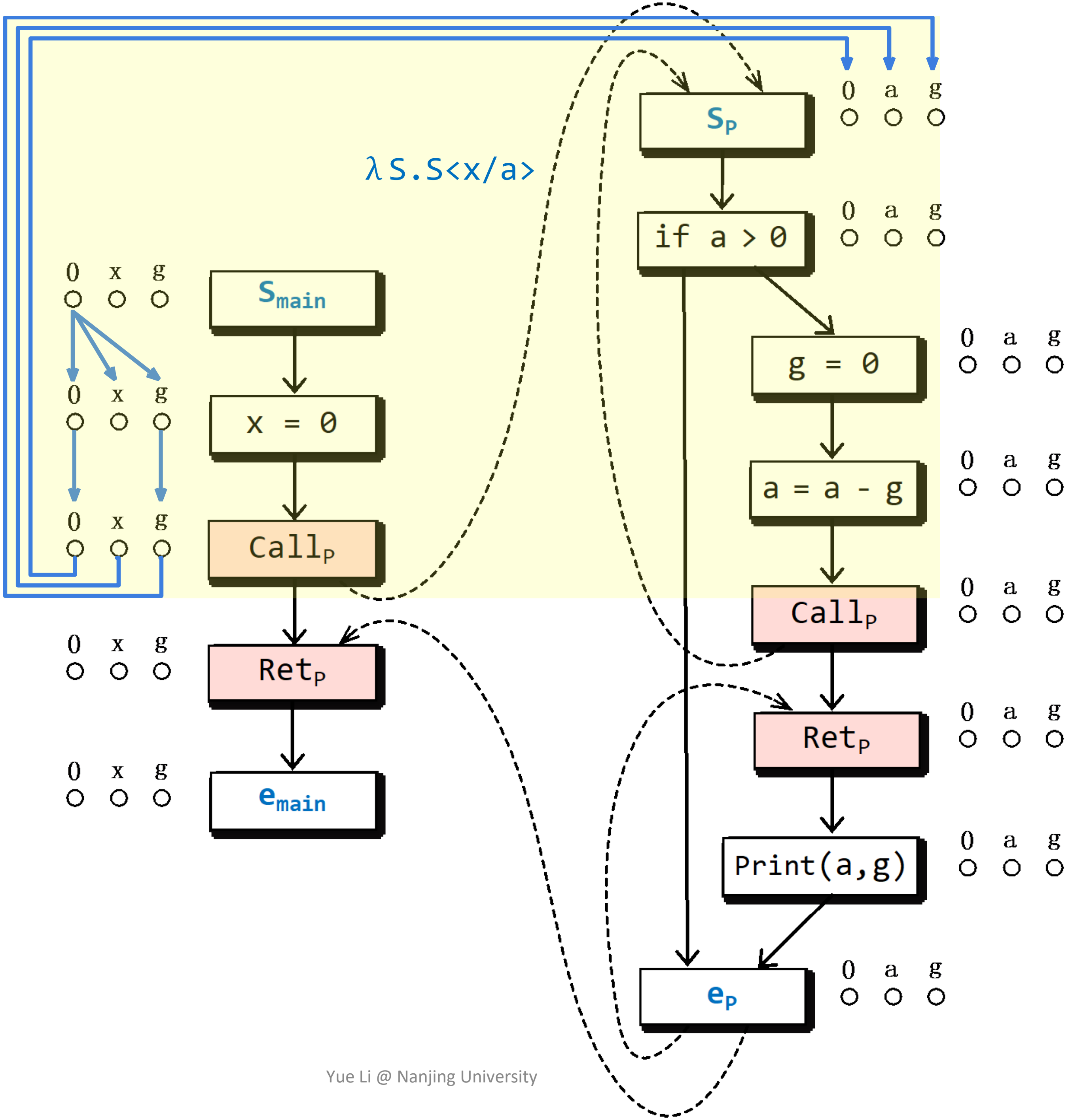
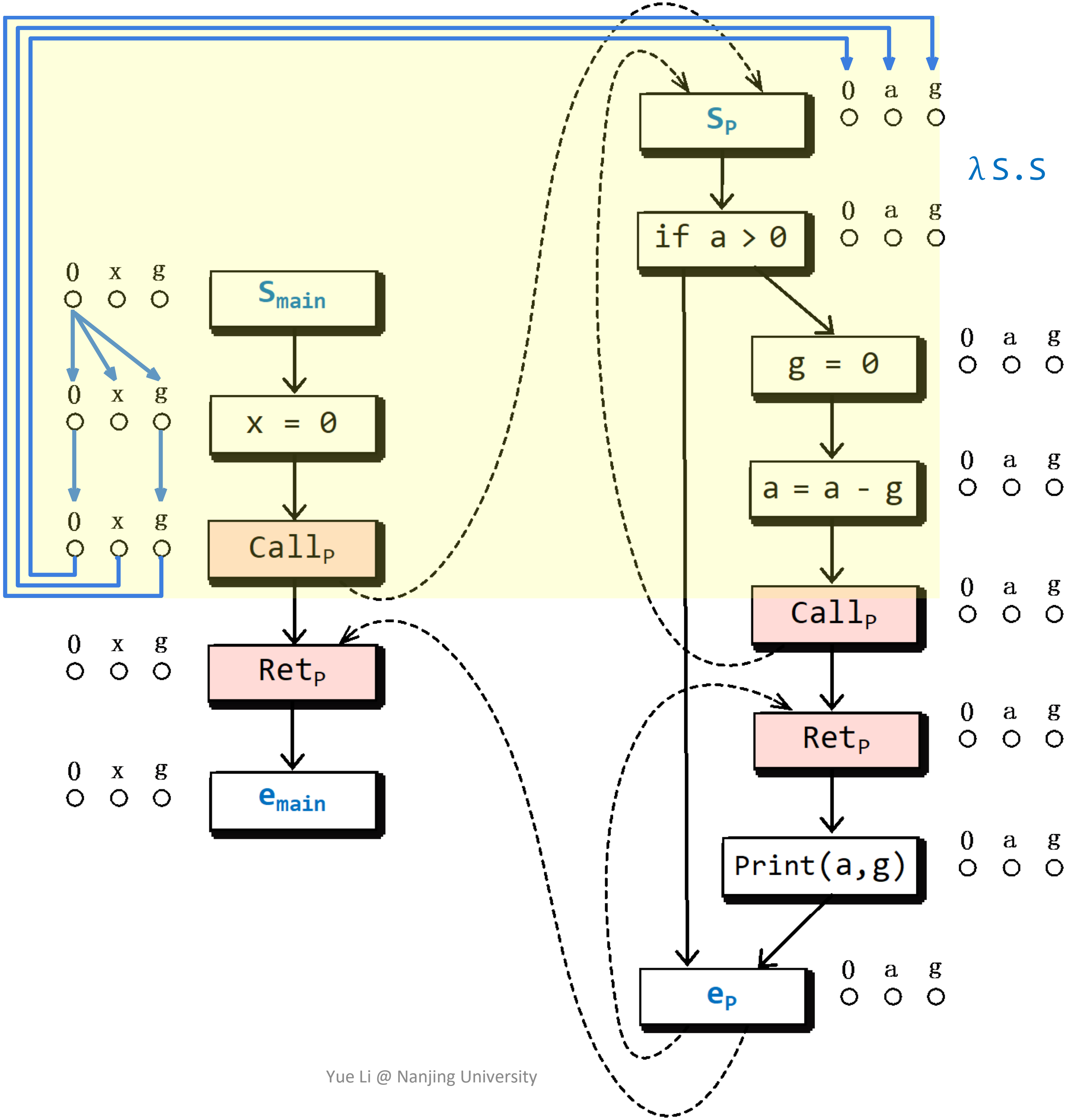
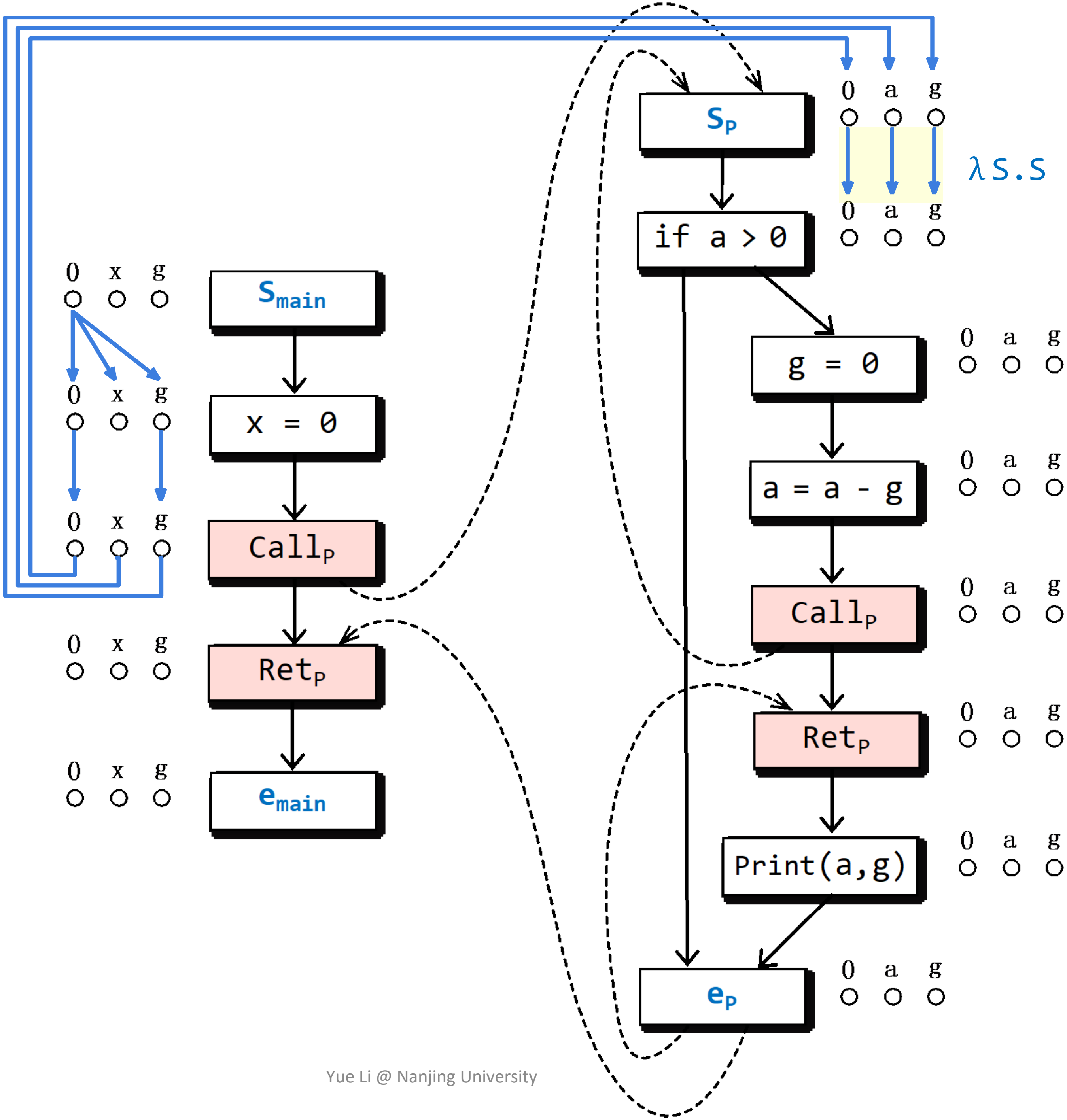
g = 0
a = a - g
Call_P
Ret_P
Print(a,g)
e_P
0 a g


λS.S<x/a>
0 x g
S_{main}
x = 0
Call_P
Ret_P
e_{main}
0 a g
S_P
if a > 0
g = 0
a = a - g
Call_P
Ret_P
Print(a,g)
e_P


λS.S<x/a>
Smain
x = 0
Callp
Retp
emain
Sp
if a > 0
g = 0
a = a - g
Callp
Retp
Print(a,g)
ep
0 x g
0 a g


S_main
x = 0
Call_P
Ret_P
e_main
S_P
if a > 0
g = 0
a = a - g
Call_P
Ret_P
Print(a,g)
e_P
0 x g
0 a g
λS.S



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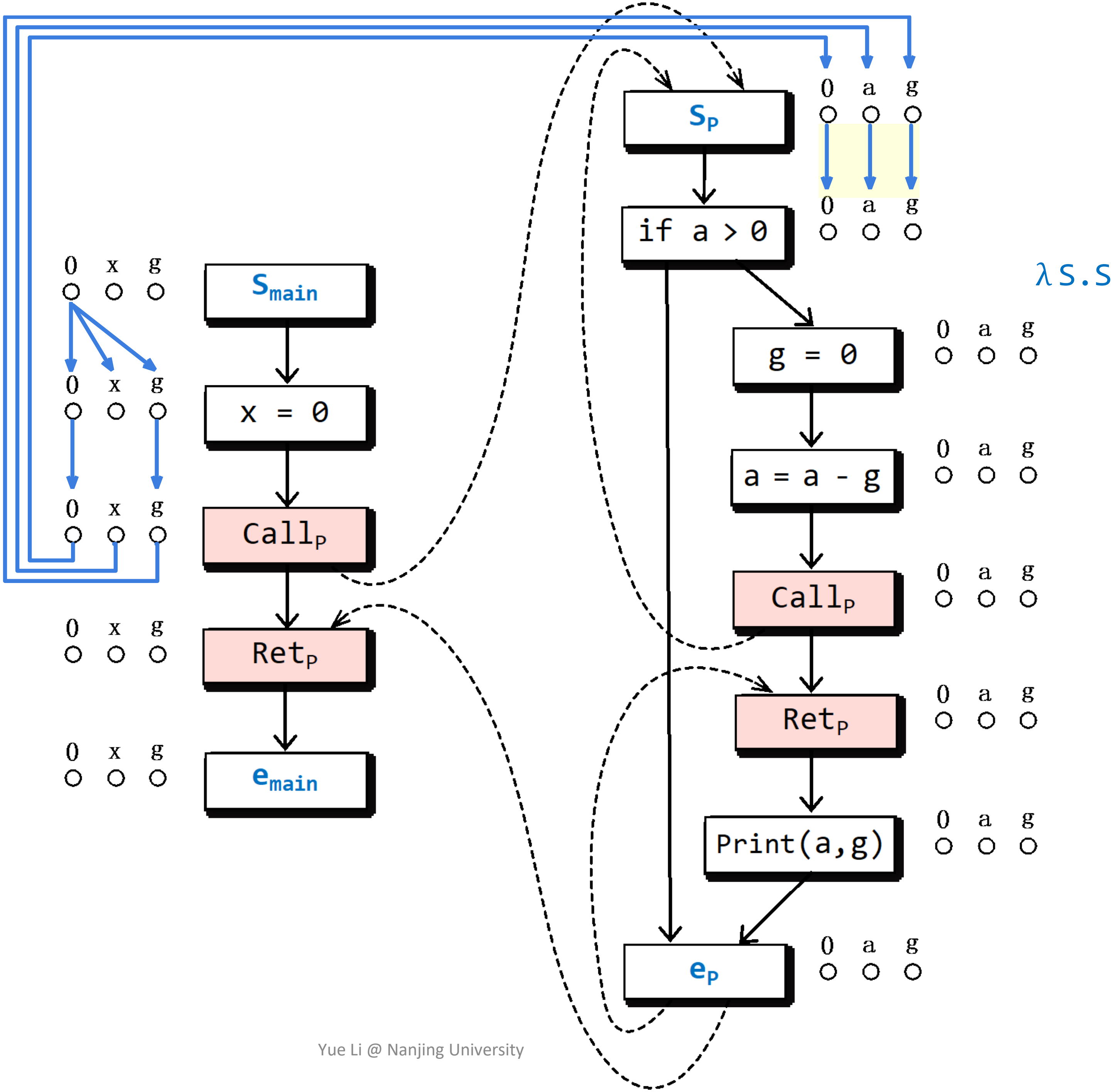
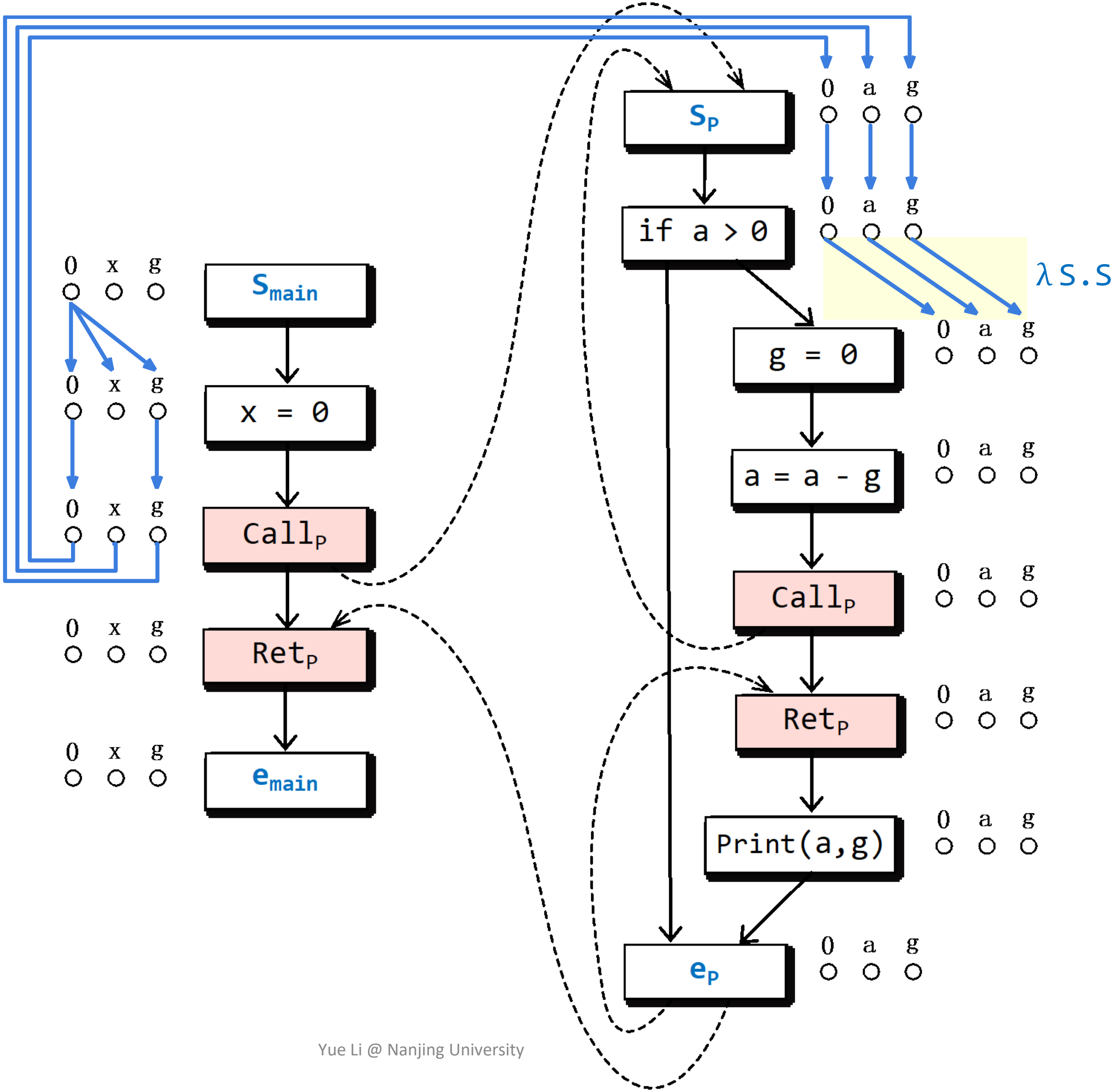


λS.S
S_main
x = 0
Call_p
Ret_p
e_main
S_p
if a > 0
g = 0
a = a - g
Call_p
Ret_p
Print(a,g)
e_p
0 x g
0 a g



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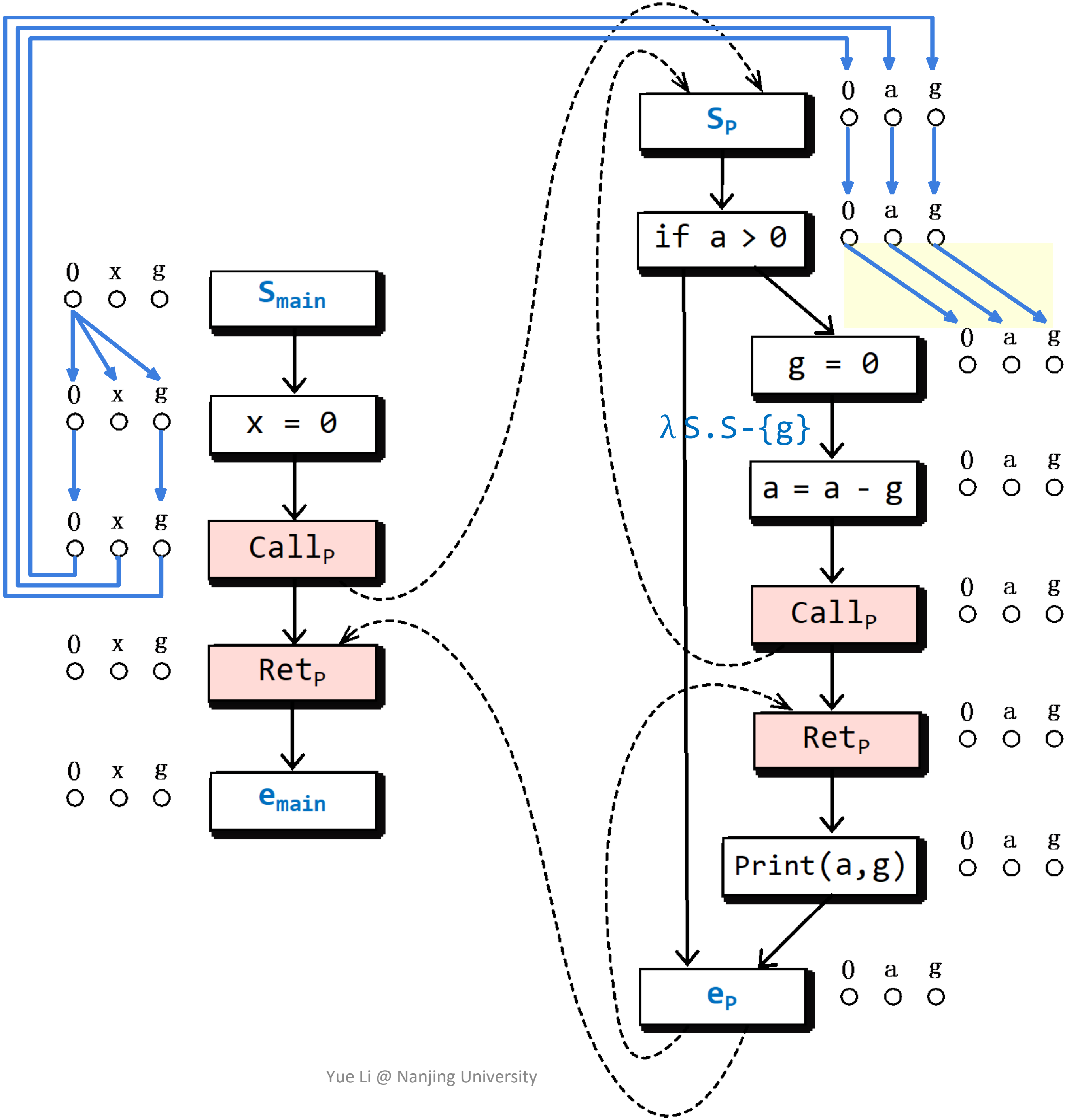

Smain
x = 0
Callp
Retp
emain
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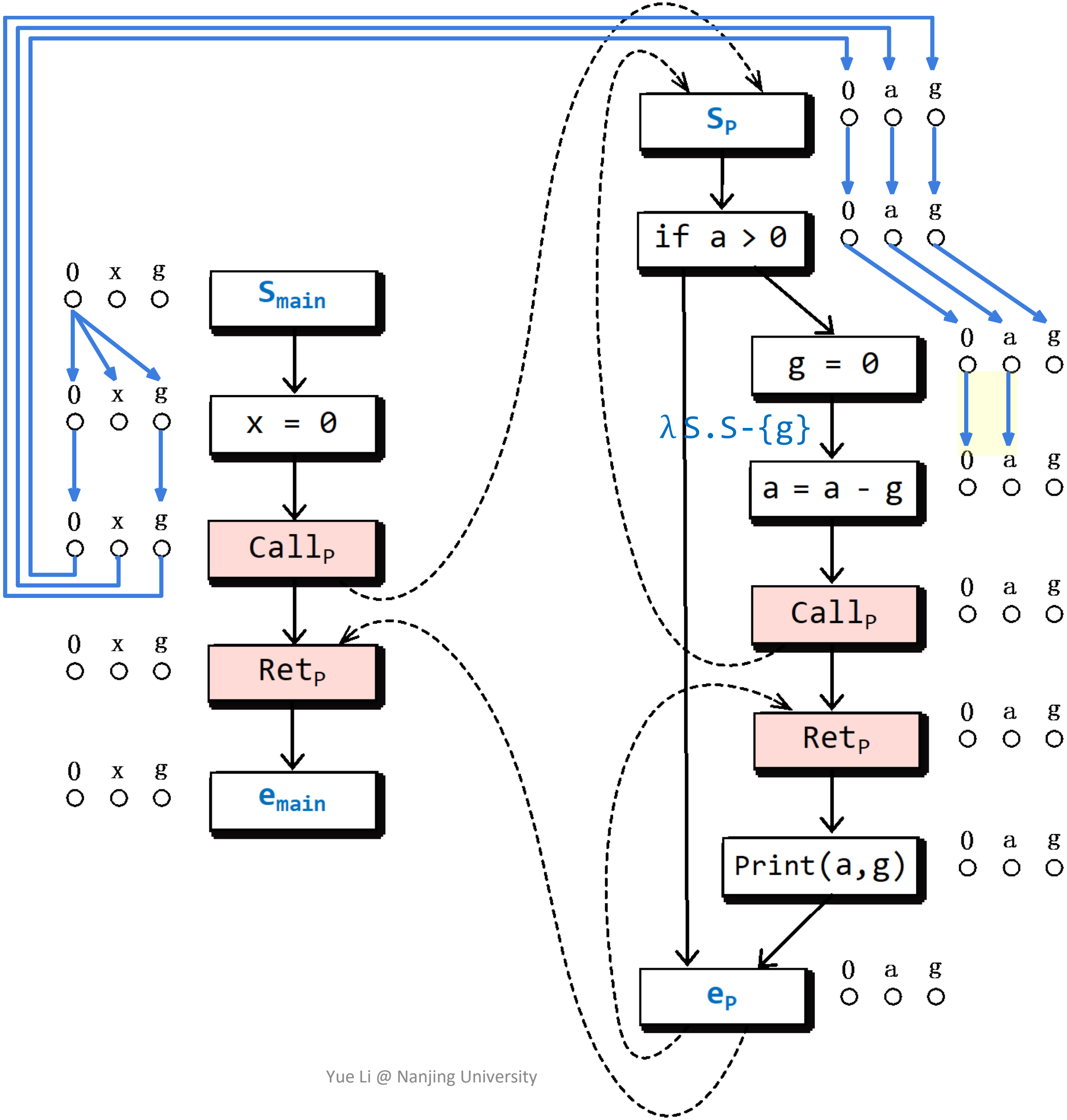
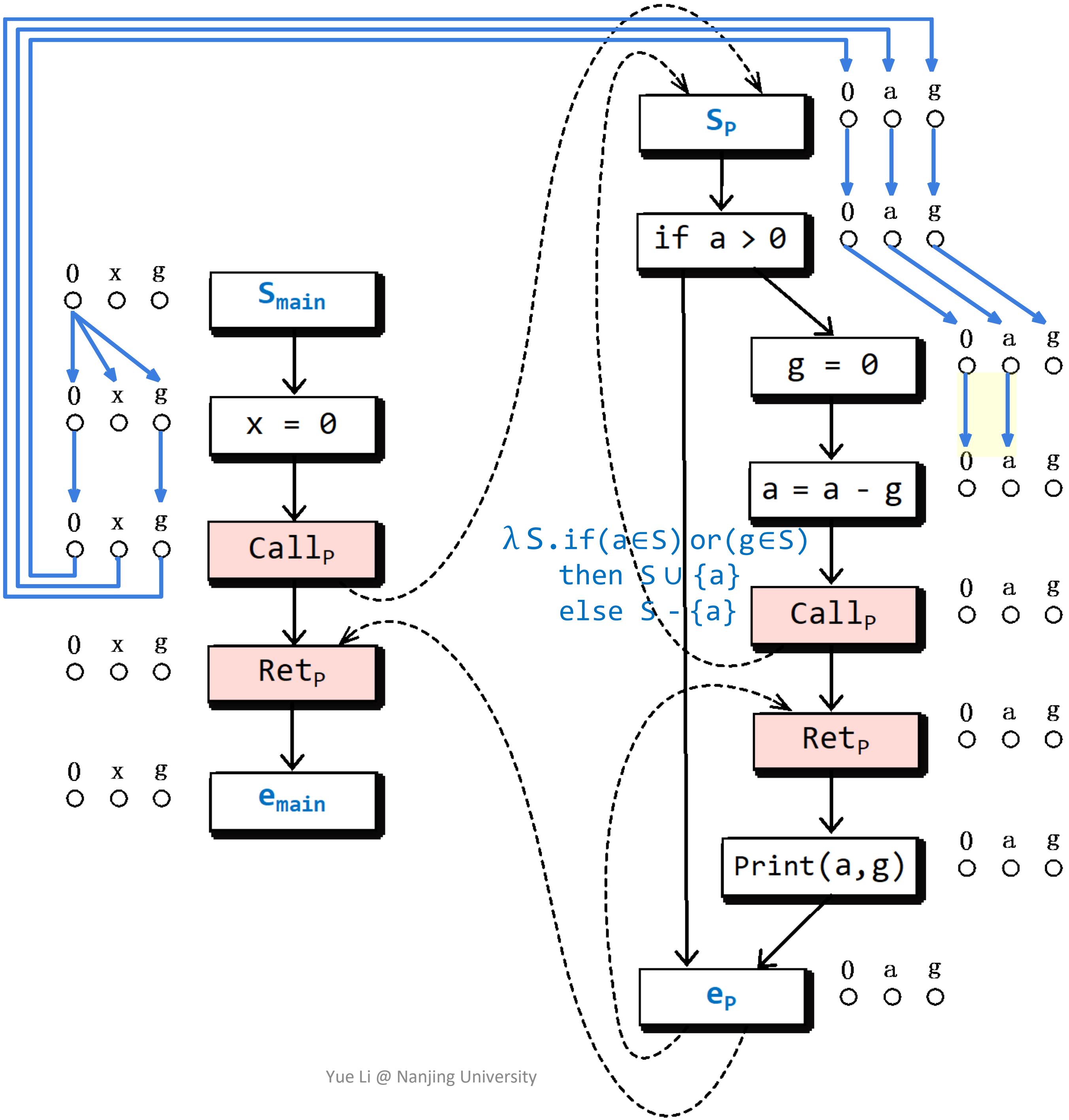
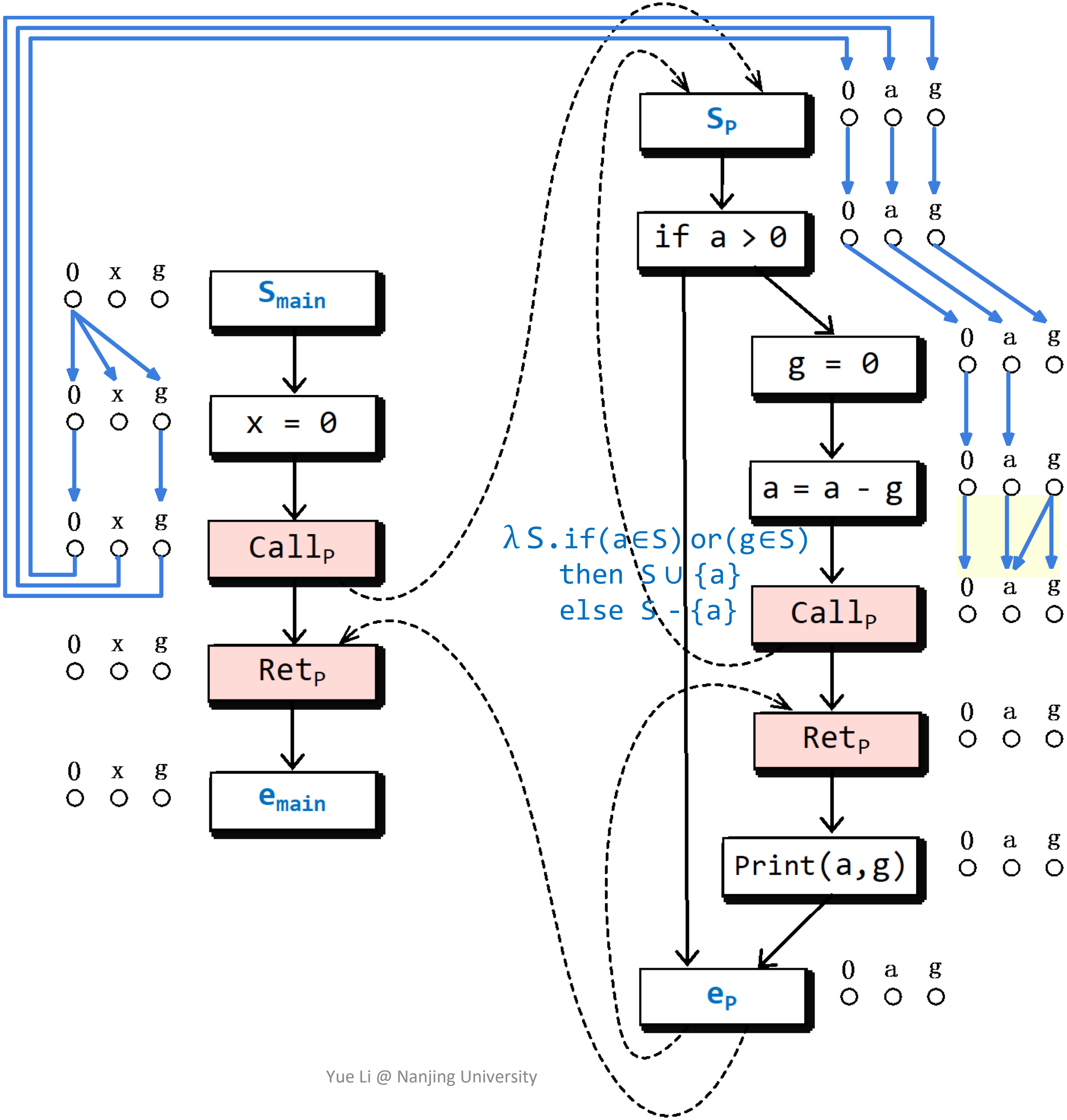
Sp
if a > 0
g = 0
a = a - g
Callp
Retp
Print(a,g)
ep
0 a g
λS.S-{g}

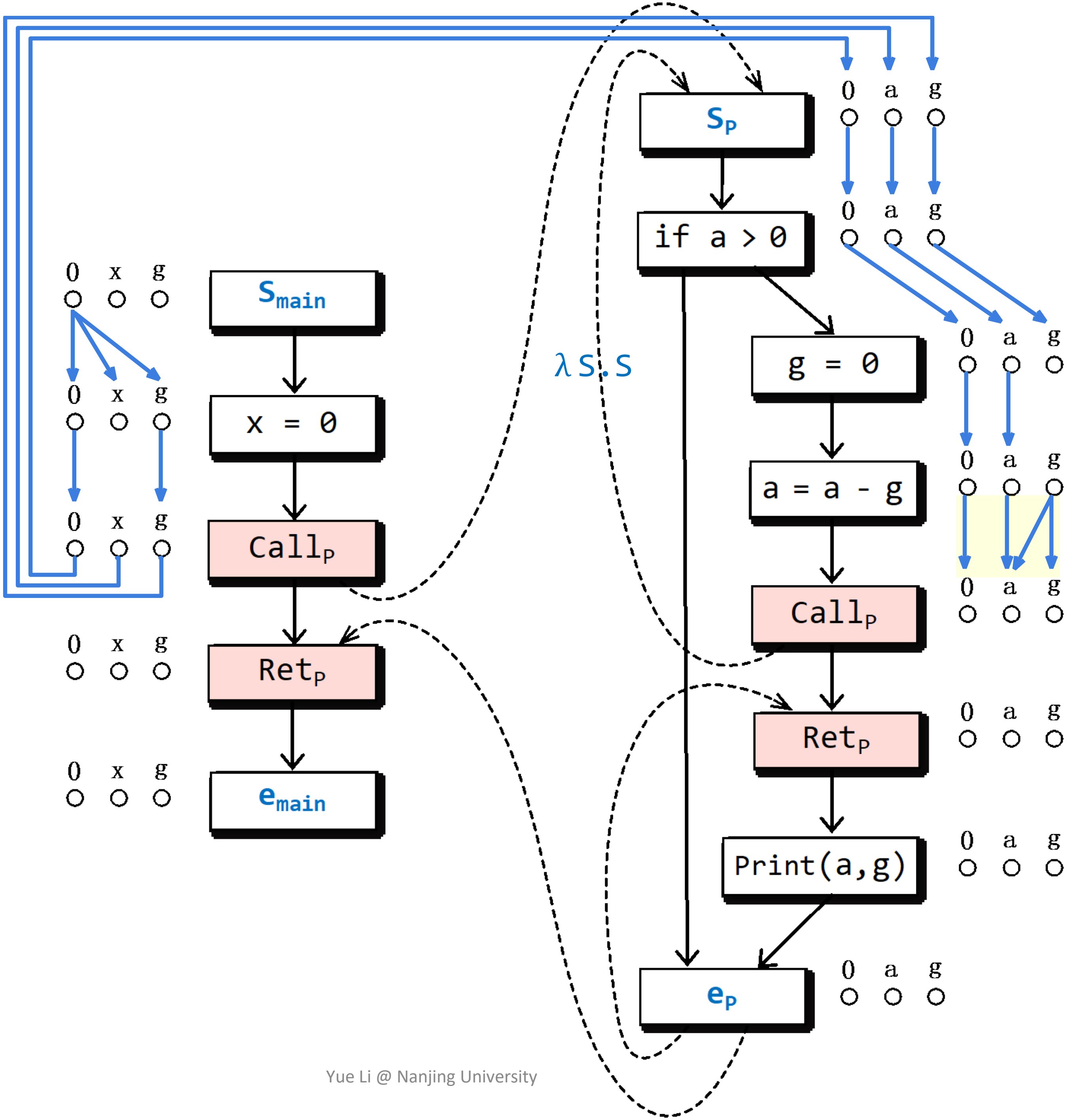

0
x
g
S_main
x = 0
Call_P
Ret_P
e_main
0
a
g
S_P
if a > 0
g = 0
λS.S-{g}
a = a - g
Call_P
Ret_P
Print(a,g)
e_P



λS.if(a∈S) or(g∈S)
then S ∪ {a}
else S - {a}



λS.if(a∈S)or(g∈S)
then S∪{a}
else S-{a}



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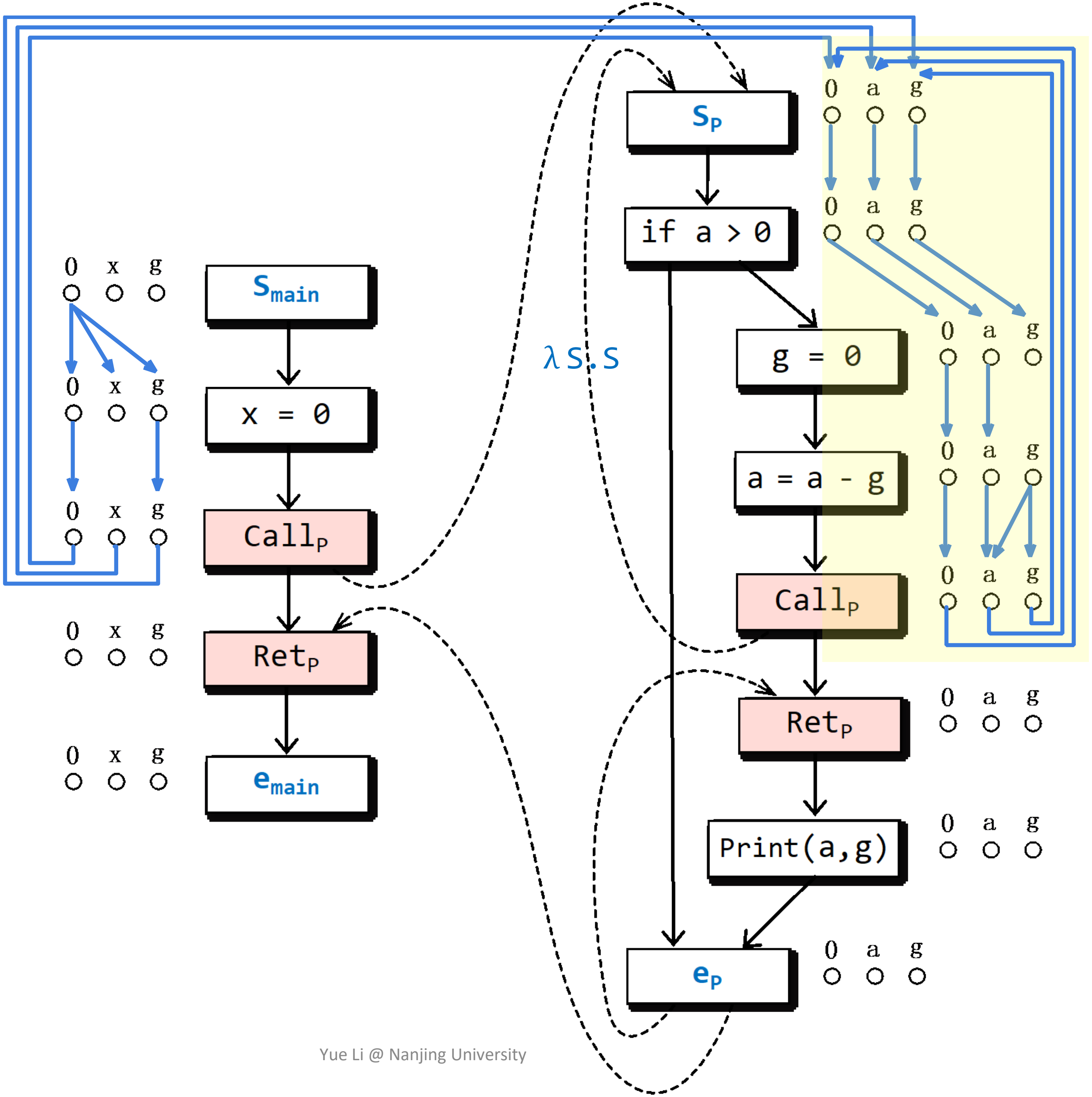

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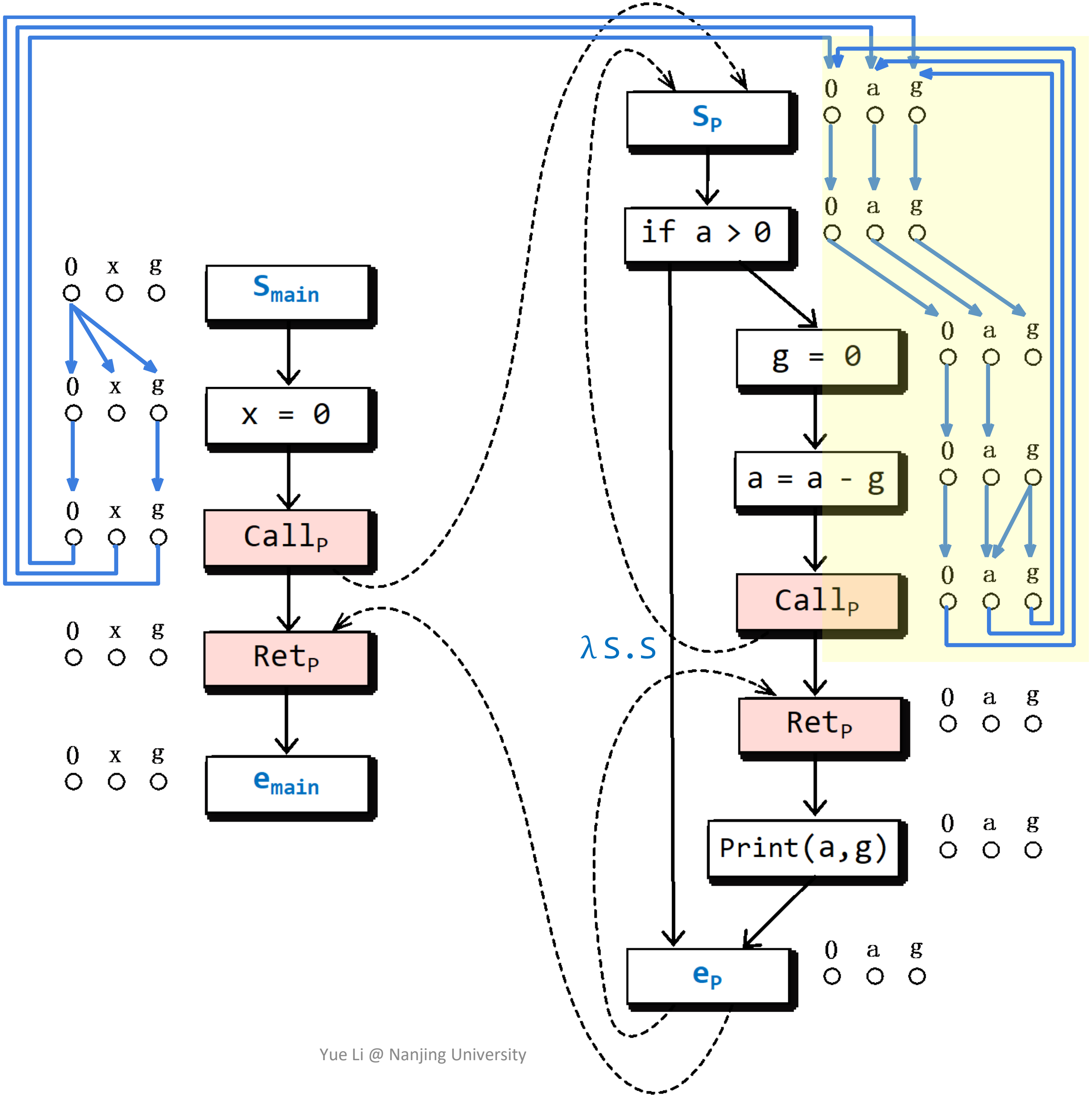

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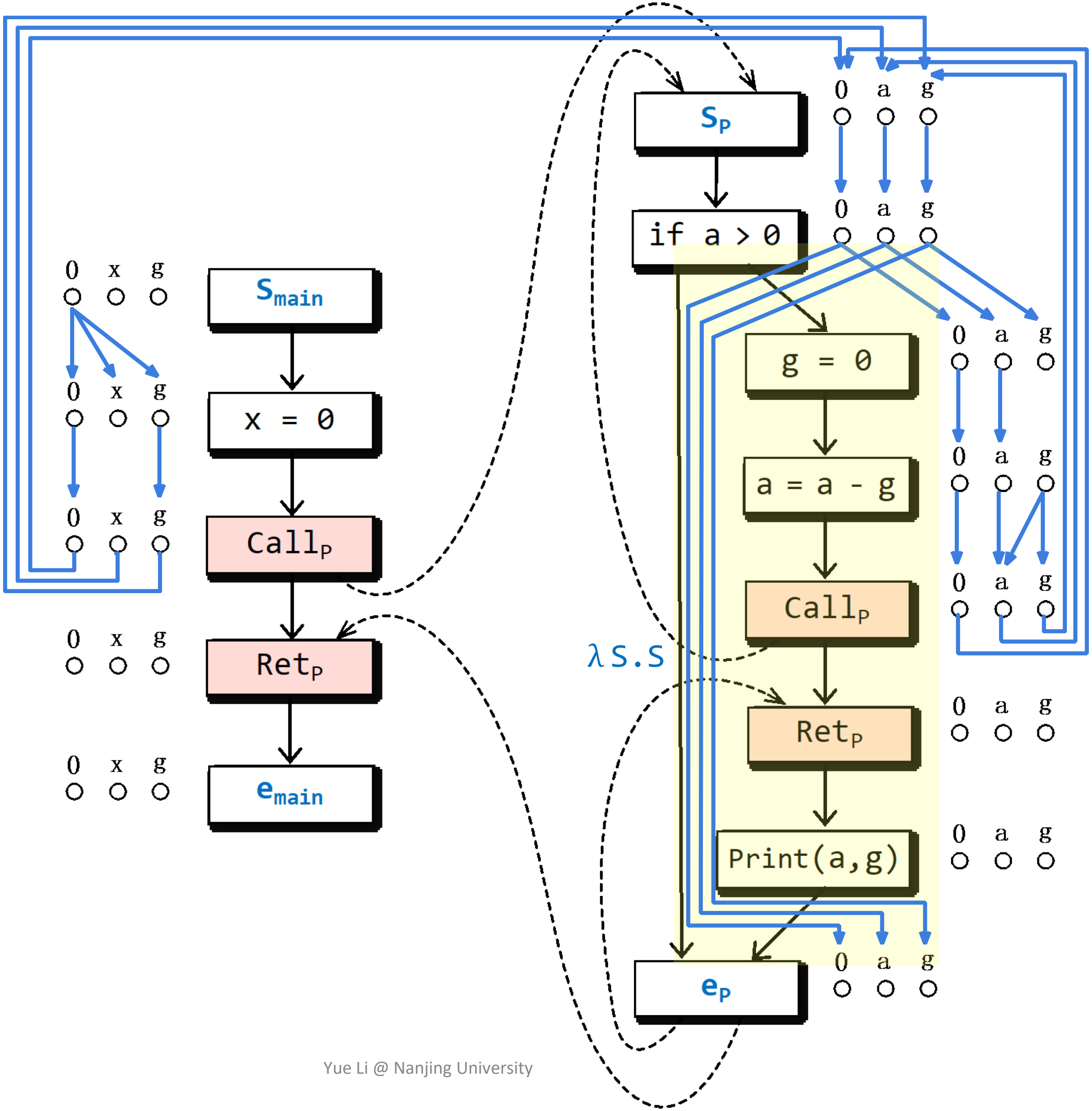

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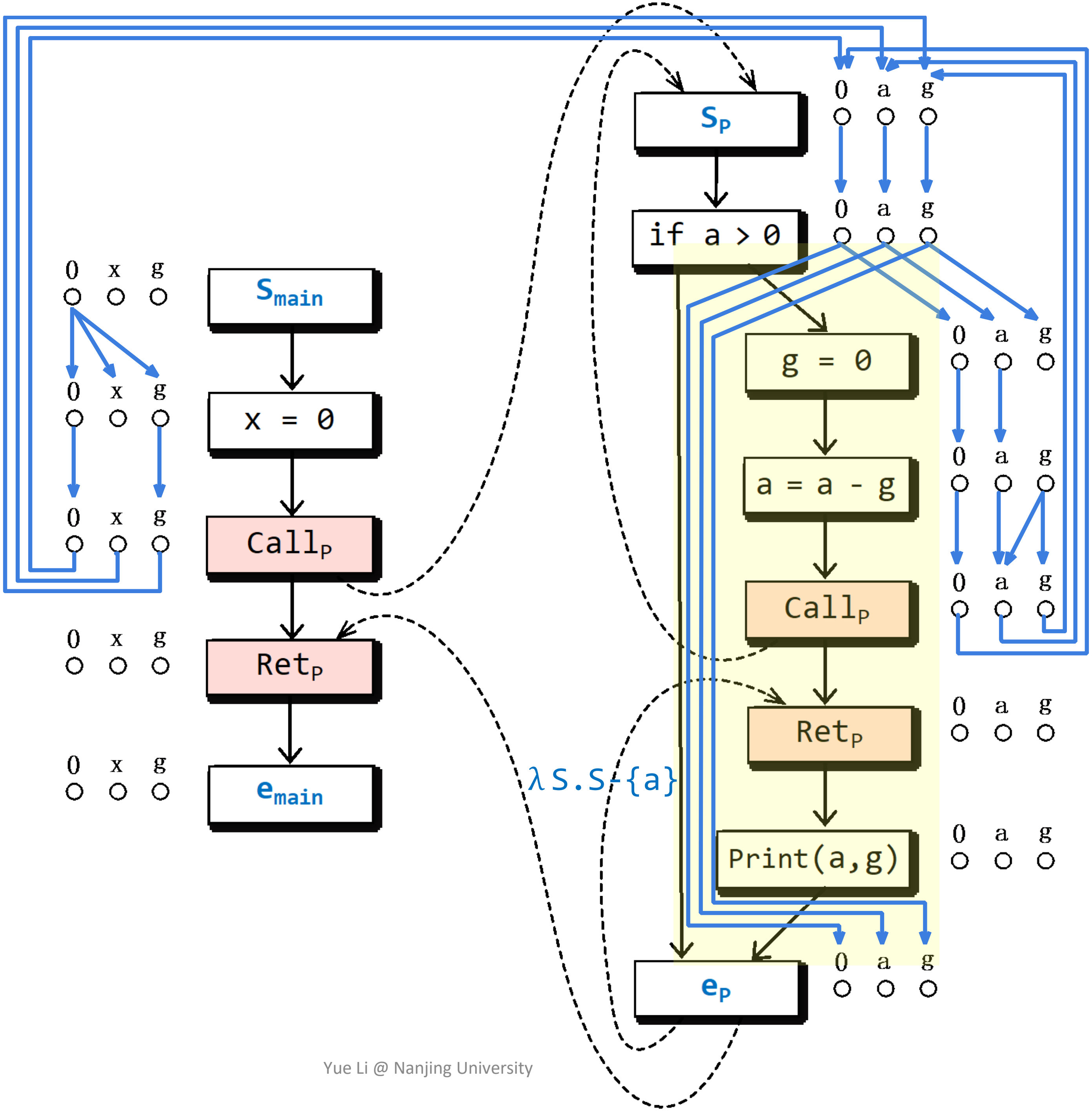
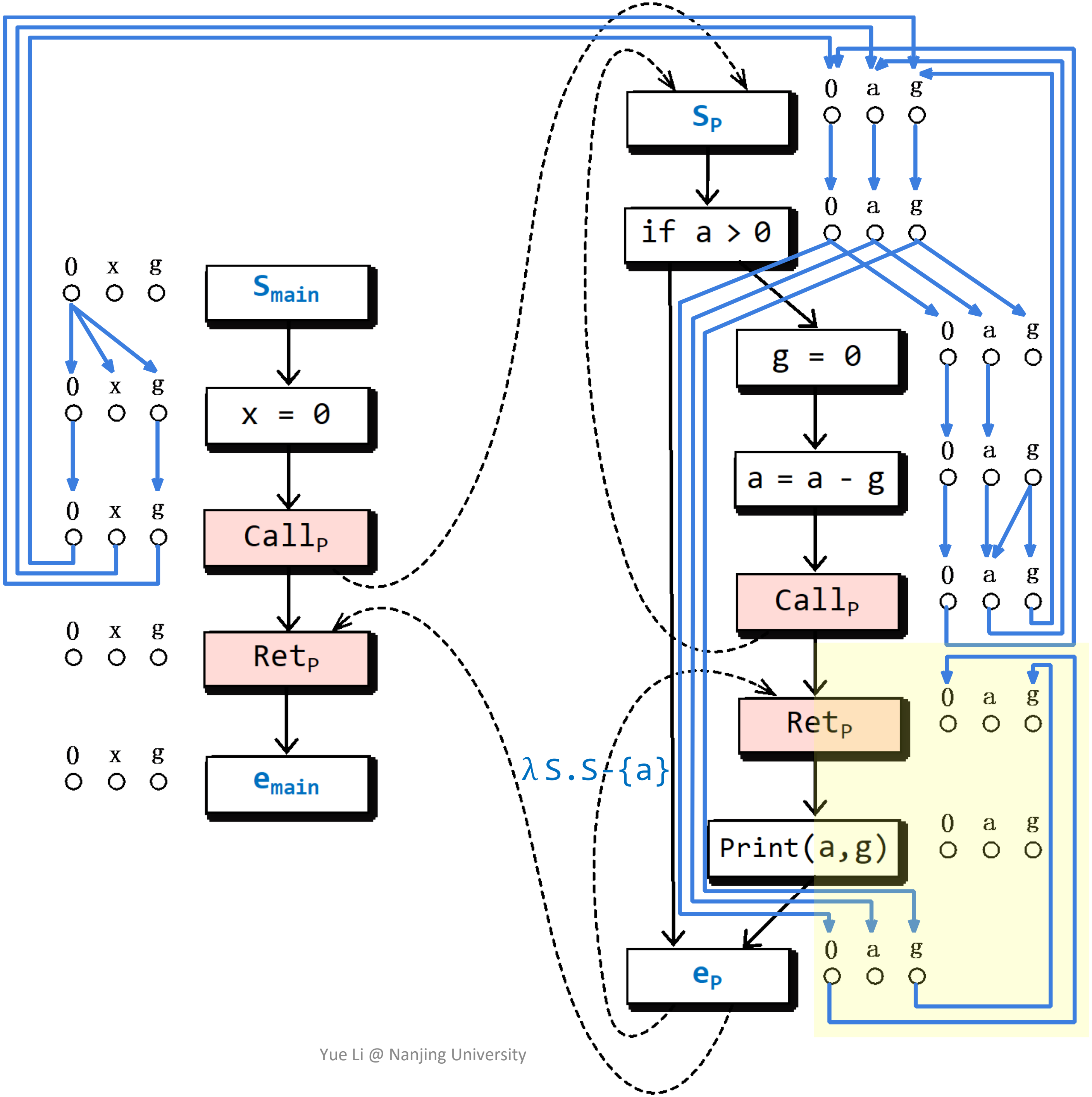


Yue Li @ Nanjing University


Smain
x = 0
Callp
Retp
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0 x g
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if a > 0
g = 0
a = a - g
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Retp
Print(a,g)
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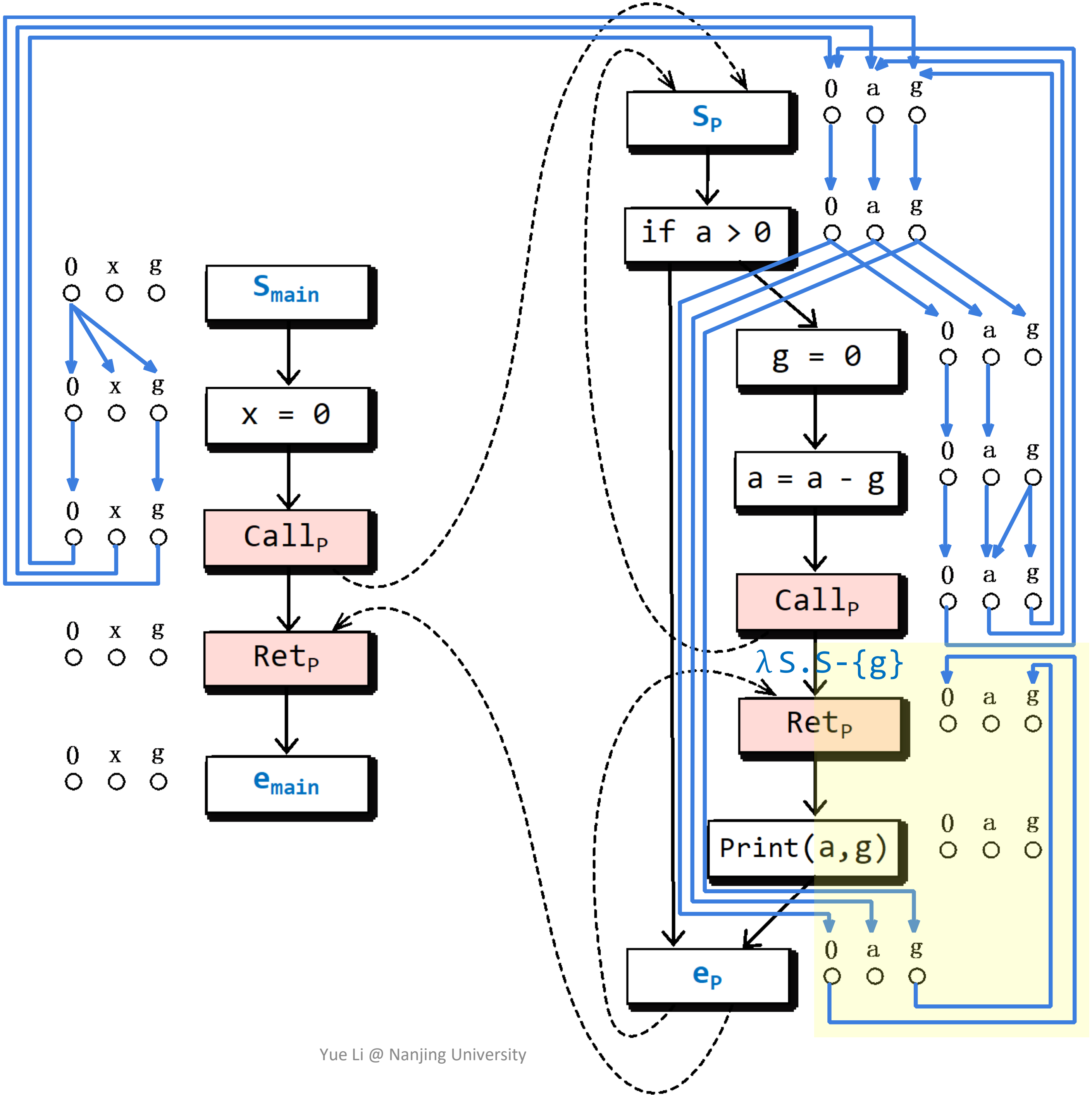
S_main
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S_P
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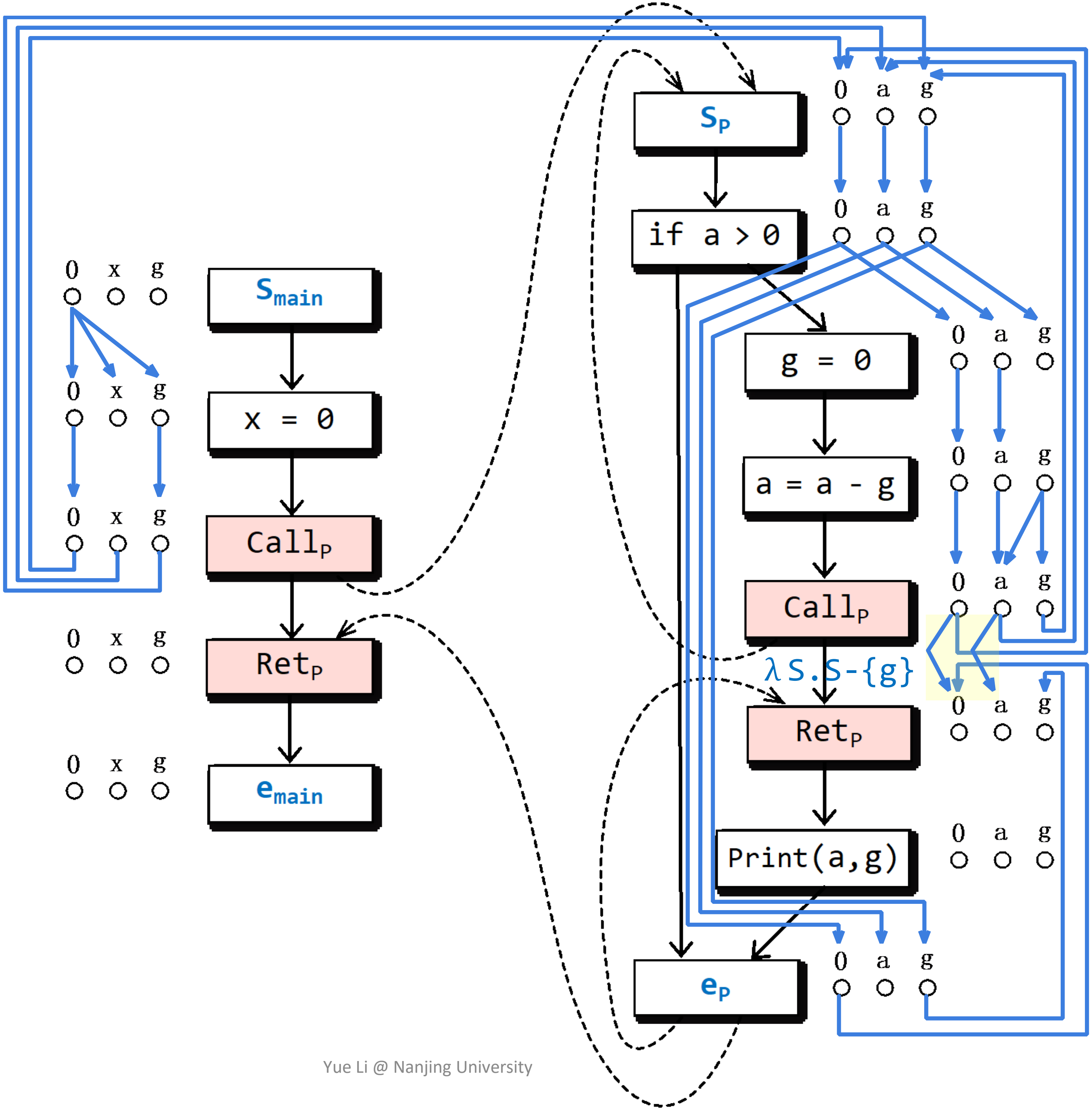

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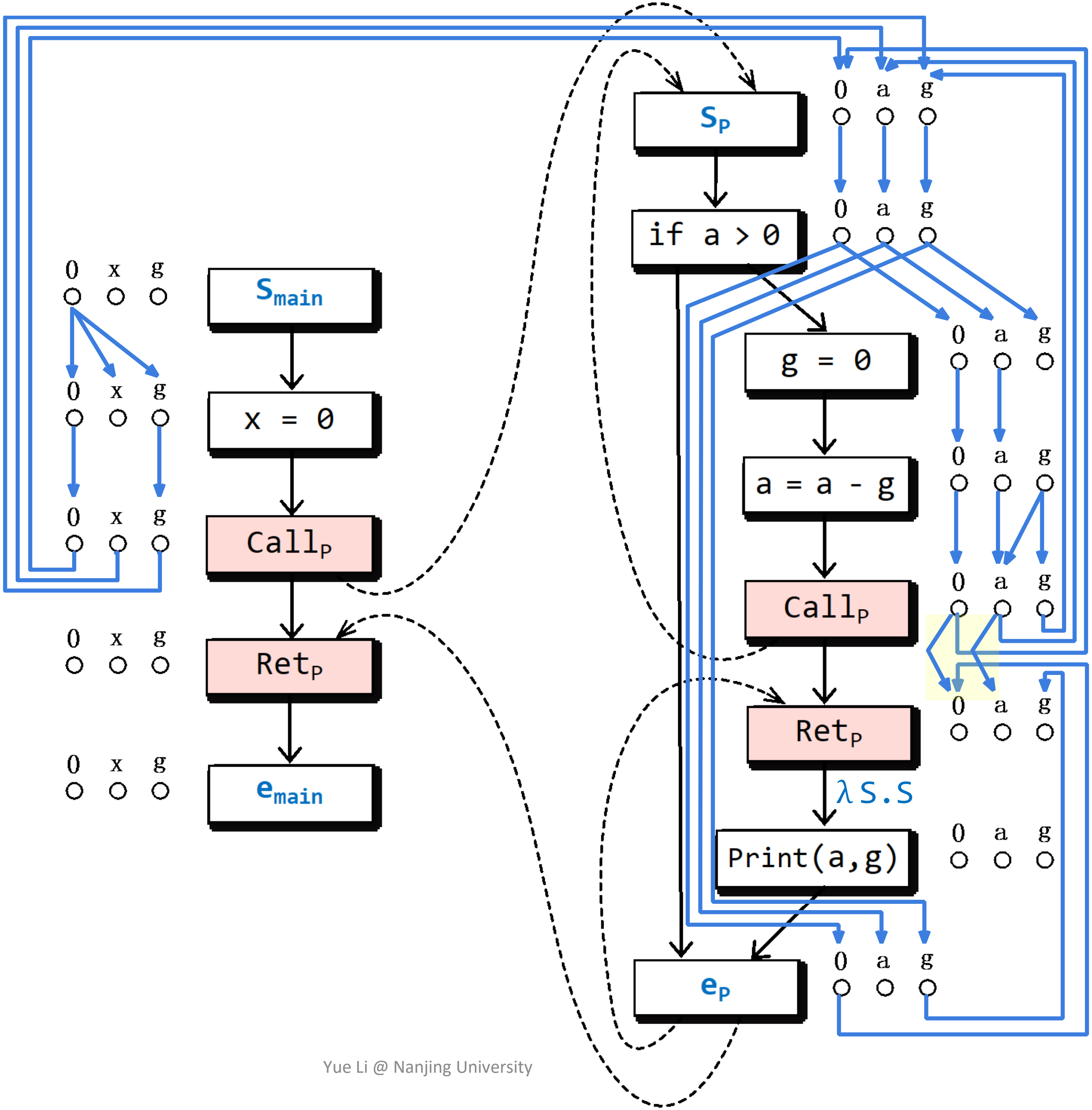
Smain
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Callp
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0 a g
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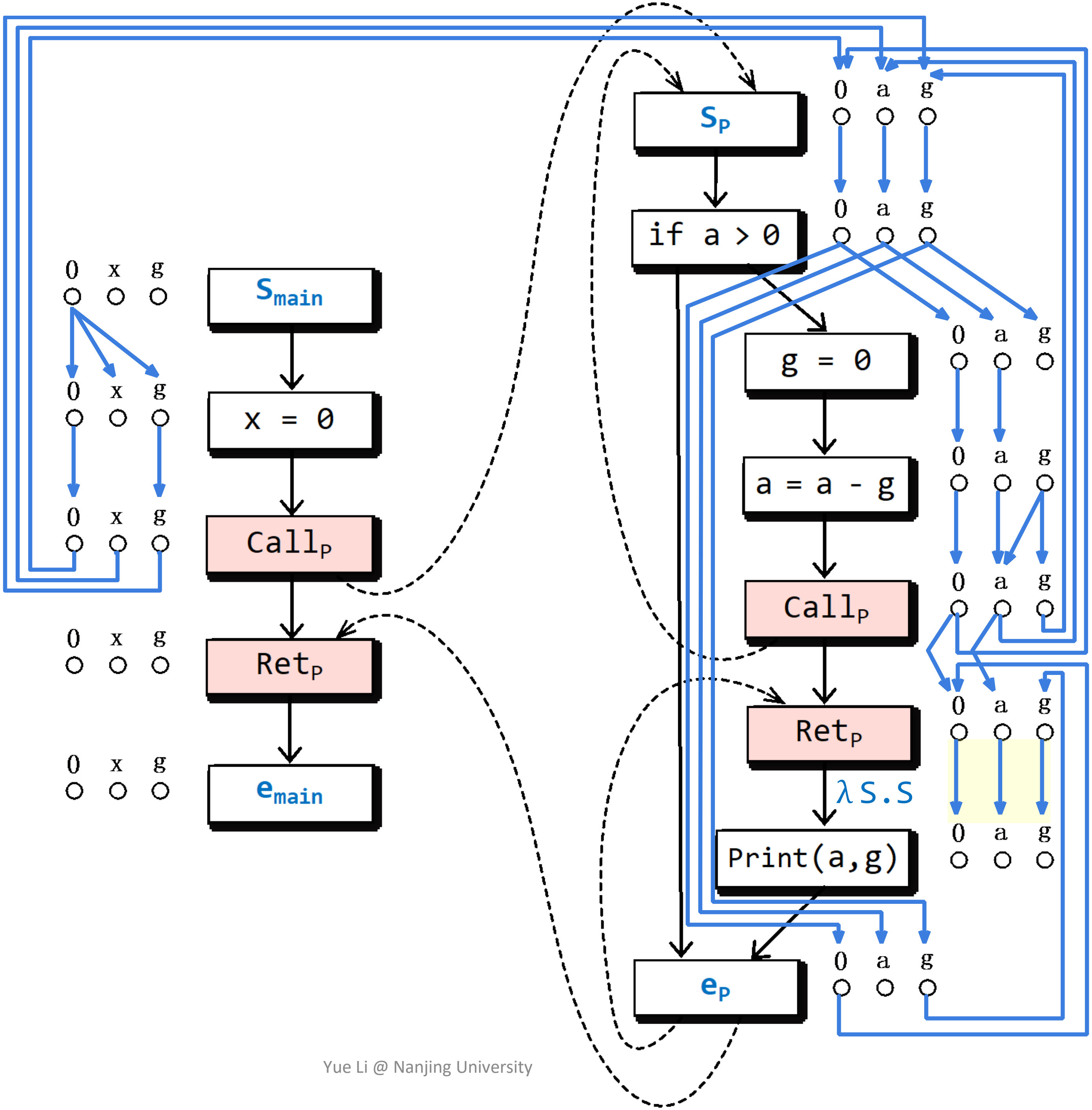
0 a g
0 a g



0 x g
S_main
x = 0
Call_p
Ret_p
e_main
0 a g
S_p
if a > 0
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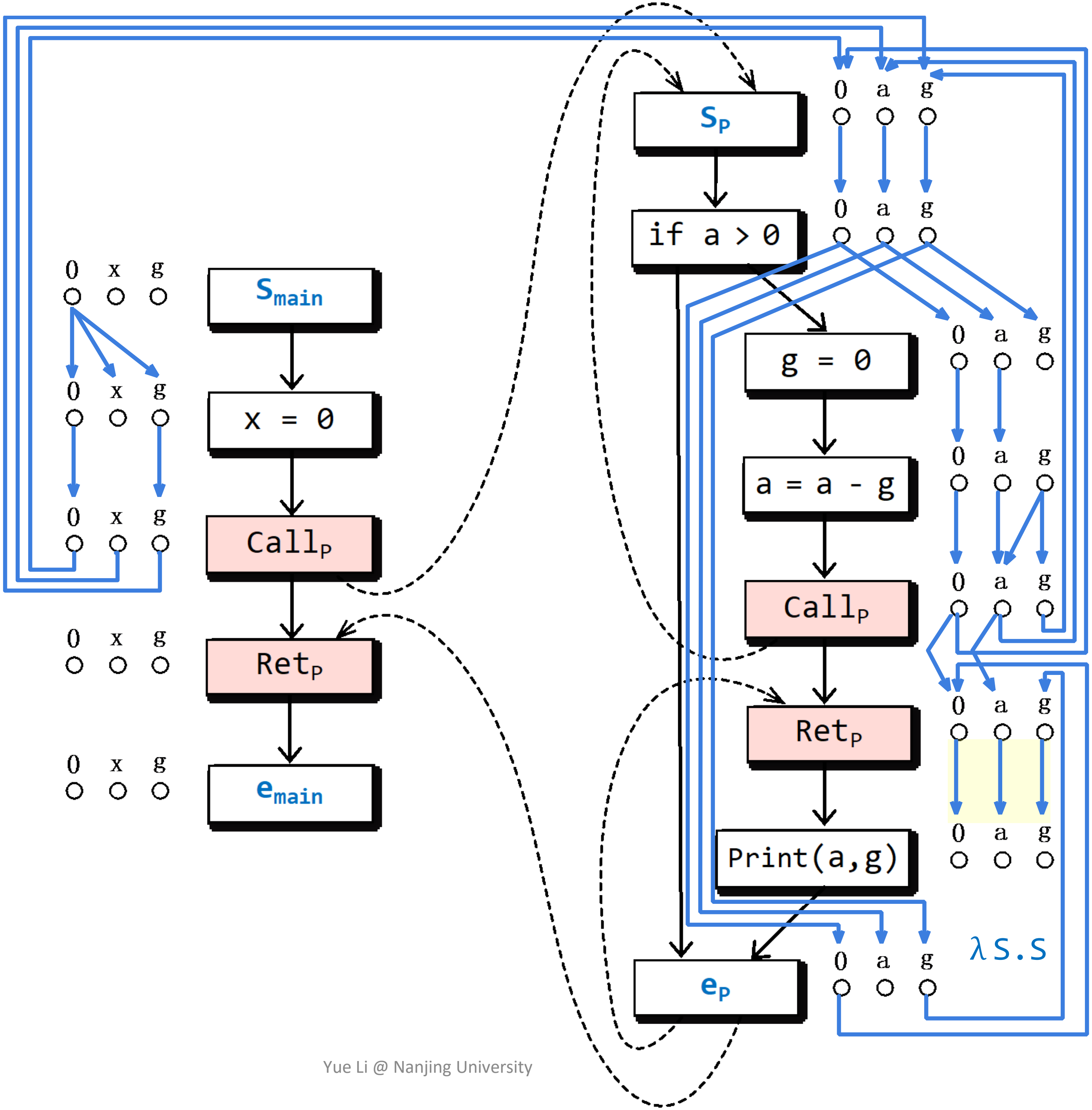
a = a - g
Call_p
Ret_p
λS.S
Print(a,g)
e_p



s_{main}

x = 0

$Call_p$

Ret_p

e_{main}

s_p

if a > 0

g = 0

a = a - g

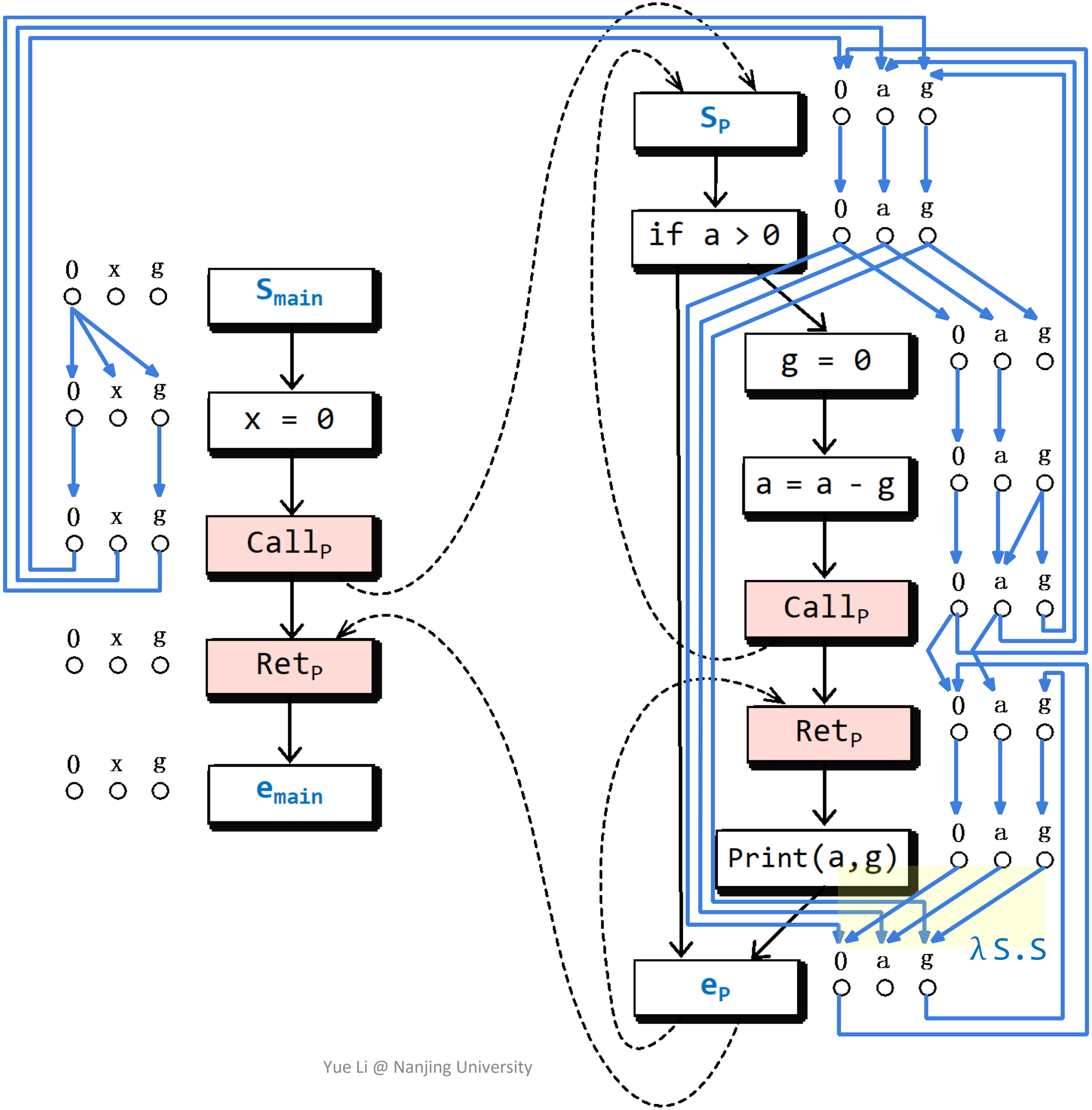
$Call_p$

Ret_p

Print(a,g)

e_p

λS.S



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S_{main}
x = 0
$Call_P$
Ret_P
e_{main}
S_P
if a > 0
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a = a - g
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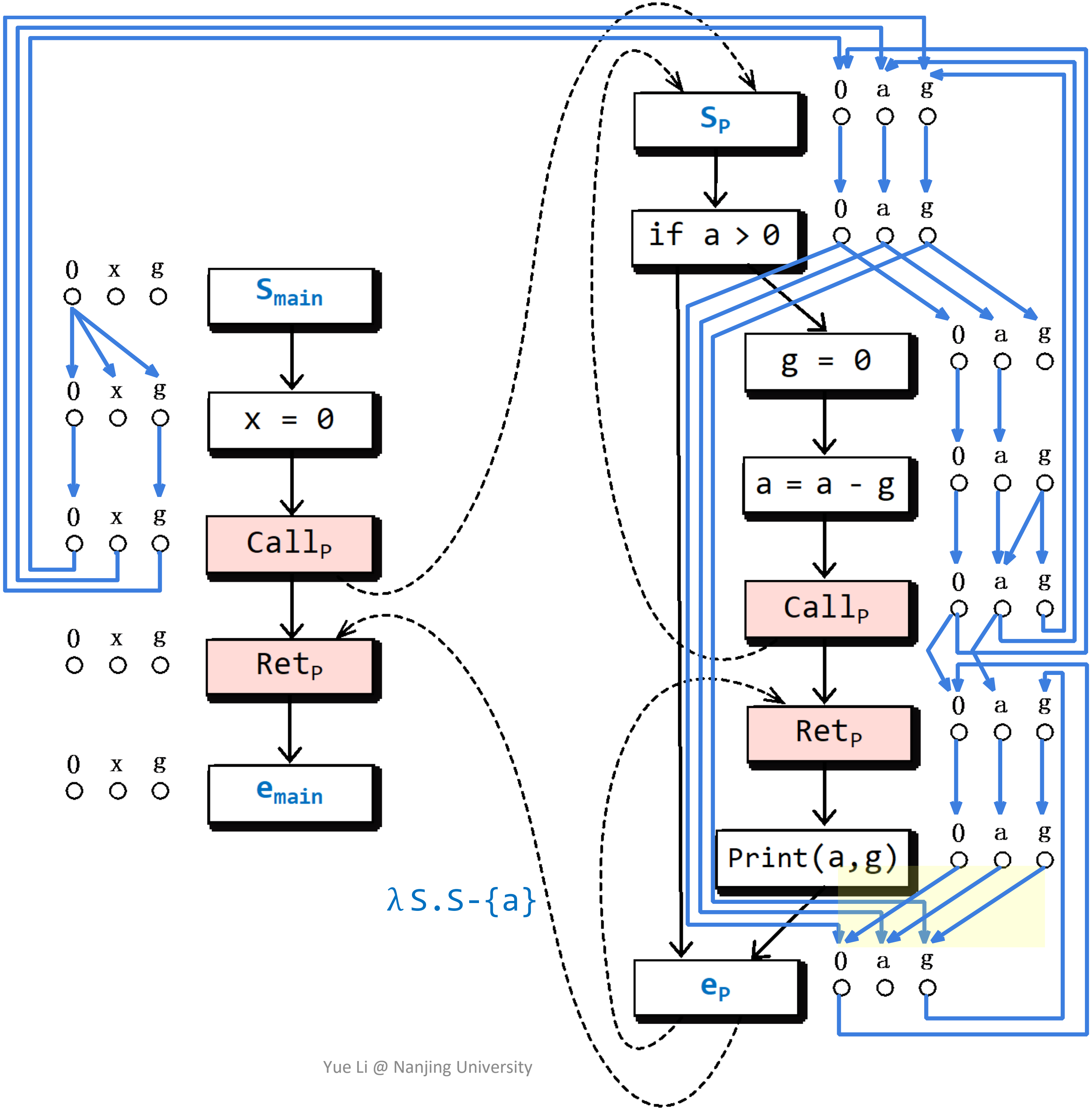
λS.S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0 a g
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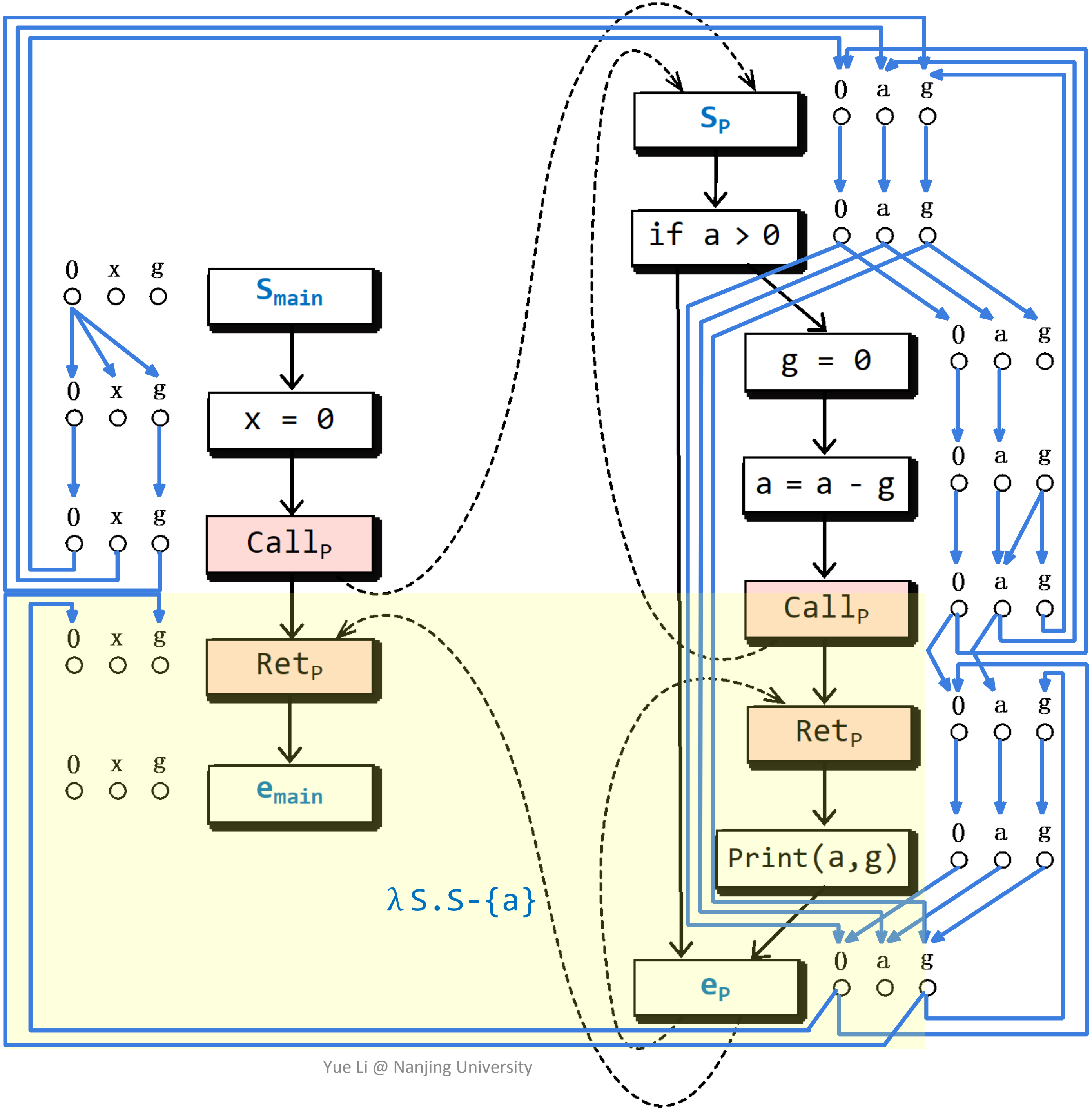
Print(a,g)
e_P

λS.S-{a}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S_{main}
x = 0
$Call_p$
Ret_p
e_{main}
S_p
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Print(a,g)
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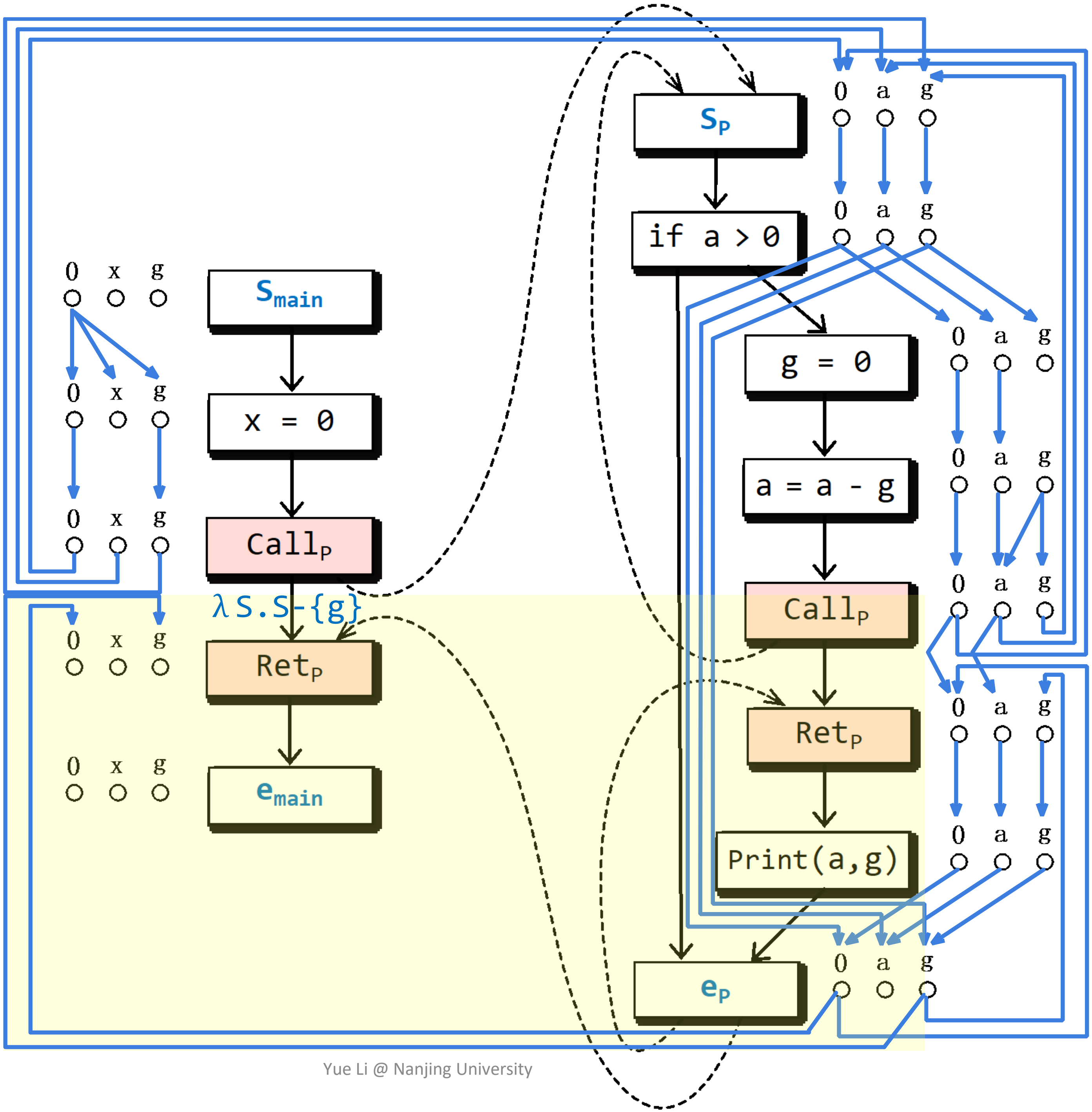
S_main
x = 0
Call_p
λS.S-{g}
Ret_p
e_main
0 x g
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if a > 0
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a = a - g
Call_p
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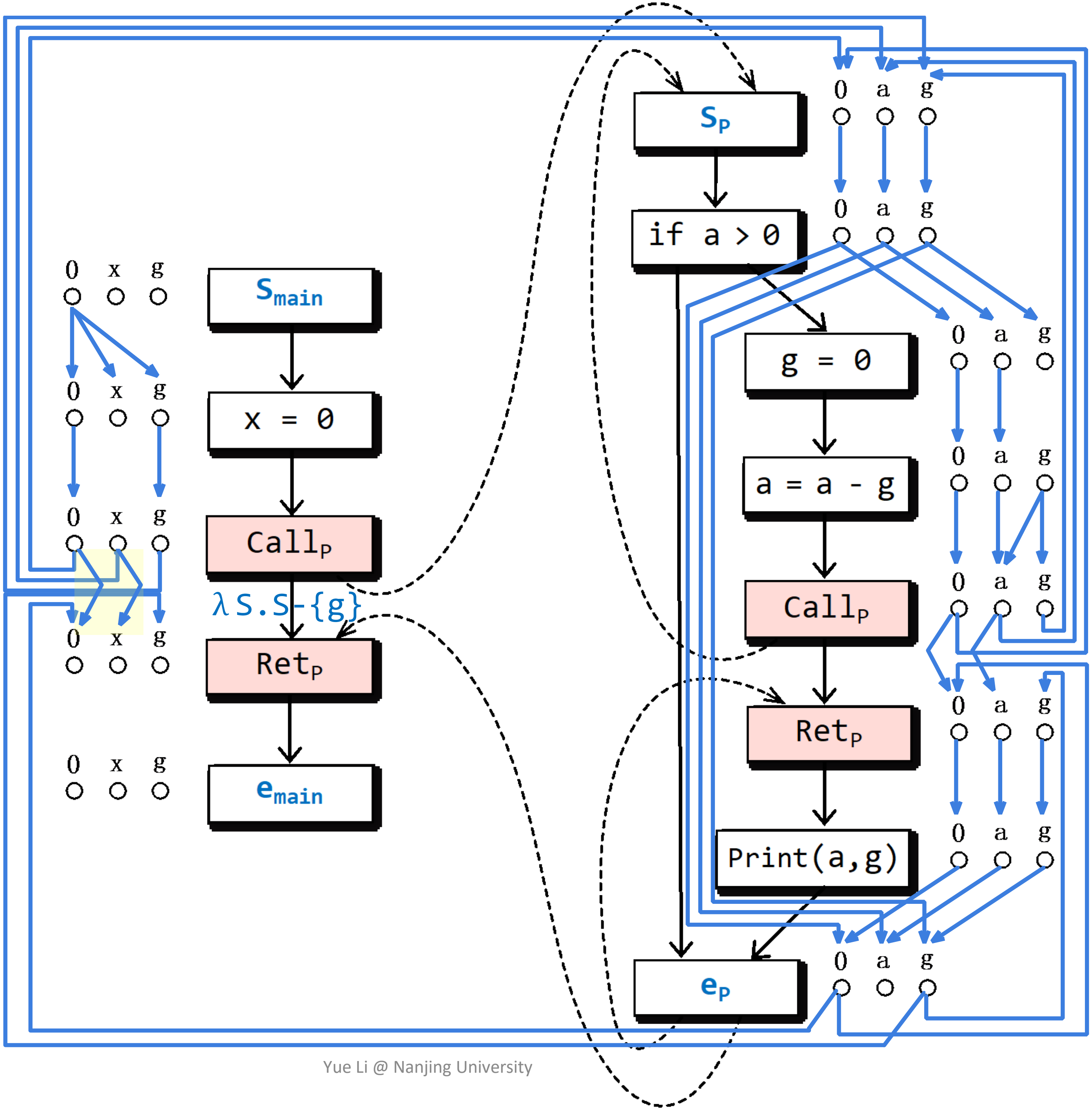
Print(a,g)
e_p
0 a g



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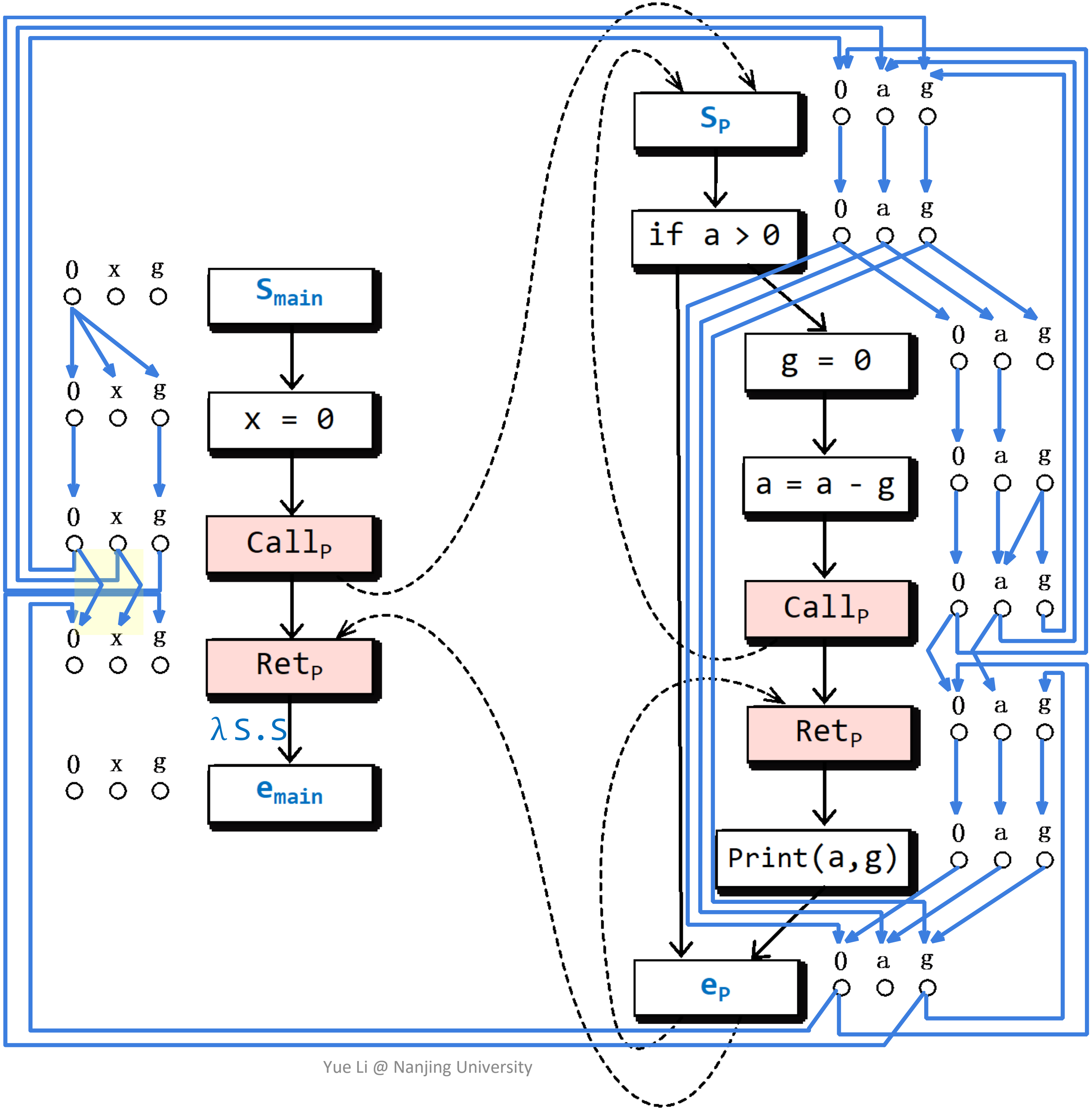
S_{main}
x = 0
$Call_p$
Ret_p
λS.S
e_{main}
S_p
if a > 0
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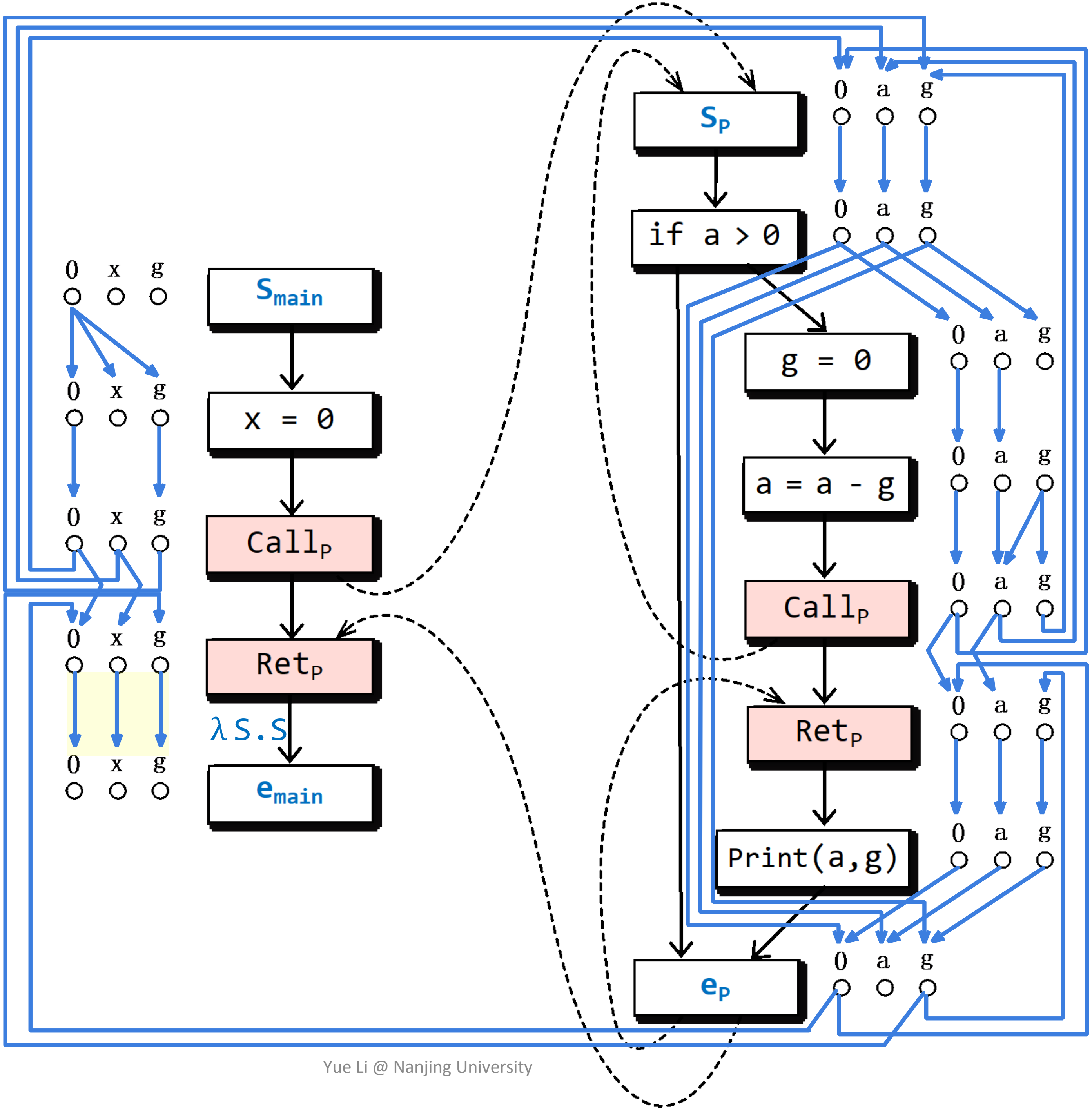
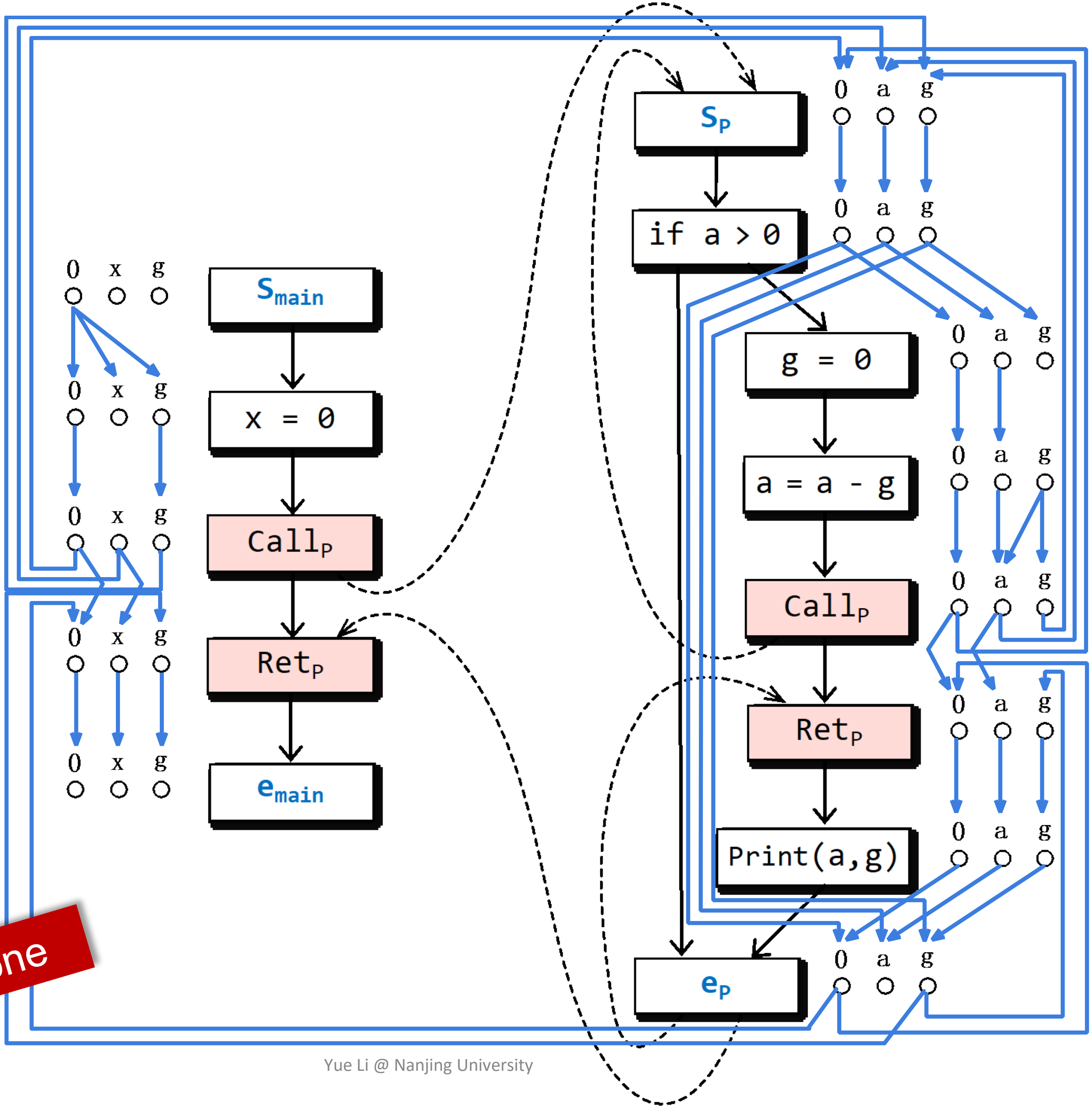
a = a - g
$Call_p$
Ret_p
Print(a,g)
e_p
0 x g
0 a g


0 x g
S_main
x = 0
Call_P
Ret_P
λS.S
e_main
0 a g
S_P
if a > 0
g = 0
a = a - g
Call_P
Ret_P
Print(a,g)
e_P



S_{main}

x = 0

$Call_p$

Ret_p

e_{main}

S_p

if a > 0

g = 0

a = a - g

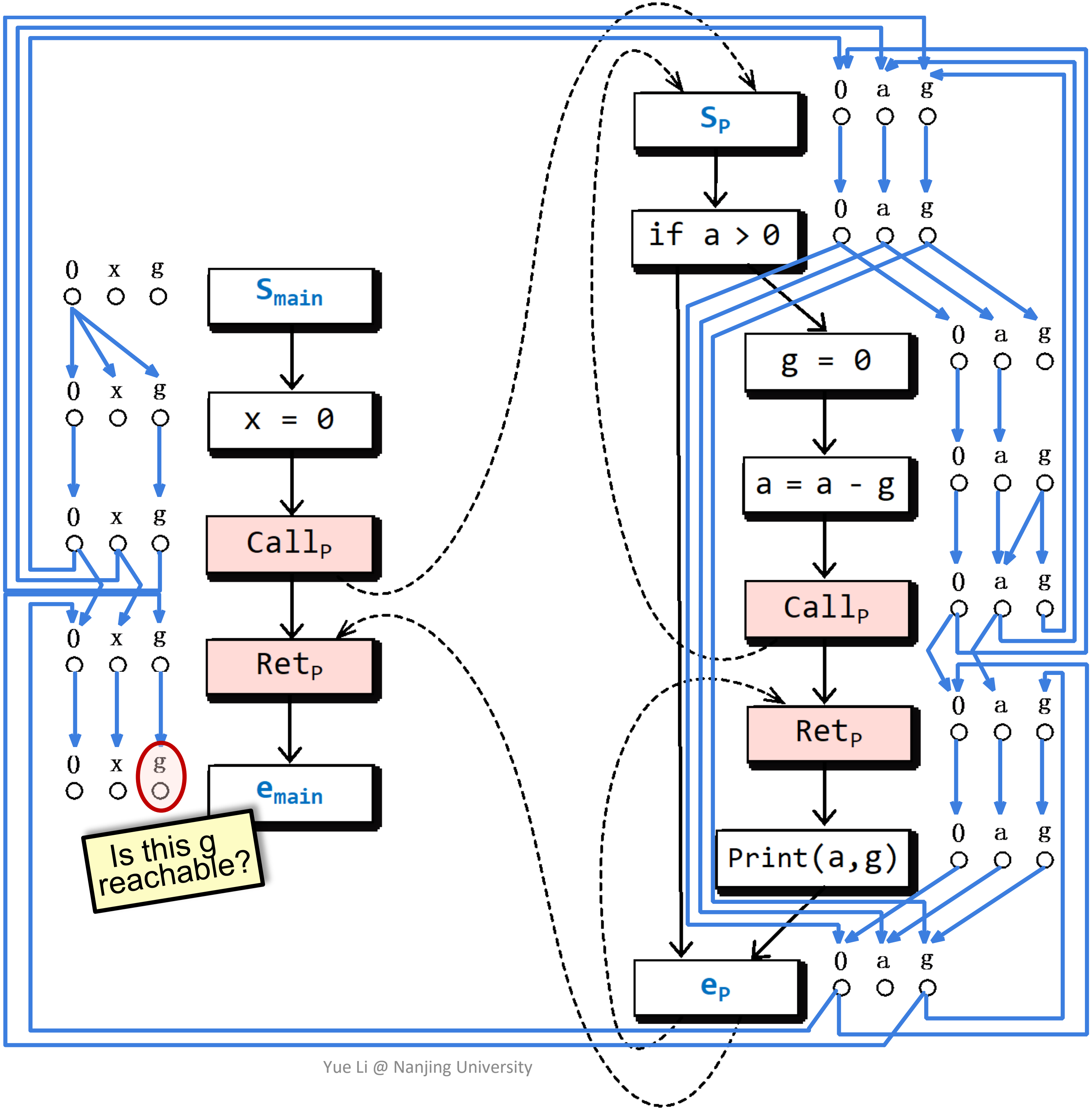
$Call_p$

Ret_p

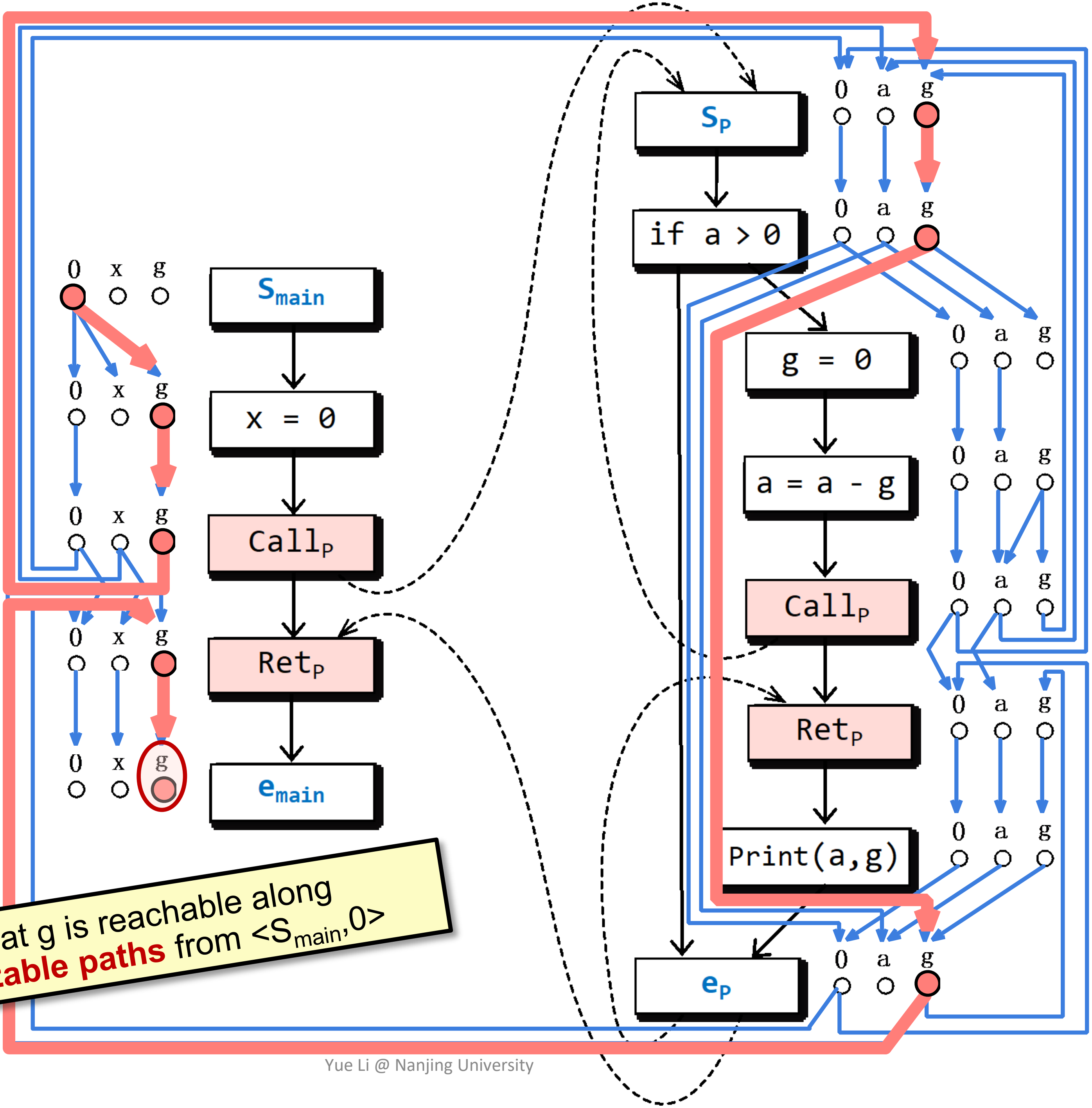
Print(a,g)

e_p

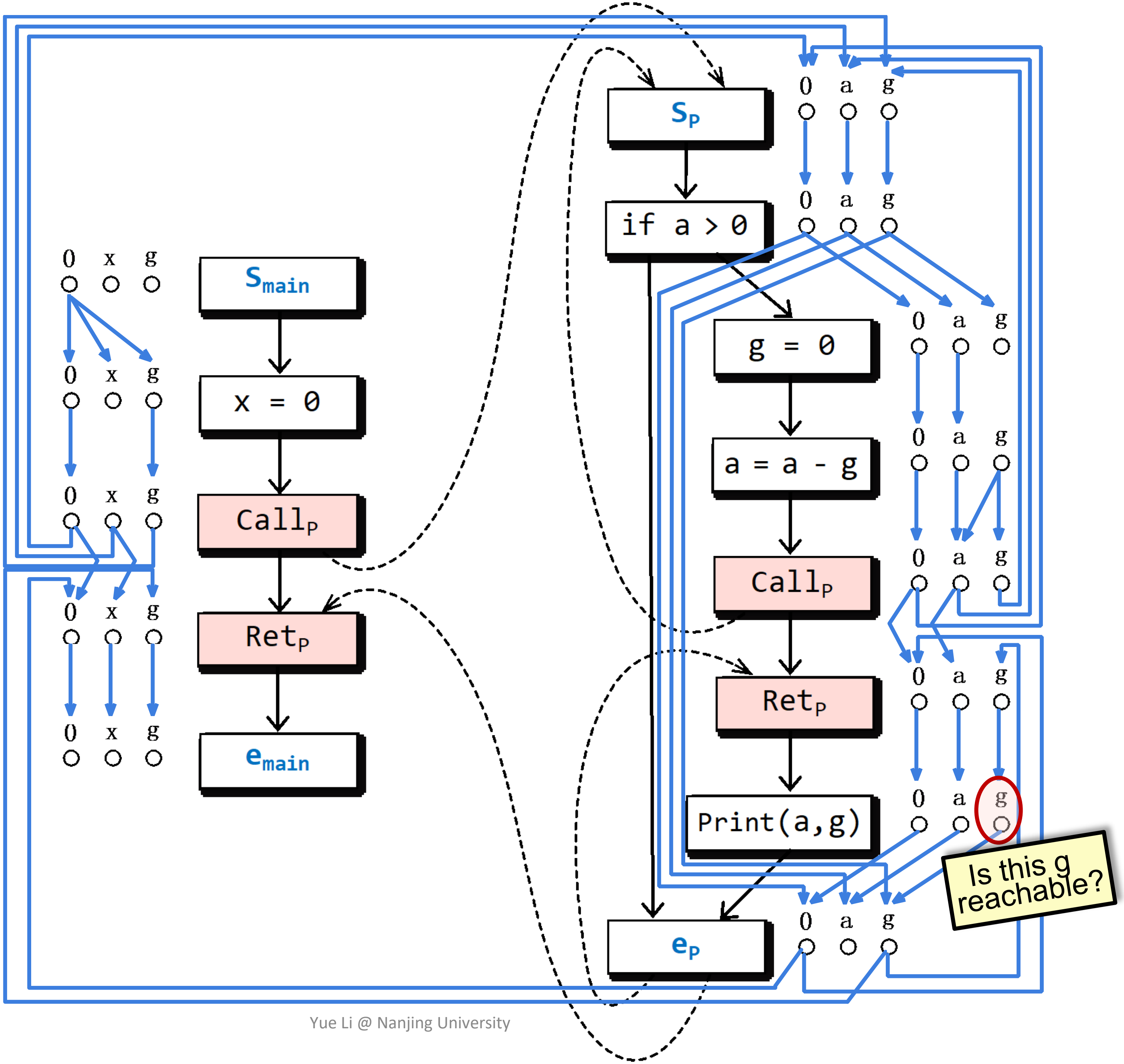
Done

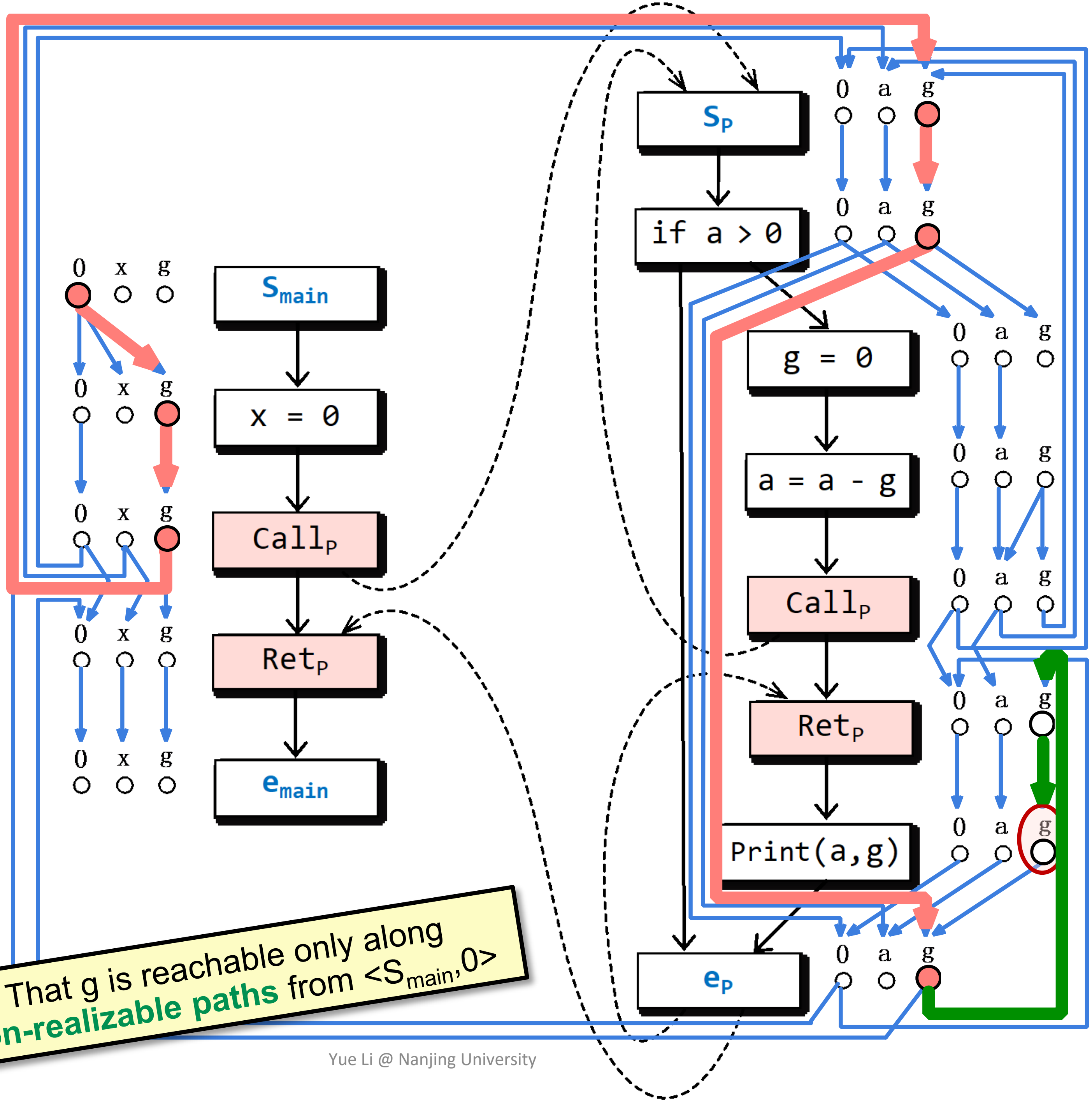


Is this g reachable?



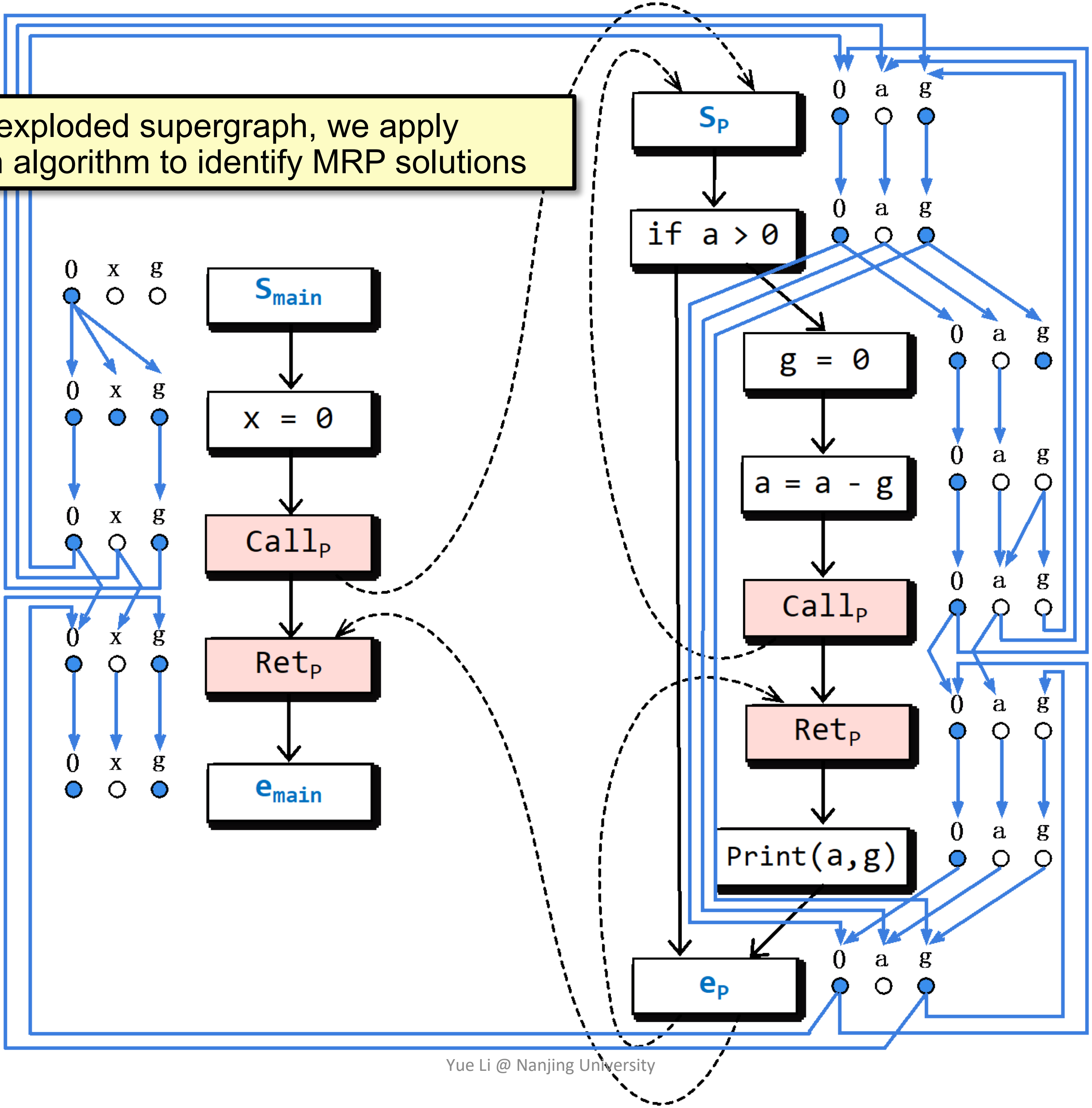
That g is reachable along **realizable paths** from $<S_{main},0>$


S_main
x = 0
Call_P
Ret_P
e_main
S_P
if a > 0
g = 0
a = a - g
Call_P
Ret_P
Print(a,g)
e_P
0 x g
0 a g
Is this g reachable?

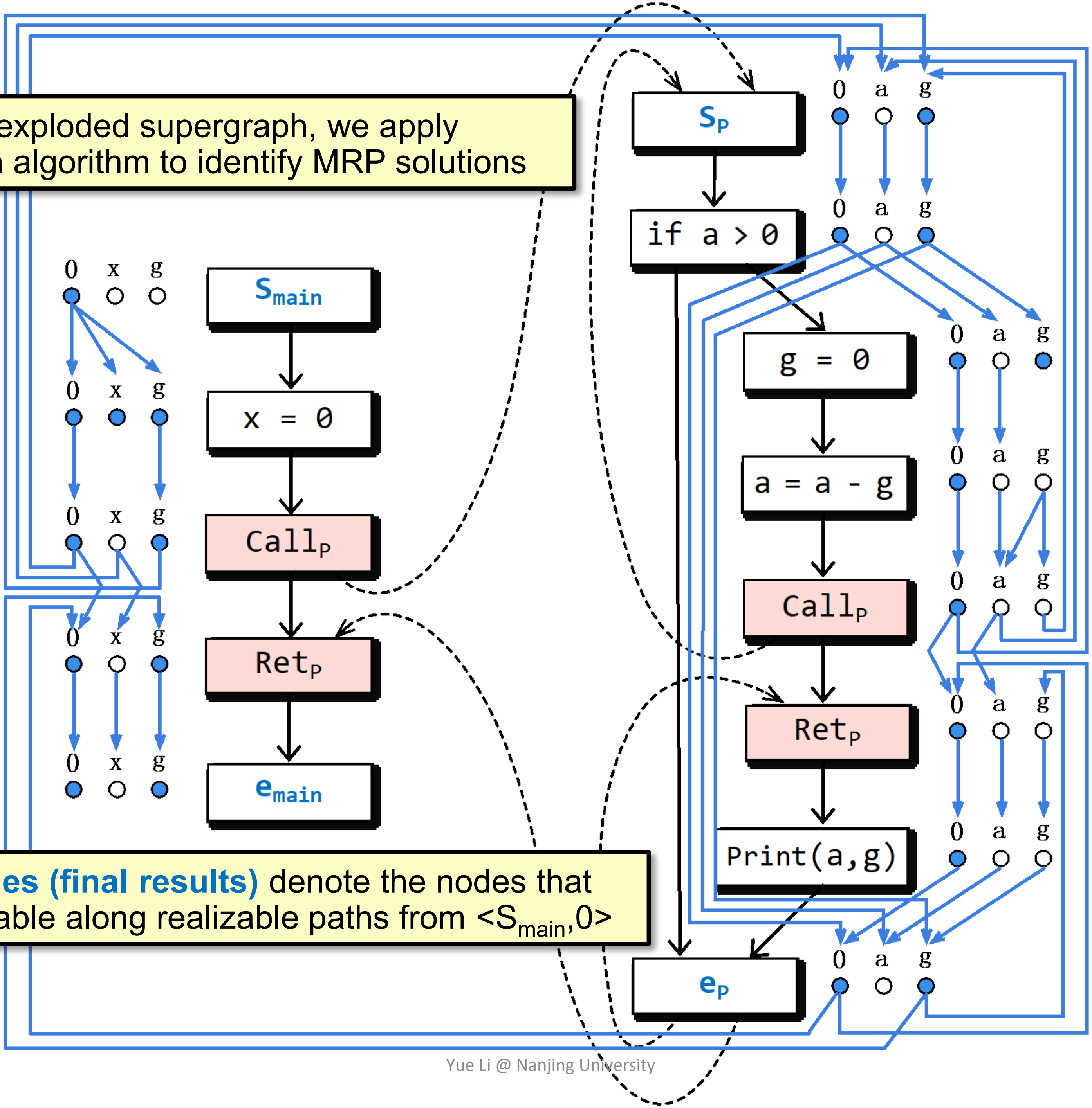


That g is reachable only along **non-realizable paths** from <S_{main},0>

Given an exploded supergraph, we apply Tabulation algorithm to identify MRP solutions



Given an exploded supergraph, we apply Tabulation algorithm to identify MRP solutions



Blue circles (final results) denote the nodes that are reachable along realizable paths from <S_{main},0>

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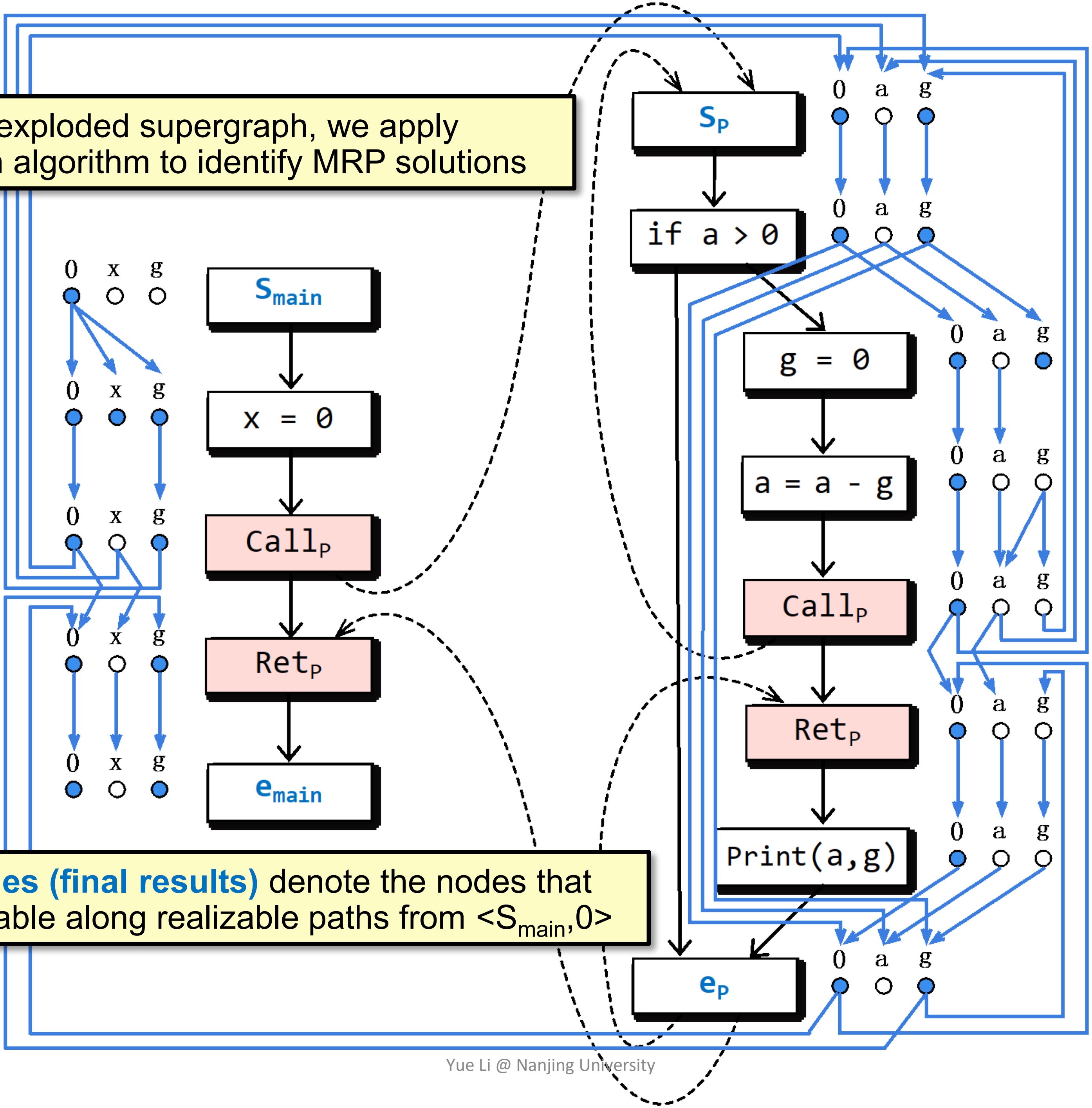
How?

ven an exploded supergraph, we apply Tabulation algorithm to identify MRP solutions

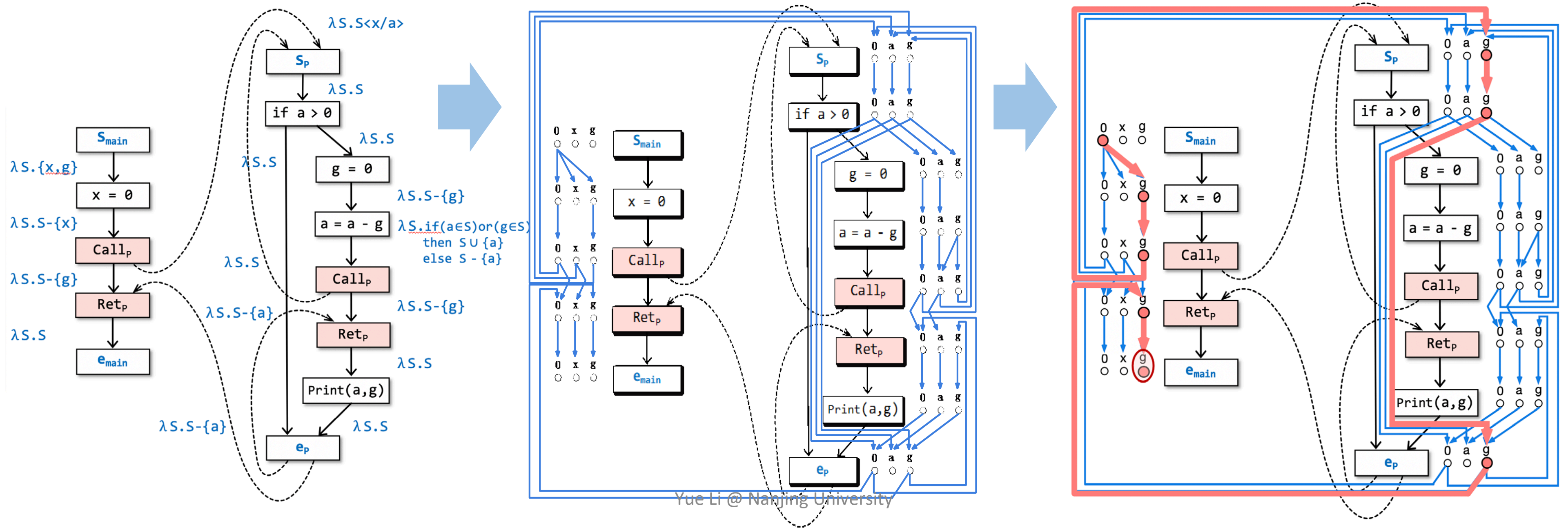


Blue circles (final results) denote the nodes that are reachable along realizable paths from <S_{main},0>

Overview of IFDS

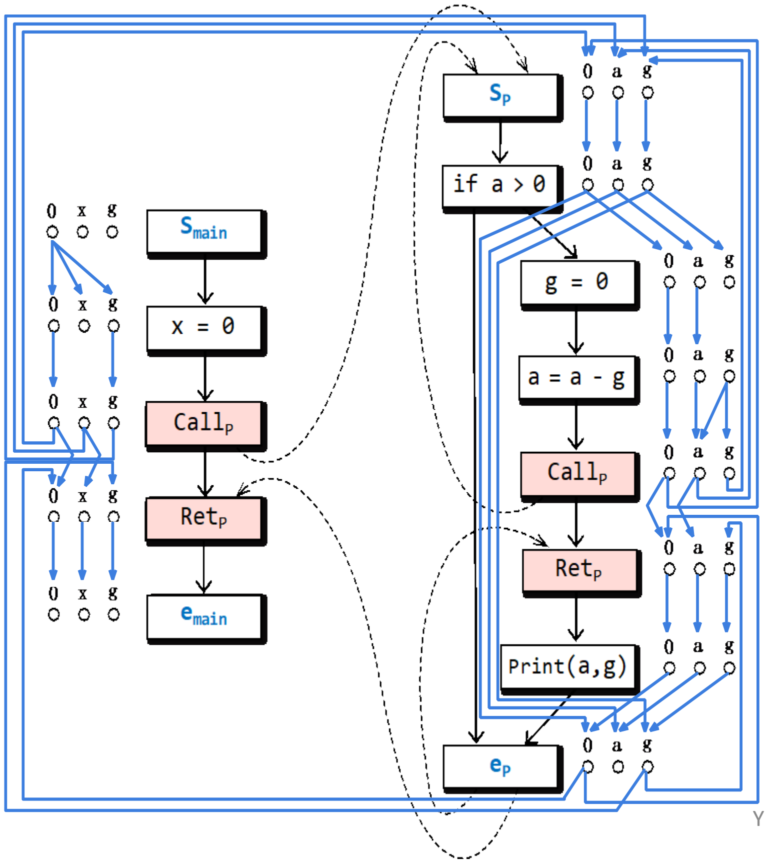
Given a program P, and a dataflow-analysis problem Q

- Build a supergraph G* for P and define flow functions for edges in G* based on Q
- Build exploded supergraph G# for P by transforming flow functions to representation relations (graphs)
- Q can be solved as graph reachability problems (find out MRP solutions) via applying Tabulation algorithm on G#

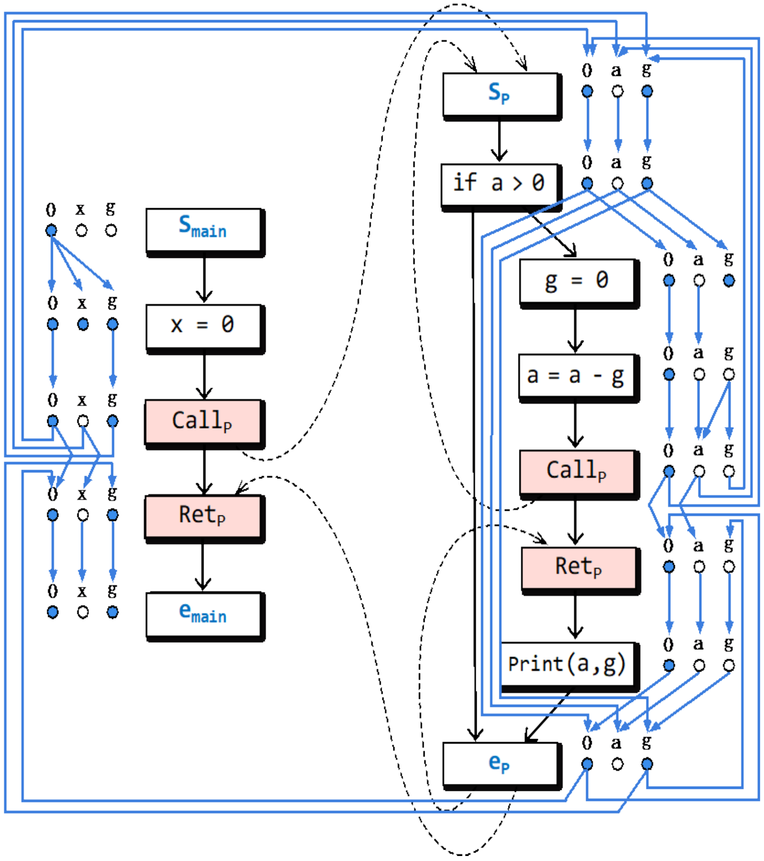


Tabulation Algorithm

Given an exploded supergraph G$^{\#}$, Tabulation algorithm determines the MRP solution by finding out all realizable paths starting from <s_{main}, 0>



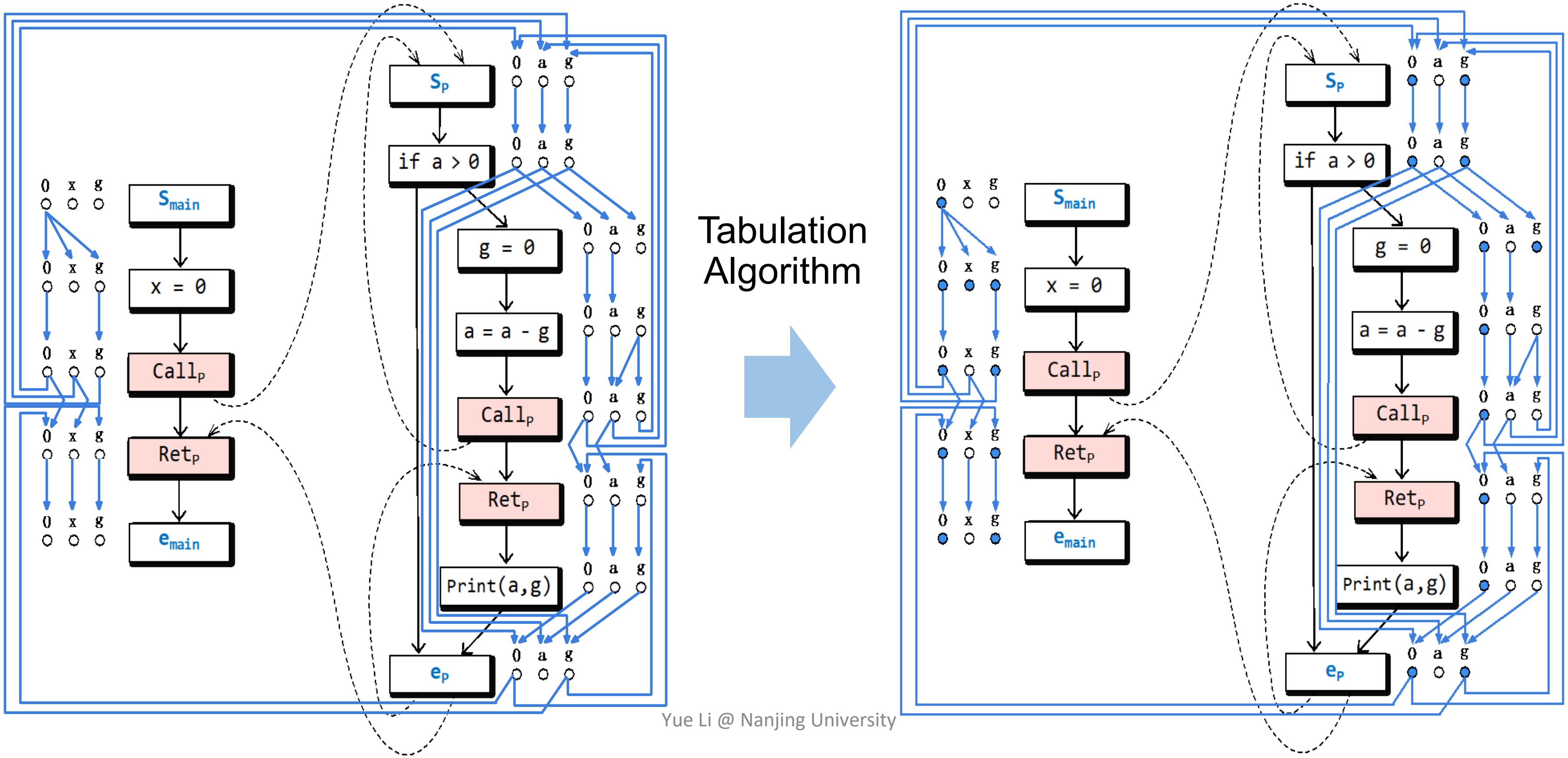
Tabulation Algorithm



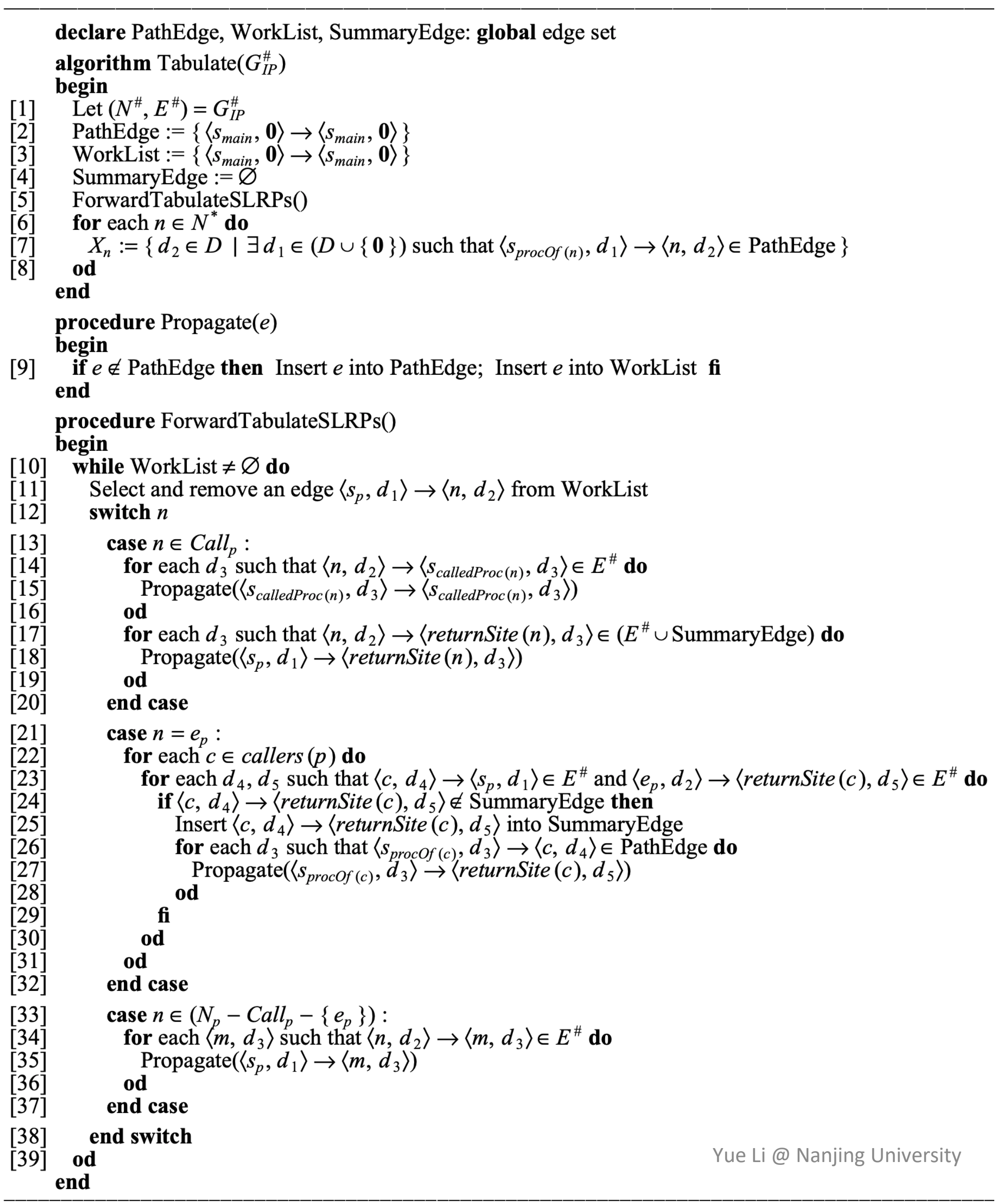
Tabulation Algorithm

Given an exploded supergraph $G^{\#}$, Tabulation algorithm determines the MRP solution by finding out all realizable paths starting from <s_{main}, 0>

Let n be a program point, data fact d ∈ MRP_n, iff there is a realizable path in $G^{\#}$ from <s_{main}, 0> to <n, d>. (then d's white circle turns to blue)



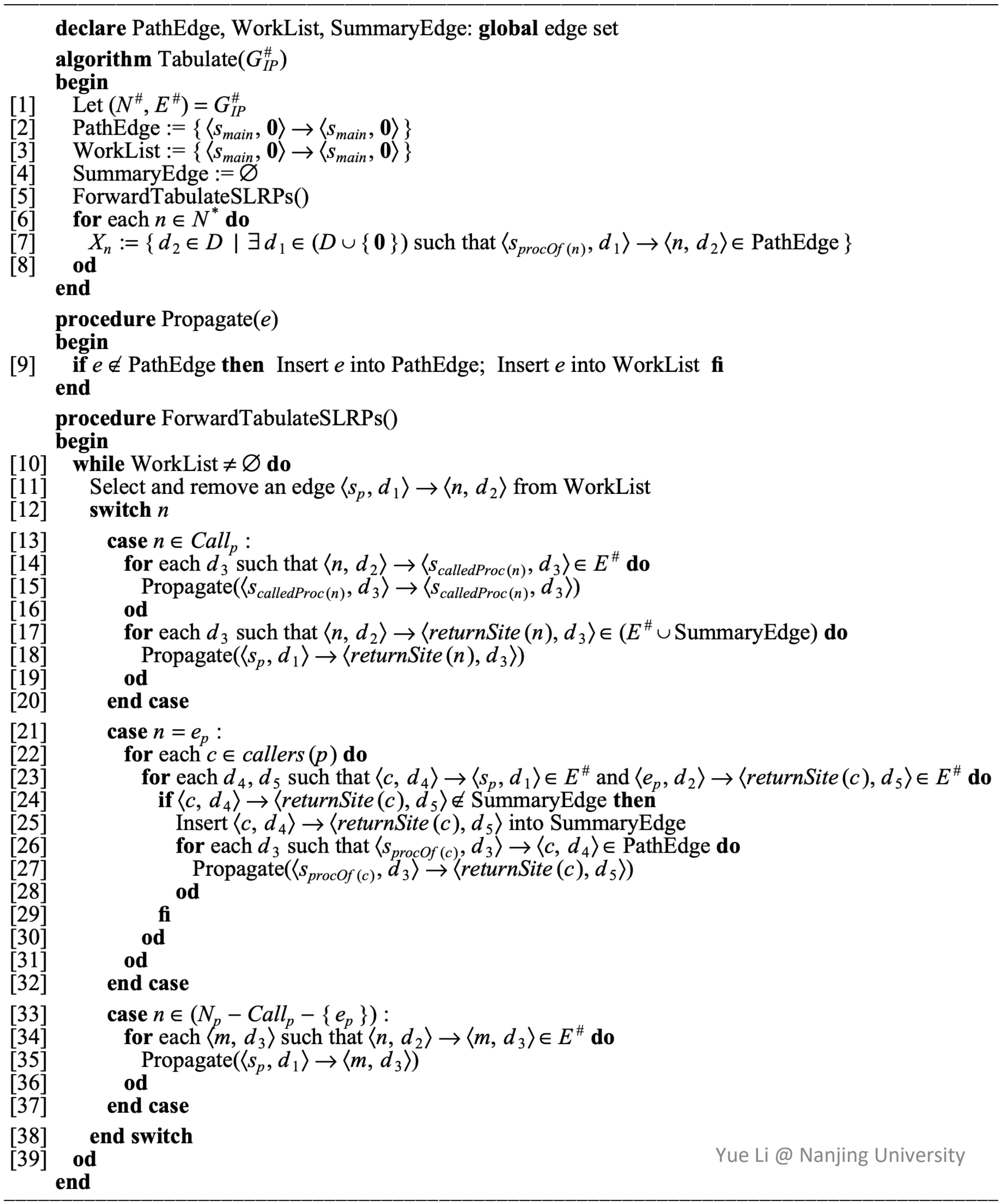
Tabulation Algorithm



```
declare PathEdge, WorkList, SummaryEdge: global edge set
algorithm Tabulate($G^{\#}_{IP}$)
begin
  Let $(N^{\#}, E^{\#}) = G^{\#}_{IP}$
  PathEdge := $\{ \langle s_{main}, \mathbf{0} \rangle \rightarrow \langle s_{main}, \mathbf{0} \rangle \}$
  WorkList := $\{ \langle s_{main}, \mathbf{0} \rangle \rightarrow \langle s_{main}, \mathbf{0} \rangle \}$
  SummaryEdge := $\emptyset$
  ForwardTabulateSLRPs()
  for each $n \in N^*$ do
    $X_n := \{ d_2 \in D \mid \exists d_1 \in (D \cup \{ \mathbf{0} \})$ such that $\langle s_{procOf(n)}, d_1 \rangle \rightarrow \langle n, d_2 \rangle \in$ PathEdge $\}$
  od
end
procedure Propagate($e$)
begin
  if $e \notin$ PathEdge then  Insert $e$ into PathEdge;  Insert $e$ into WorkList  fi
end
procedure ForwardTabulateSLRPs()
begin
  while WorkList $\neq \emptyset$ do
    Select and remove an edge $\langle s_p, d_1 \rangle \rightarrow \langle n, d_2 \rangle$ from WorkList
    switch $n$
      case $n \in Call_p$ :
        for each $d_3$ such that $\langle n, d_2 \rangle \rightarrow \langle s_{calledProc(n)}, d_3 \rangle \in E^{\#}$ do
          Propagate($\langle s_{calledProc(n)}, d_3 \rangle \rightarrow \langle s_{calledProc(n)}, d_3 \rangle$)
        od
        for each $d_3$ such that $\langle n, d_2 \rangle \rightarrow \langle returnSite(n), d_3 \rangle \in (E^{\#} \cup$ SummaryEdge$)$ do
          Propagate($\langle s_p, d_1 \rangle \rightarrow \langle returnSite(n), d_3 \rangle$)
        od
      end case
      case $n = e_p$ :
        for each $c \in callers(p)$ do
          for each $d_4, d_5$ such that $\langle c, d_4 \rangle \rightarrow \langle s_p, d_1 \rangle \in E^{\#}$ and $\langle e_p, d_2 \rangle \rightarrow \langle returnSite(c), d_5 \rangle \in E^{\#}$ do
            if $\langle c, d_4 \rangle \rightarrow \langle returnSite(c), d_5 \rangle \notin$ SummaryEdge then
              Insert $\langle c, d_4 \rangle \rightarrow \langle returnSite(c), d_5 \rangle$ into SummaryEdge
              for each $d_3$ such that $\langle s_{procOf(c)}, d_3 \rangle \rightarrow \langle c, d_4 \rangle \in$ PathEdge do
                Propagate($\langle s_{procOf(c)}, d_3 \rangle \rightarrow \langle returnSite(c), d_5 \rangle$)
              od
            fi
          od
        od
      end case
      case $n \in (N_p - Call_p - \{ e_p \})$ :
        for each $\langle m, d_3 \rangle$ such that $\langle n, d_2 \rangle \rightarrow \langle m, d_3 \rangle \in E^{\#}$ do
          Propagate($\langle s_p, d_1 \rangle \rightarrow \langle m, d_3 \rangle$)
        od
      end case
    end switch
  od
end
```

$$O(\mathrm{ED}^3)$$

Tabulation Algorithm



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  SummaryEdge := $\varnothing$
  ForwardTabulateSLRPs()
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    $X_n := \{ d_2 \in D \mid \exists d_1 \in (D \cup \{ \mathbf{0} \})$ such that $\langle s_{procOf(n)}, d_1 \rangle \rightarrow \langle n, d_2 \rangle \in$ PathEdge $\}$
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procedure ForwardTabulateSLRPs()
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  while WorkList $\neq \varnothing$ do
    Select and remove an edge $\langle s_p, d_1 \rangle \rightarrow \langle n, d_2 \rangle$ from WorkList
    switch $n$

      case $n \in Call_p$ :
        for each $d_3$ such that $\langle n, d_2 \rangle \rightarrow \langle s_{calledProc(n)}, d_3 \rangle \in E^{\#}$ do
          Propagate($\langle s_{calledProc(n)}, d_3 \rangle \rightarrow \langle s_{calledProc(n)}, d_3 \rangle$)
        od
        for each $d_3$ such that $\langle n, d_2 \rangle \rightarrow \langle returnSite(n), d_3 \rangle \in (E^{\#} \cup$ SummaryEdge) do
          Propagate($\langle s_p, d_1 \rangle \rightarrow \langle returnSite(n), d_3 \rangle$)
        od
      end case

      case $n = e_p$ :
        for each $c \in callers(p)$ do
          for each $d_4, d_5$ such that $\langle c, d_4 \rangle \rightarrow \langle s_p, d_1 \rangle \in E^{\#}$ and $\langle e_p, d_2 \rangle \rightarrow \langle returnSite(c), d_5 \rangle \in E^{\#}$ do
            if $\langle c, d_4 \rangle \rightarrow \langle returnSite(c), d_5 \rangle \notin$ SummaryEdge then
              Insert $\langle c, d_4 \rangle \rightarrow \langle returnSite(c), d_5 \rangle$ into SummaryEdge
              for each $d_3$ such that $\langle s_{procOf(c)}, d_3 \rangle \rightarrow \langle c, d_4 \rangle \in$ PathEdge do
                Propagate($\langle s_{procOf(c)}, d_3 \rangle \rightarrow \langle returnSite(c), d_5 \rangle$)
              od
            fi
          od
        od
      end case

      case $n \in (N_p - Call_p - \{ e_p \})$ :
        for each $\langle m, d_3 \rangle$ such that $\langle n, d_2 \rangle \rightarrow \langle m, d_3 \rangle \in E^{\#}$ do
          Propagate($\langle s_p, d_1 \rangle \rightarrow \langle m, d_3 \rangle$)
        od
      end case

    end switch
  od
end
```
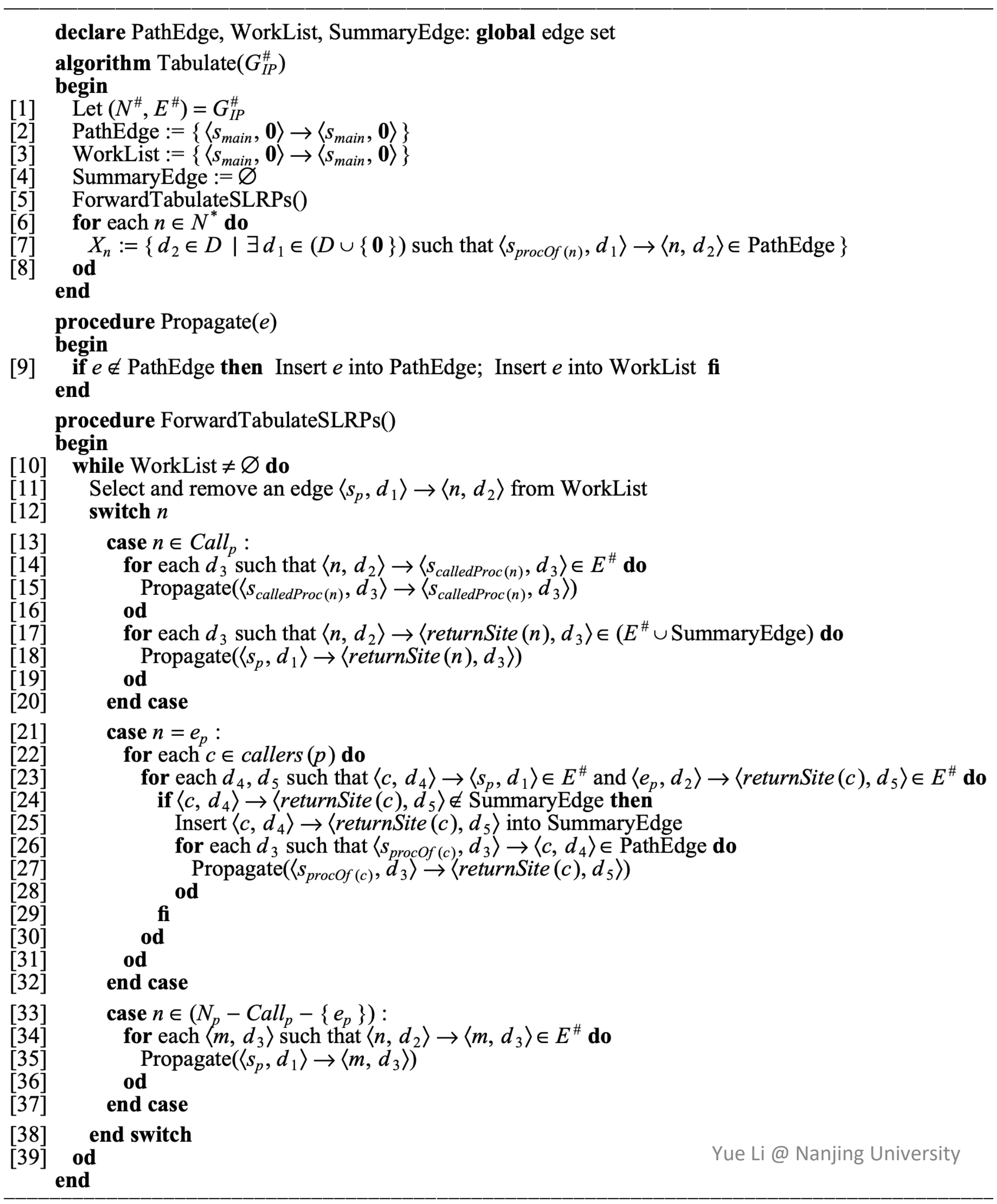

$O(\mathrm{ED}^3)$

No time to cover the whole algorithm

Tabulation Algorithm



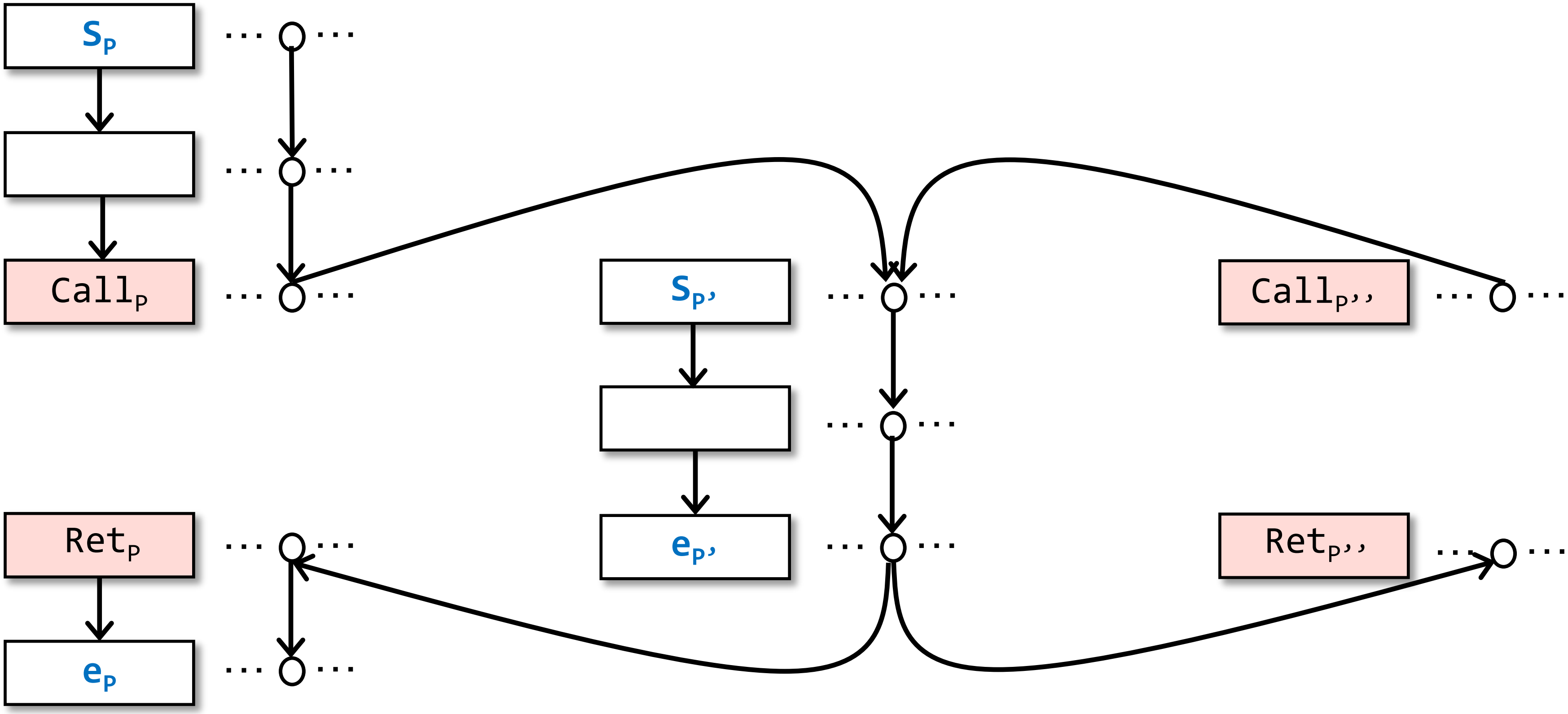
```
declare PathEdge, WorkList, SummaryEdge: global edge set
algorithm Tabulate($G^{\#}_{IP}$)
begin
  Let $(N^{\#}, E^{\#}) = G^{\#}_{IP}$
  PathEdge := $\{ \langle s_{main}, \mathbf{0} \rangle \to \langle s_{main}, \mathbf{0} \rangle \}$
  WorkList := $\{ \langle s_{main}, \mathbf{0} \rangle \to \langle s_{main}, \mathbf{0} \rangle \}$
  SummaryEdge := $\varnothing$
  ForwardTabulateSLRPs()
  for each $n \in N^{*}$ do
    $X_n := \{ d_2 \in D \mid \exists d_1 \in (D \cup \{ \mathbf{0} \})$ such that $\langle s_{procOf(n)}, d_1 \rangle \to \langle n, d_2 \rangle \in$ PathEdge $\}$
  od
end

procedure Propagate($e$)
begin
  if $e \notin$ PathEdge then  Insert $e$ into PathEdge;  Insert $e$ into WorkList  fi
end

procedure ForwardTabulateSLRPs()
begin
  while WorkList $\neq \varnothing$ do
    Select and remove an edge $\langle s_p, d_1 \rangle \to \langle n, d_2 \rangle$ from WorkList
    switch $n$

      case $n \in Call_p$ :
        for each $d_3$ such that $\langle n, d_2 \rangle \to \langle s_{calledProc(n)}, d_3 \rangle \in E^{\#}$ do
          Propagate($\langle s_{calledProc(n)}, d_3 \rangle \to \langle s_{calledProc(n)}, d_3 \rangle$)
        od
        for each $d_3$ such that $\langle n, d_2 \rangle \to \langle returnSite(n), d_3 \rangle \in (E^{\#} \cup$ SummaryEdge) do
          Propagate($\langle s_p, d_1 \rangle \to \langle returnSite(n), d_3 \rangle$)
        od
      end case

      case $n = e_p$ :
        for each $c \in callers(p)$ do
          for each $d_4, d_5$ such that $\langle c, d_4 \rangle \to \langle s_p, d_1 \rangle \in E^{\#}$ and $\langle e_p, d_2 \rangle \to \langle returnSite(c), d_5 \rangle \in E^{\#}$ do
            if $\langle c, d_4 \rangle \to \langle returnSite(c), d_5 \rangle \notin$ SummaryEdge then
              Insert $\langle c, d_4 \rangle \to \langle returnSite(c), d_5 \rangle$ into SummaryEdge
              for each $d_3$ such that $\langle s_{procOf(c)}, d_3 \rangle \to \langle c, d_4 \rangle \in$ PathEdge do
                Propagate($\langle s_{procOf(c)}, d_3 \rangle \to \langle returnSite(c), d_5 \rangle$)
              od
            fi
          od
        od
      end case

      case $n \in (N_p - Call_p - \{ e_p \})$ :
        for each $\langle m, d_3 \rangle$ such that $\langle n, d_2 \rangle \to \langle m, d_3 \rangle \in E^{\#}$ do
          Propagate($\langle s_p, d_1 \rangle \to \langle m, d_3 \rangle$)
        od
      end case

    end switch
  od
end
```

$$O(\mathrm{ED}^3)$$

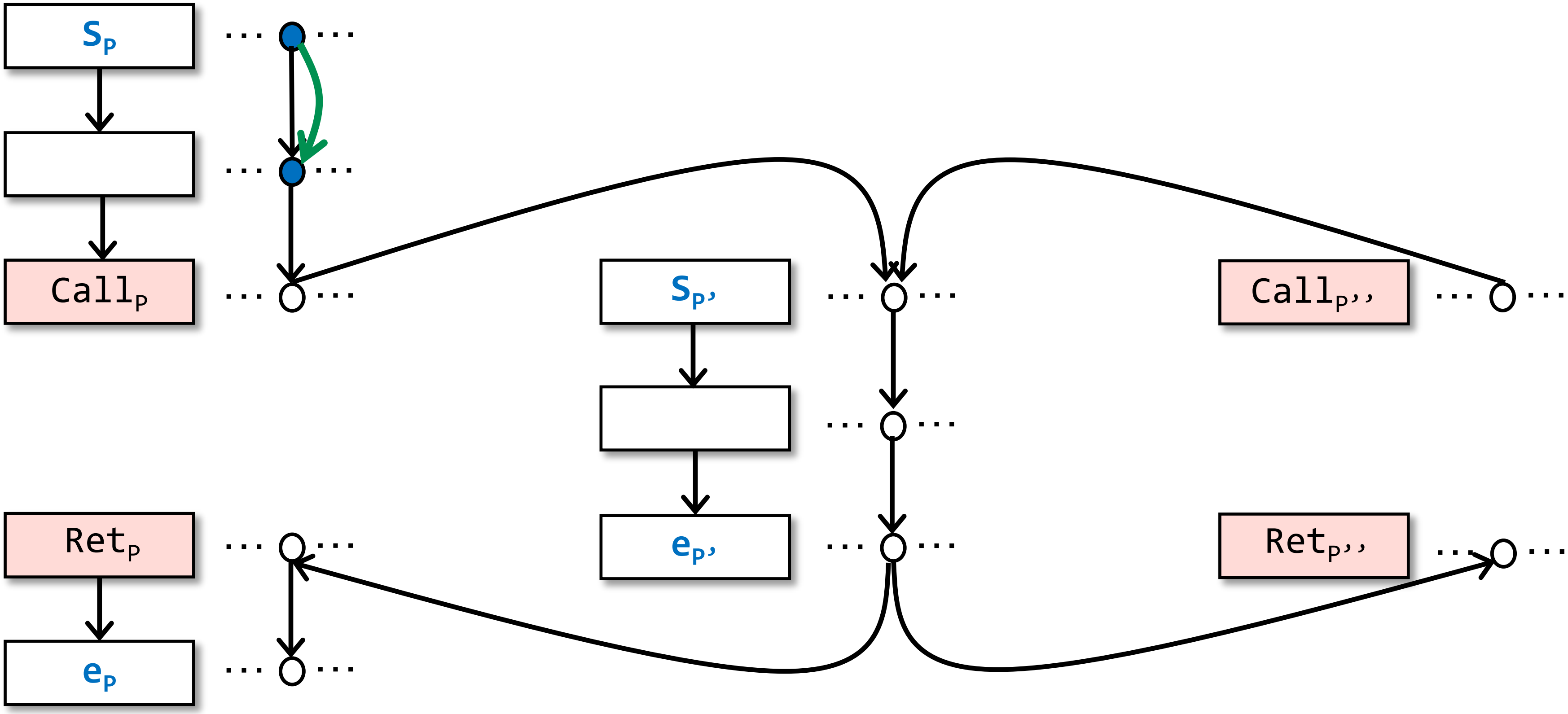
No time to cover the whole algorithm

But we will introduce its core working mechanism by a simple example

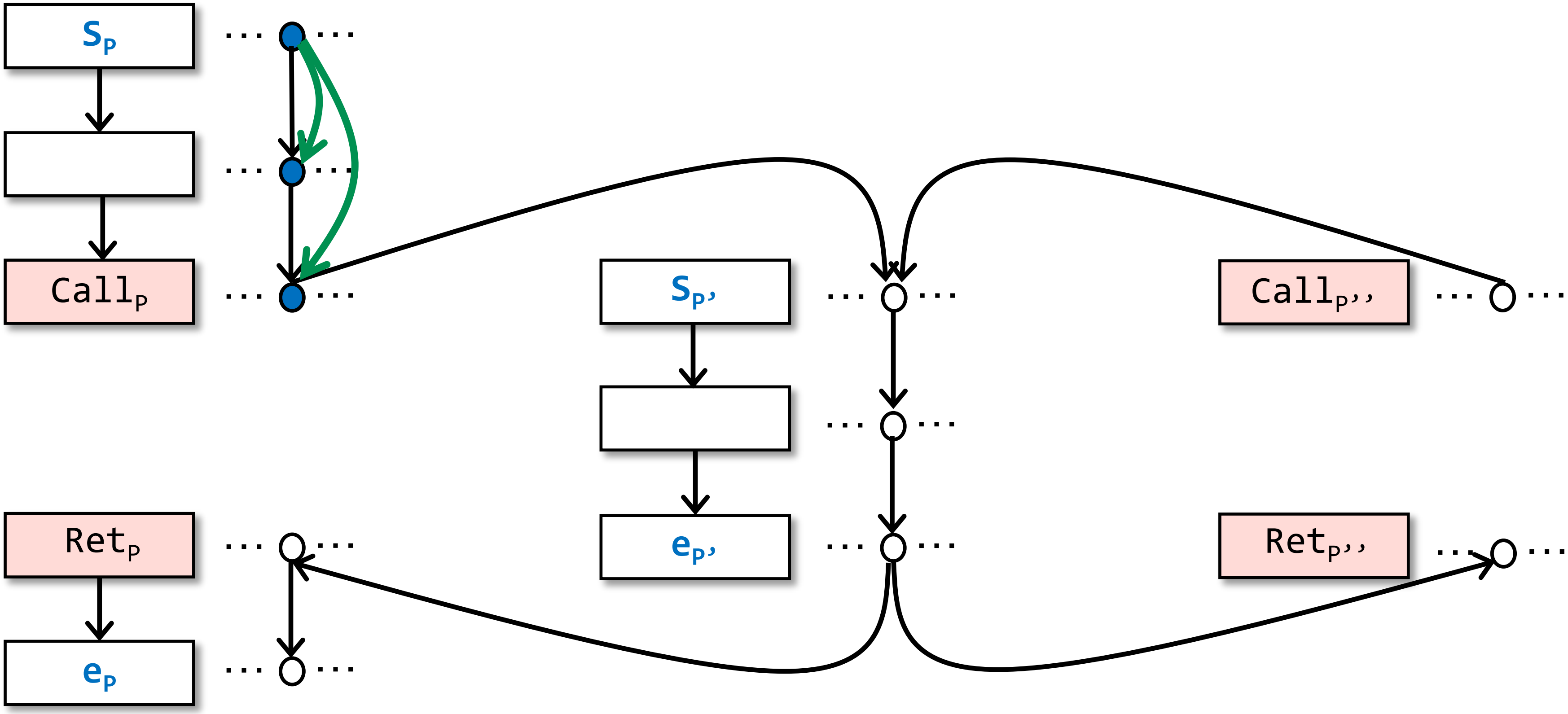
Core Working Mechanism of Tabulation Algorithm



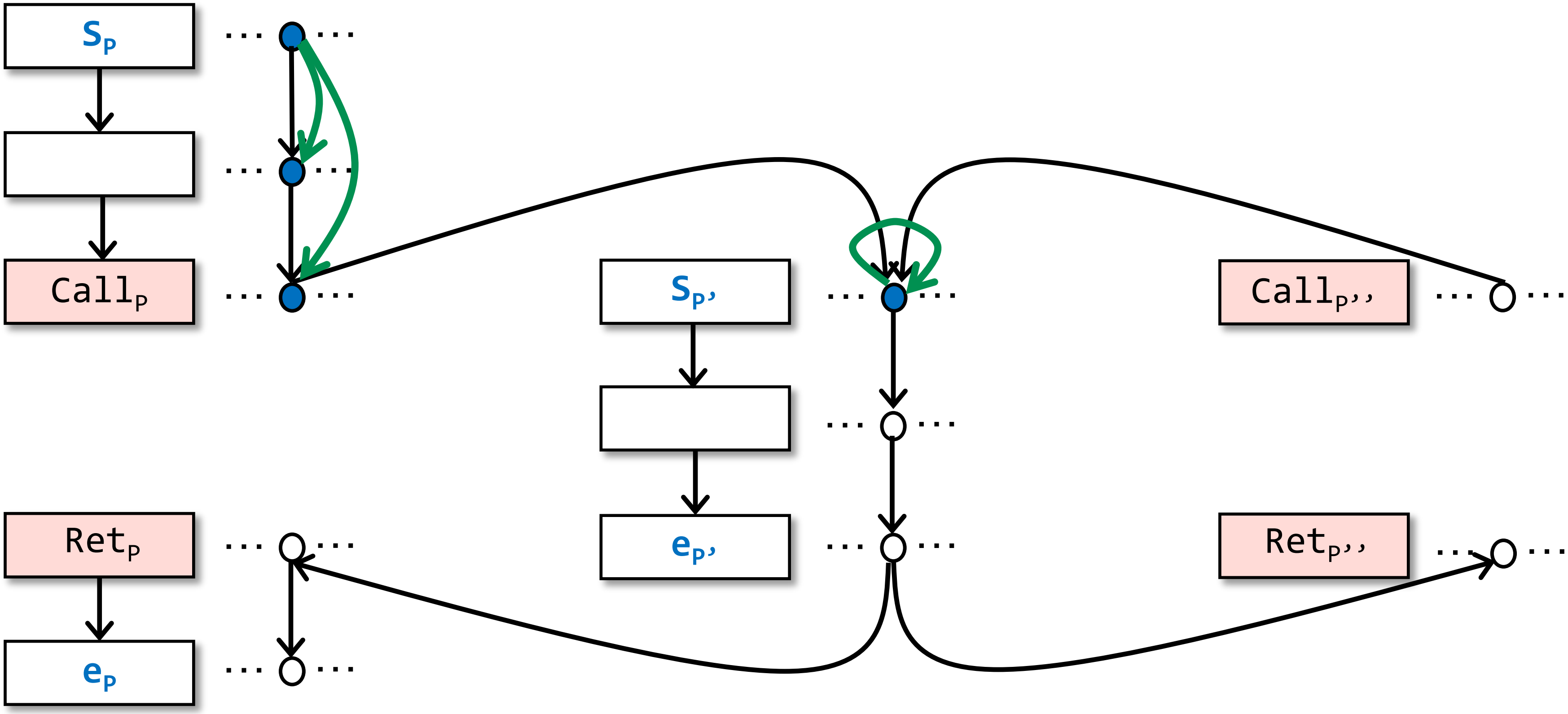
Core Working Mechanism of Tabulation Algorithm



Core Working Mechanism of Tabulation Algorithm



Core Working Mechanism of Tabulation Algorithm



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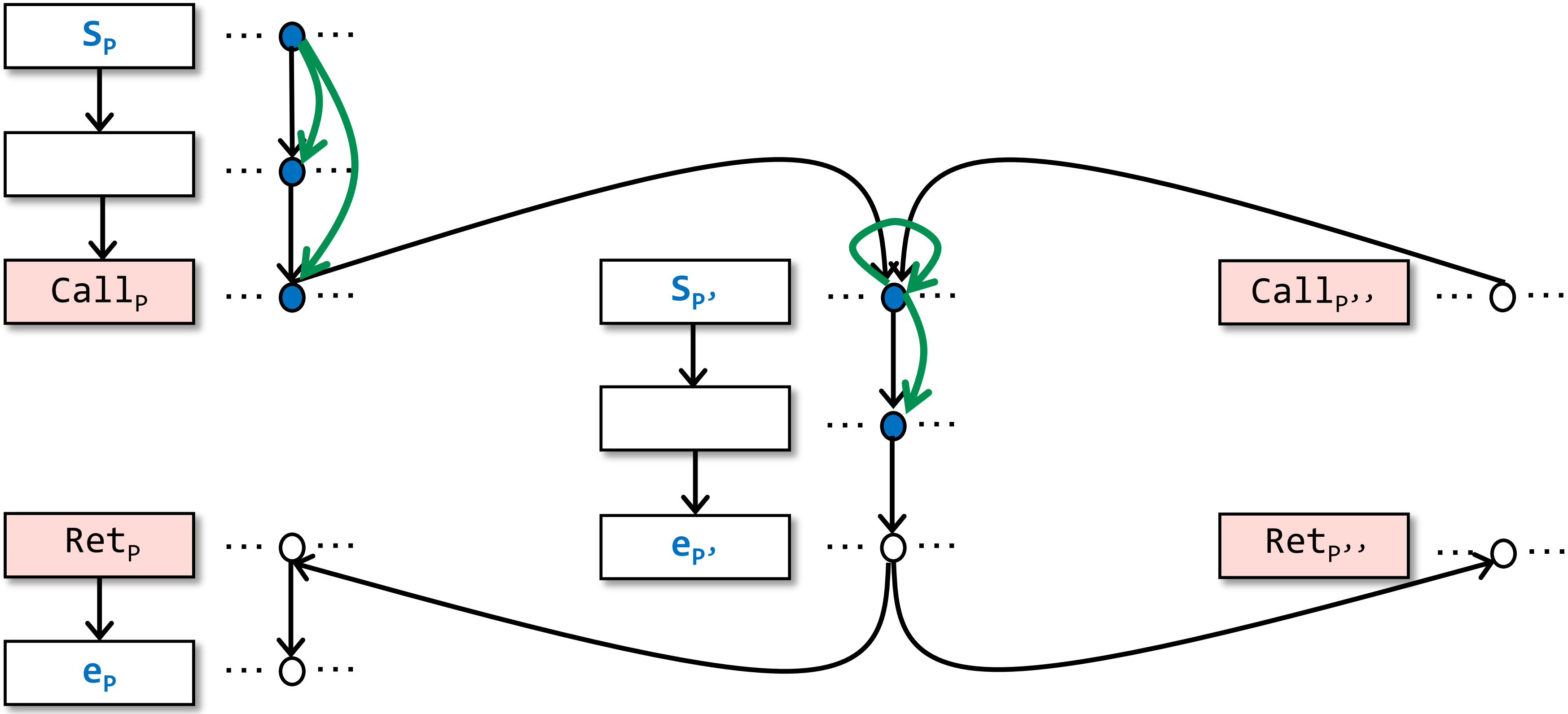

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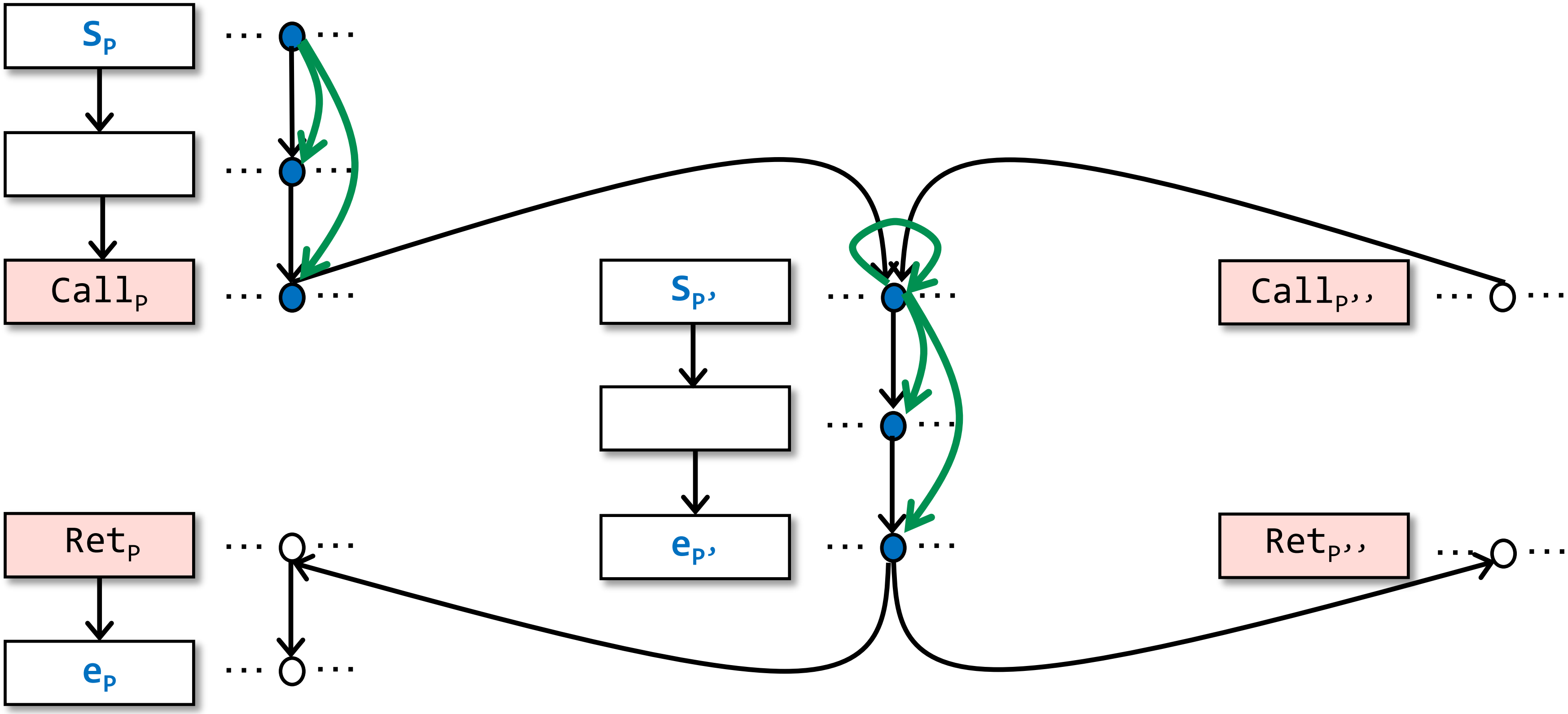
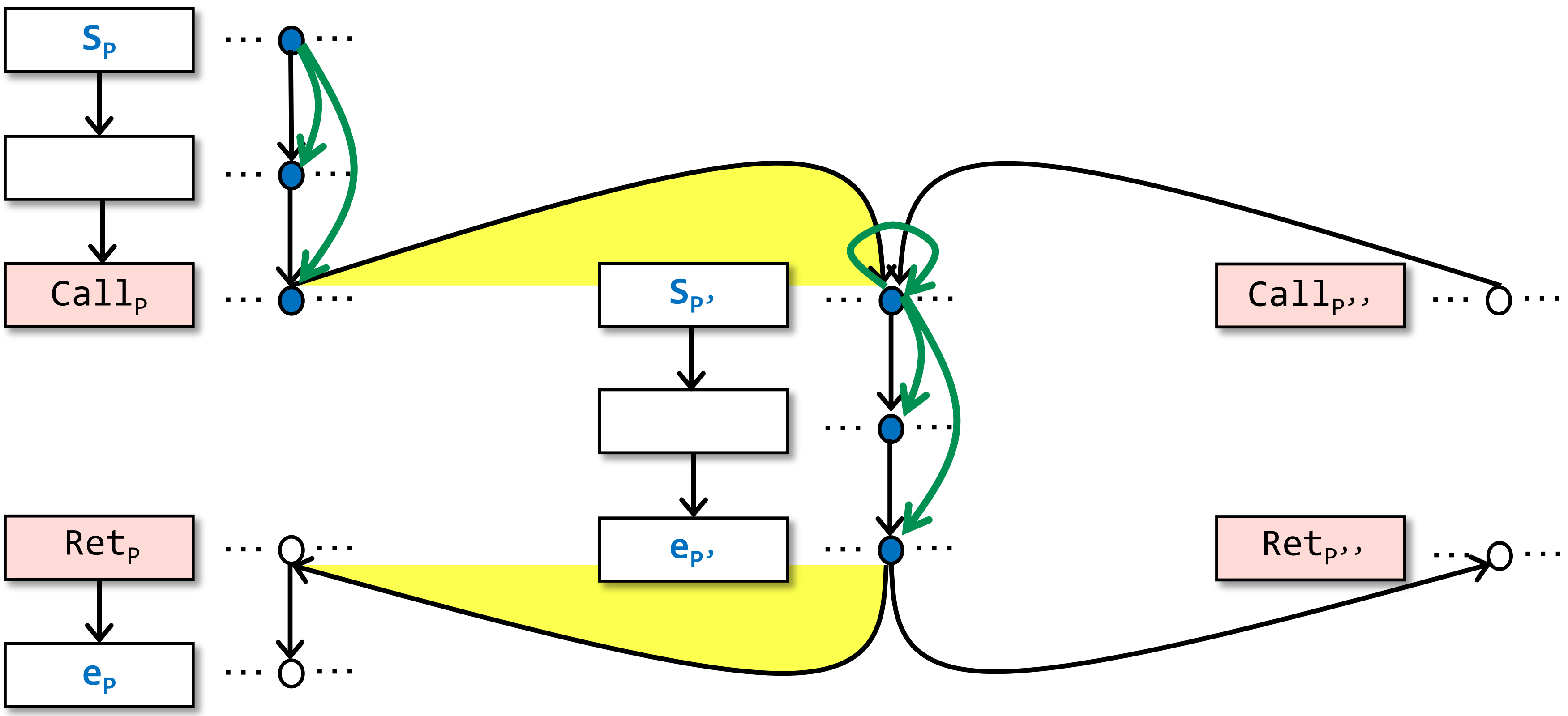


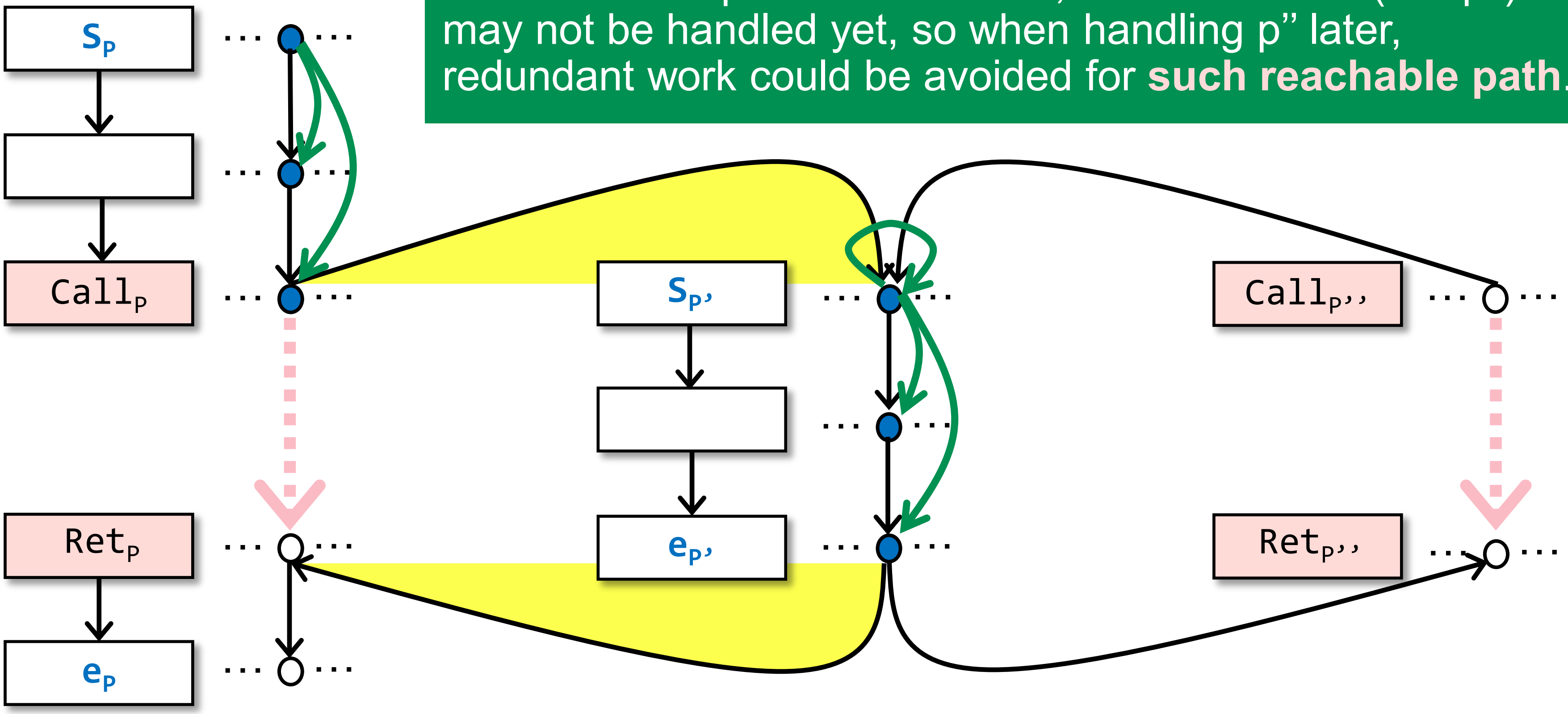
Core Working Mechanism of Tabulation Algorithm



When handling each exit node ($e_{p'}$), call-to-return matching begins: find out the call-sites calling p' ($Call_p$, $Call_{p''}$) and then find out their corresponding return-sites (Ret_p, $Ret_{p''}$).

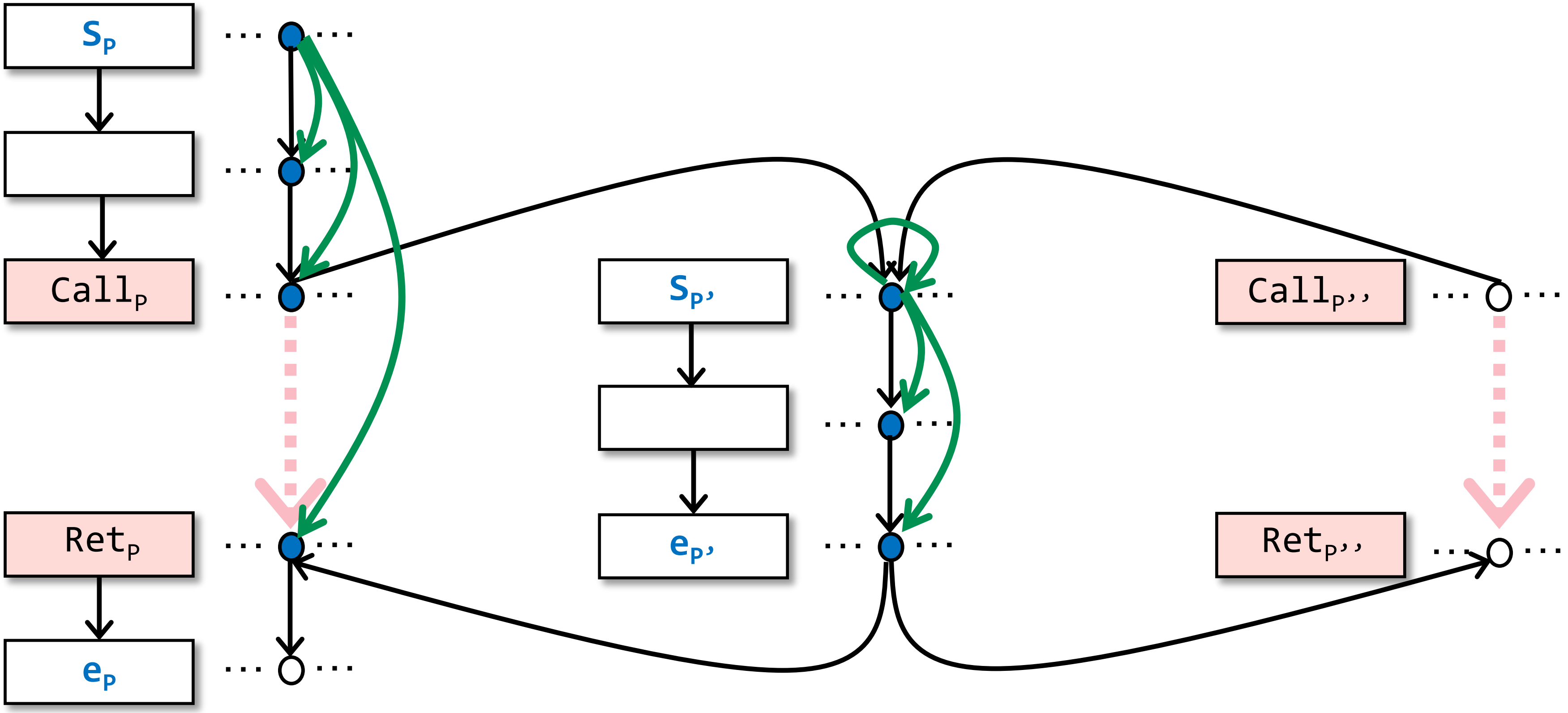
Core Working Mechanism of Tabulation Algorithm

Actually, here **a summary edge** from <Call,d_m> to <Ret,d_n> is added to indicate that d_n is **reachable** from d_m through the called method p’. At the moment, some methods (like p”) may not be handled yet, so when handling p” later, redundant work could be avoided for **such reachable path**.

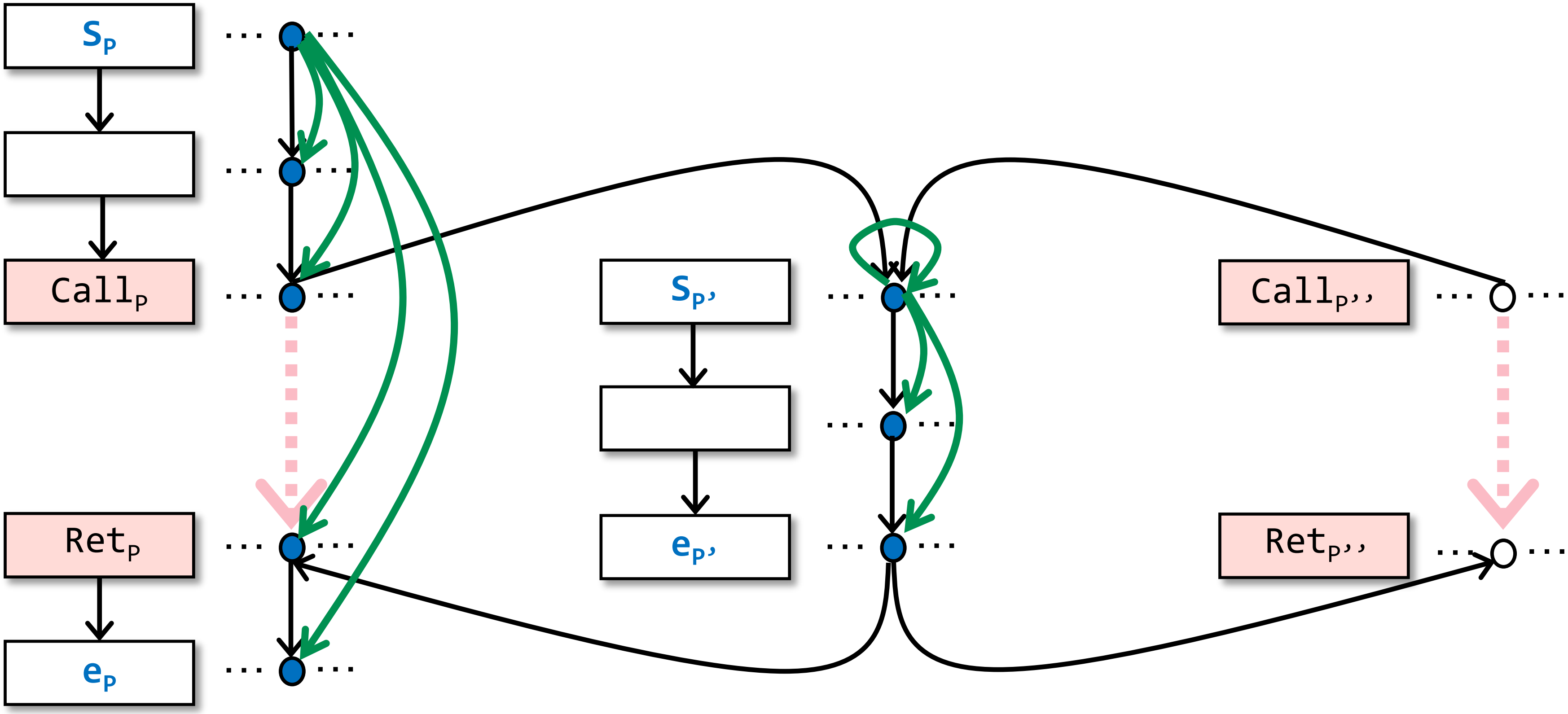


When handling each exit node ($e_{p'}$), call-to-return matching begins: find out the call-sites calling p’ (Call$_p$, Call$_{p''}$) and then find out their corresponding return-sites (Ret$_p$, Ret$_{p''}$).

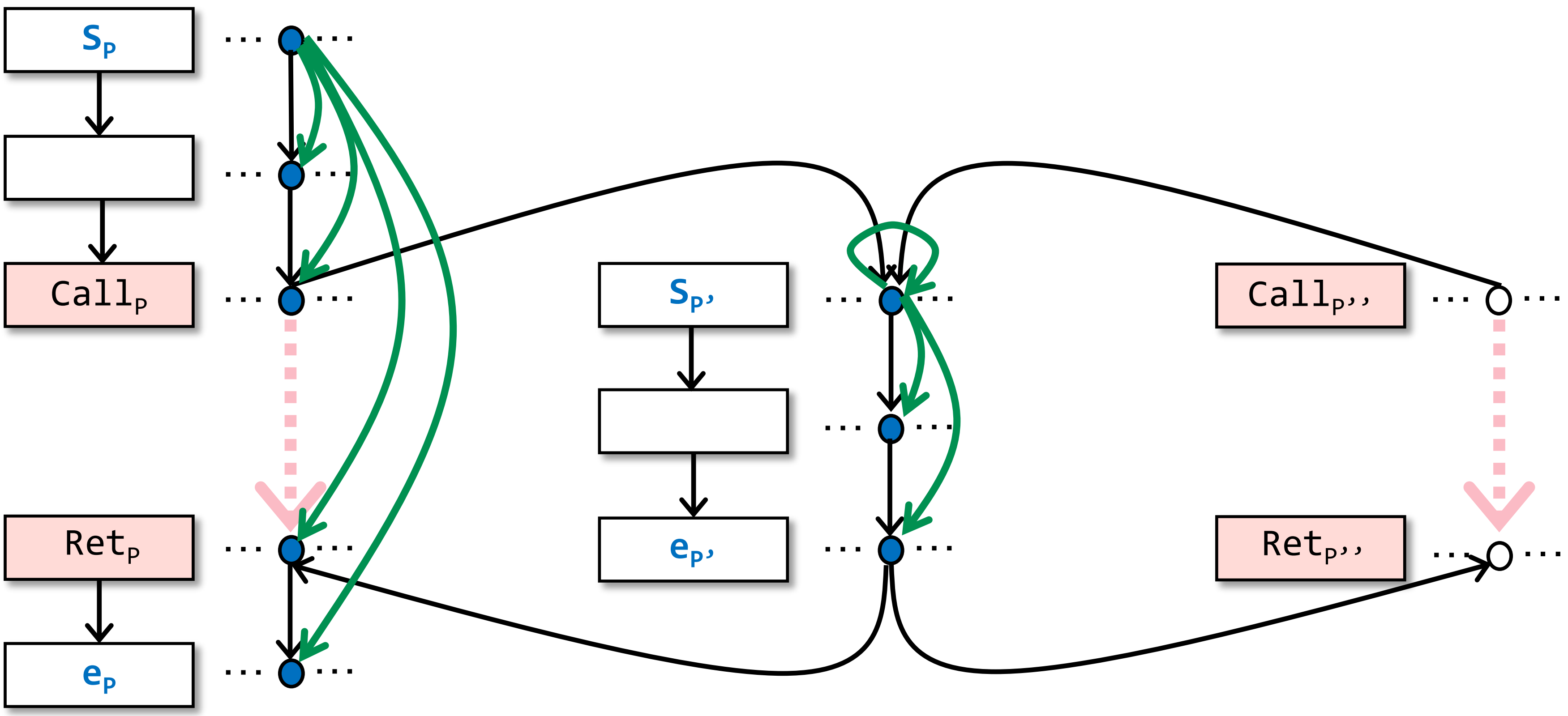
Core Working Mechanism of Tabulation Algorithm



Core Working Mechanism of Tabulation Algorithm



Core Working Mechanism of Tabulation Algorithm



When a data fact (at node n) d's circle is turned to blue, it means that <n, d> is reachable from <S_{main}, 0>

Understanding the Distributivity of IFDS

Understanding the Distributivity of IFDS

- Can we do constant propagation using IFDS?

  Constant propagation has infinite domain, but what if we only deal with finite constant values? Can we still do it using IFDS?

- Can we do pointer analysis using IFDS?

Understanding the Distributivity of IFDS

- Can we do constant propagation using IFDS? No

  Constant propagation has infinite domain, but what if we only deal with finite constant values? Can we still do it using IFDS?

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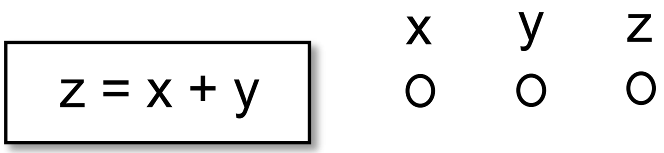
Understanding the Distributivity of IFDS

- Distributivity

  $F(x \wedge y) = F(x) \wedge F(y)$

- Constant Propagation


z = x + y

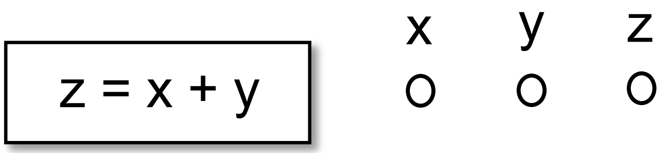
z’s value depends on both y’s and x’s

Understanding the Distributivity of IFDS

- Distributivity

$$F(x \wedge y) = F(x) \wedge F(y)$$

Each flow function in IFDS handles one input data fact per time



z = x + y

x y z

z’s value depends on both y’s and x’s

Understanding the Distributivity of IFDS

- Distributivity

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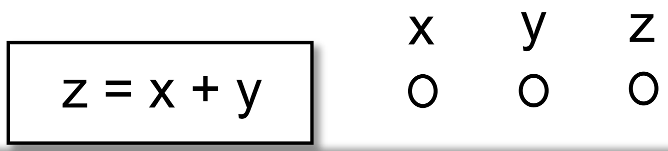

z = x + y

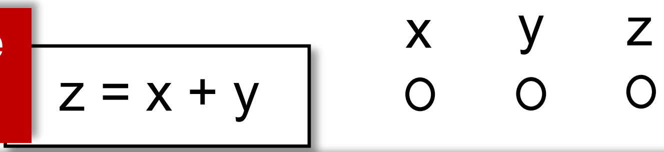
Each representation relation indicates “if x exists, then …”, “if y exists then …” But when we need “if both x and y exist”, how to draw the representation relation?

Understanding the Distributivity of IFDS

- Distributivity

Each flow function in IFDS handles one input data fact per time

For constant propagation, we cannot define F if we only know x's (or y's) value



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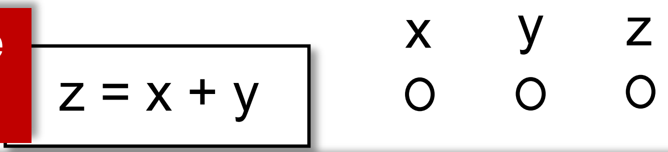

Each representation relation indicates “if x exists, then …”, “if y exists then …” But when we need “if both x and y exist”, how to draw the representation relation?

Given a statement S, besides S itself, if we need to consider **multiple** input data facts to create correct outputs, then the analysis is not distributive and should not be expressed in IFDS.

In IFDS, each data fact (circle) and its propagation (edges) could be handled **independently**, and doing so will not affect the correctness of the final results.

Understanding the Distributivity of IFDS

- Distributivity

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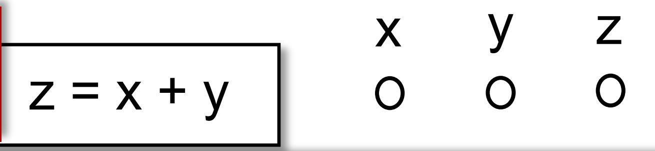
For constant propagation, we cannot define F if we only know x’s (or y’s) value



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A simple rule to determine whether your analysis could be expressed in IFDS

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- Distributivity

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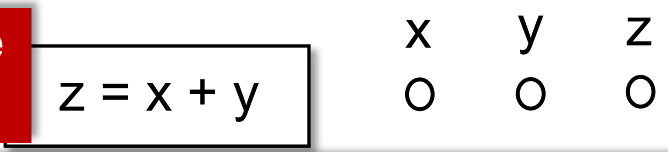

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Given a statement S, besides S itself, if we need to consider **multiple** input data facts to create correct outputs, then the analysis is not distributive and should not be expressed in IFDS.

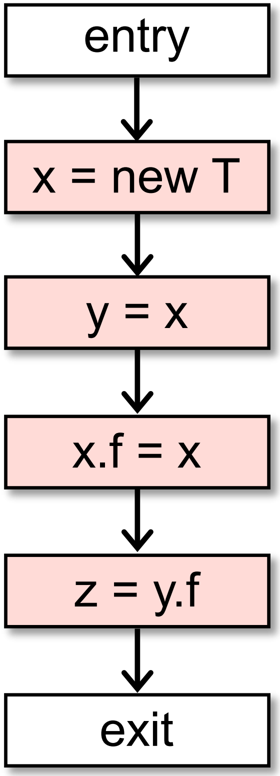
In IFDS, each data fact (circle) and its propagation (edges) could be handled **independently**, and doing so will not affect the correctness of the final results.

Regardless of the infinite domain issue, think about whether we could do *linear constant propagation*, e,g., y = 2x + 3, or
copy constant propagation, e.g., x = 2, y = x, using IFDS-style analysis?

Understanding the Distributivity of IFDS

For simplicity, assume we know the program only contains these four statements when designing flow functions

- Pointer Analysis



Understanding the Distributivity of IFDS

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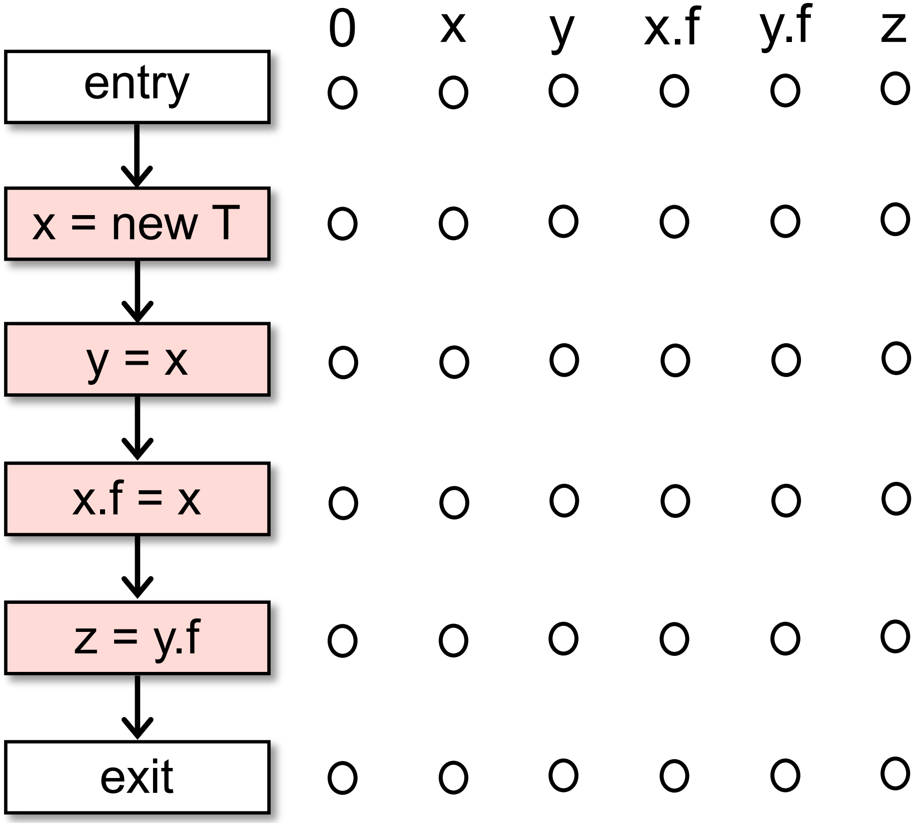

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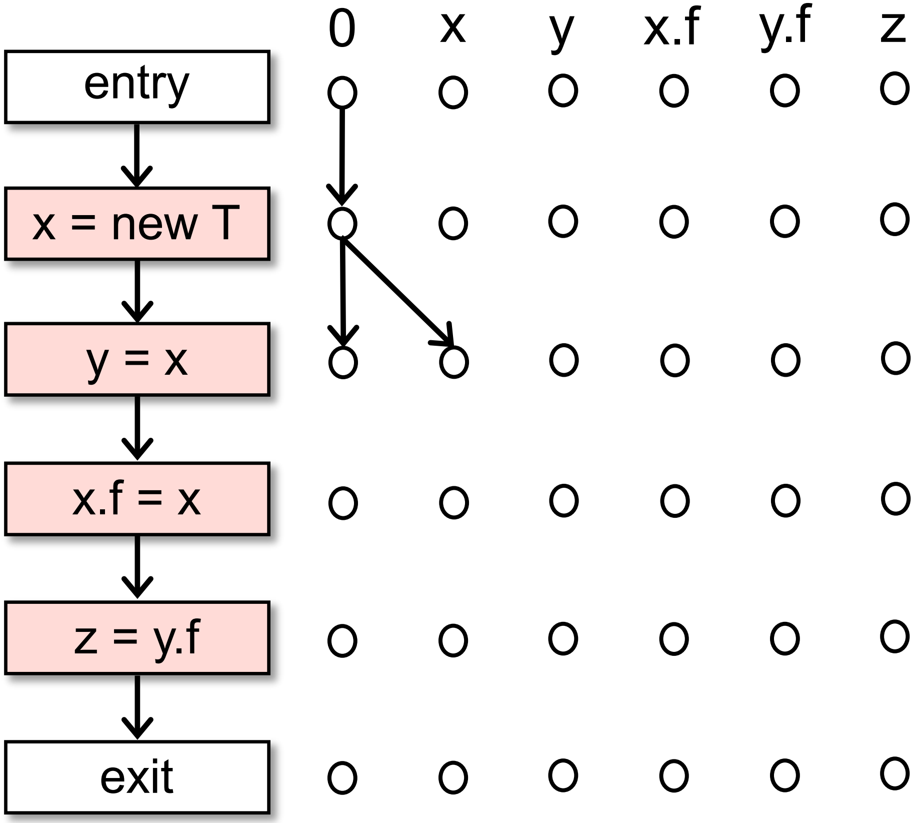
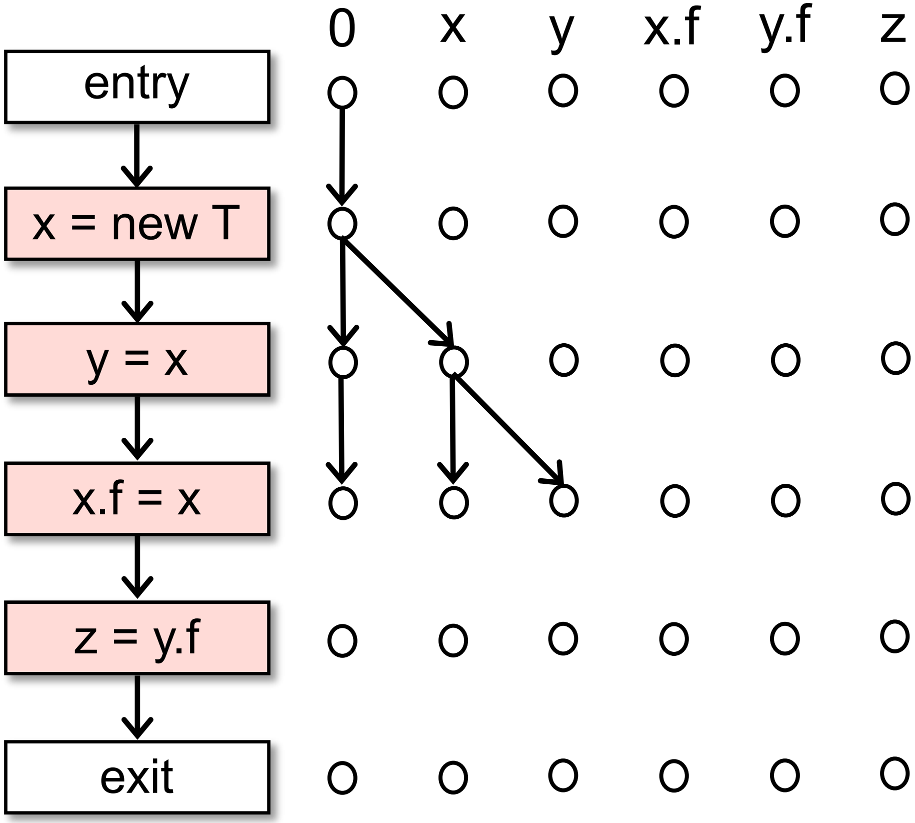


Understanding the Distributivity of IFDS

- Pointer Analysis



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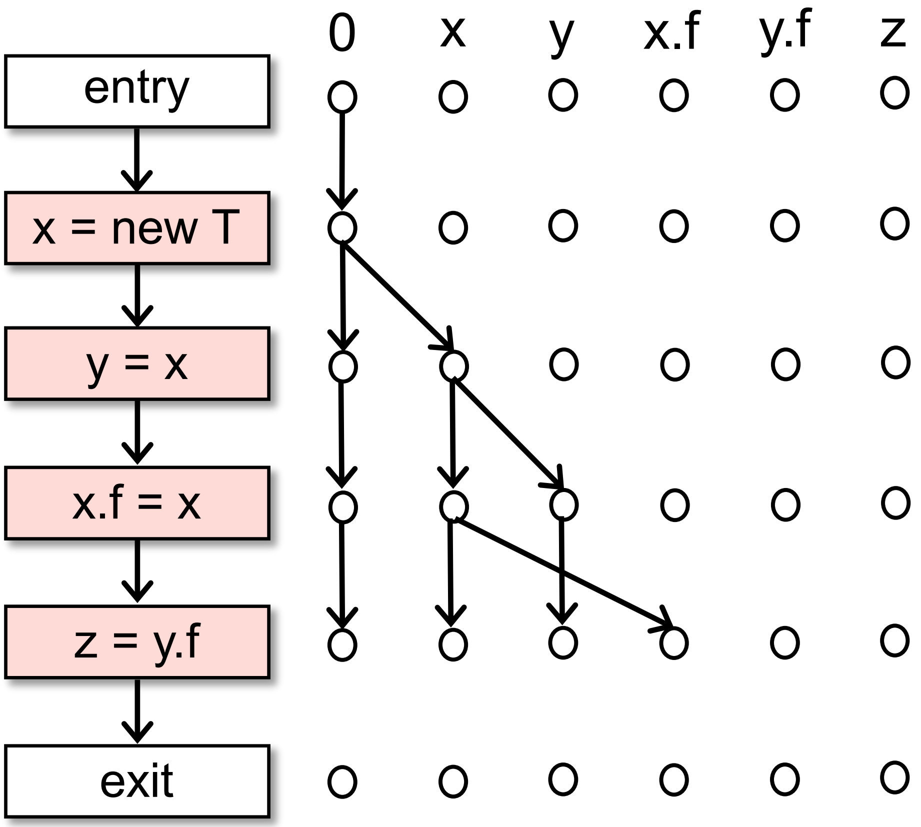
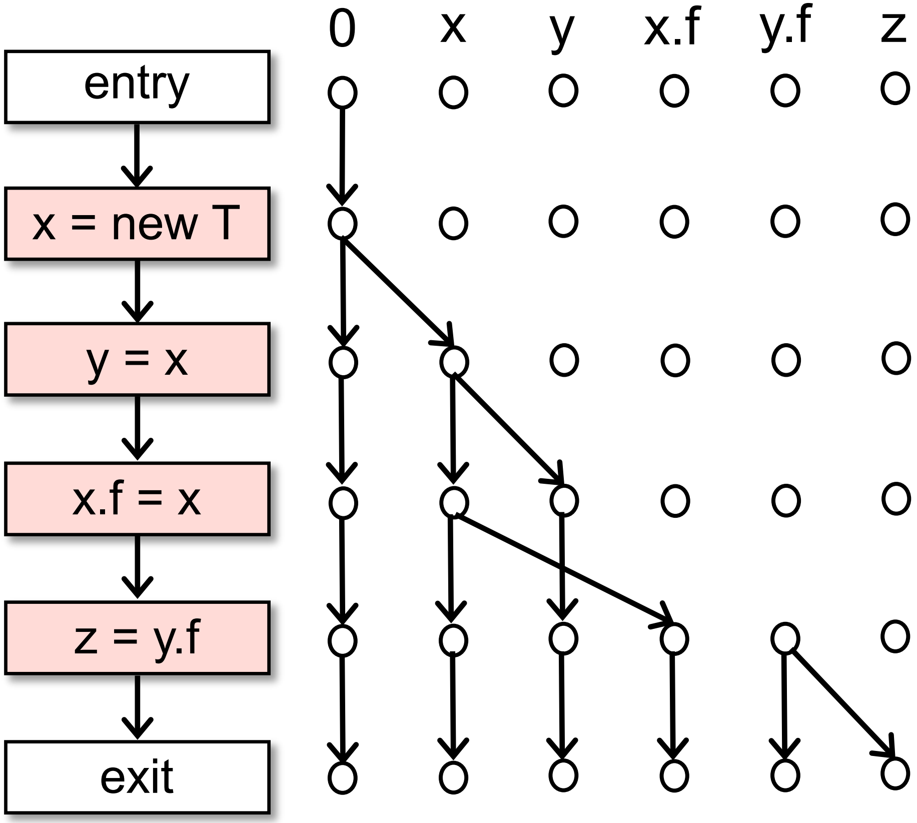


Understanding the Distributivity of IFDS

- Pointer Analysis



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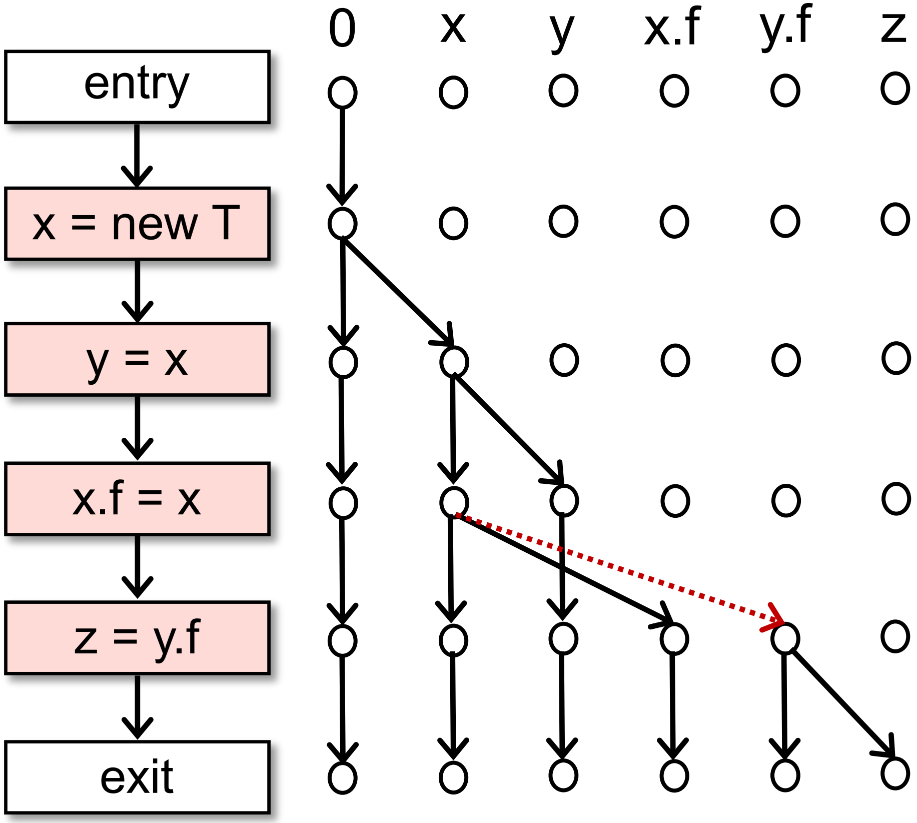
Understanding the Distributivity of IFDS

For simplicity, assume we know the program only contains these four statements when designing flow functions

- Pointer Analysis

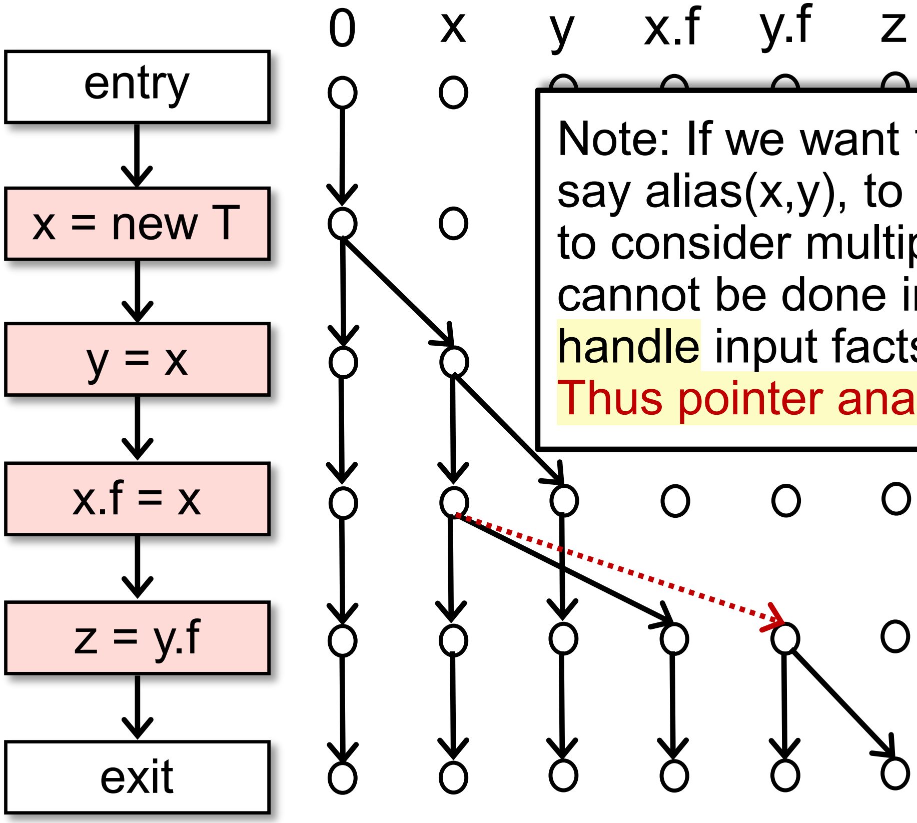


z and y.f should have pointed to object [new T]. However, flow function's input data facts lack of the alias information, alias(x,y), alias(x.f,y.f), and we need alias information to produce correct outputs.

Understanding the Distributivity of IFDS

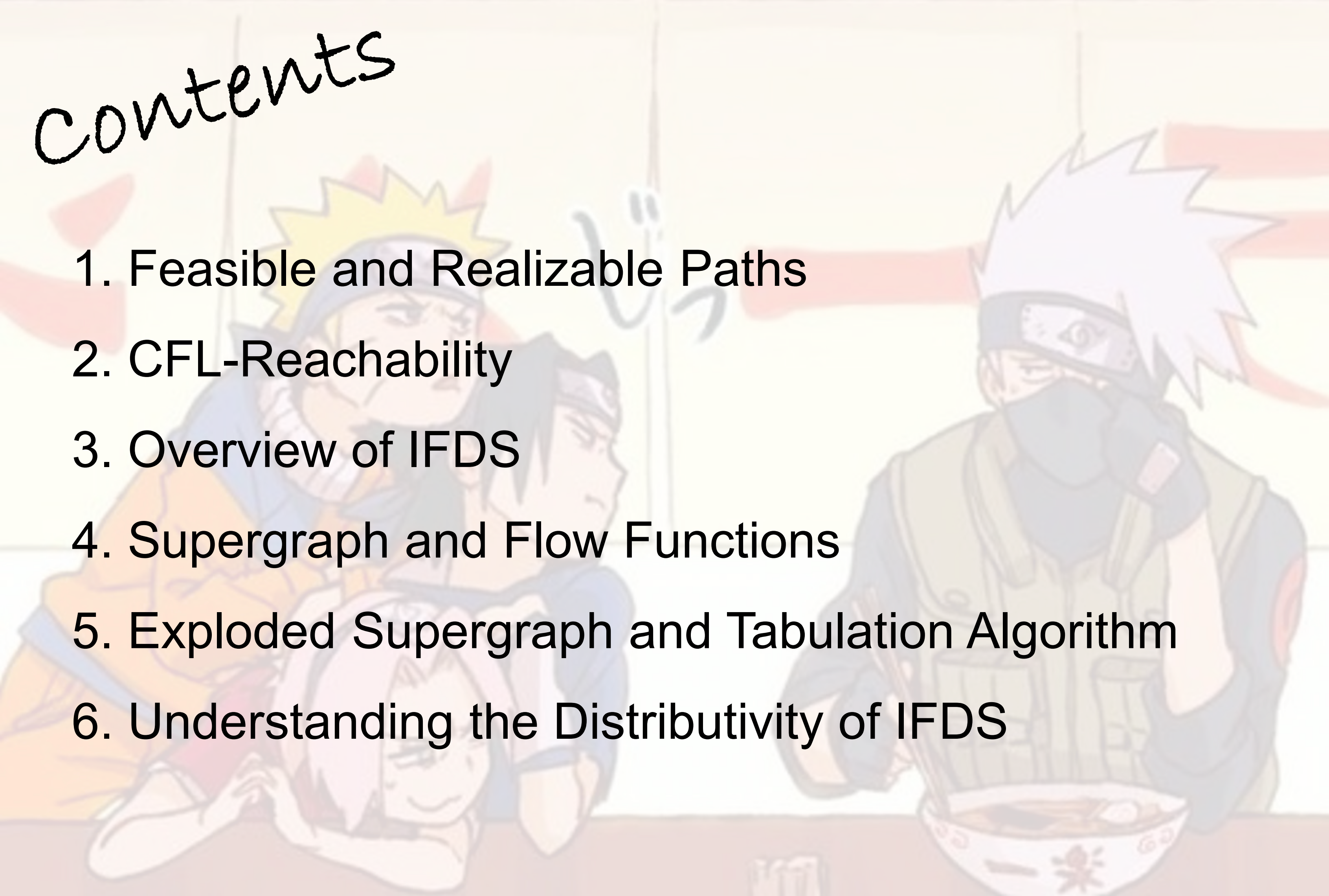
For simplicity, assume we know the program only contains these four statements when designing flow functions

- Pointer Analysis



Note: If we want to obtain alias information in IFDS, say alias(x,y), to produce correct outputs, we need to consider multiple input data facts, x and y, which cannot be done in *standard* IFDS as flow functions handle input facts independently (one fact per time). Thus pointer analysis is non-distributive.

z and y.f should have pointed to object [new T]. However, flow function's input data facts lack of the alias information, alias(x,y), alias(x.f,y.f), and we need alias information to produce correct outputs.

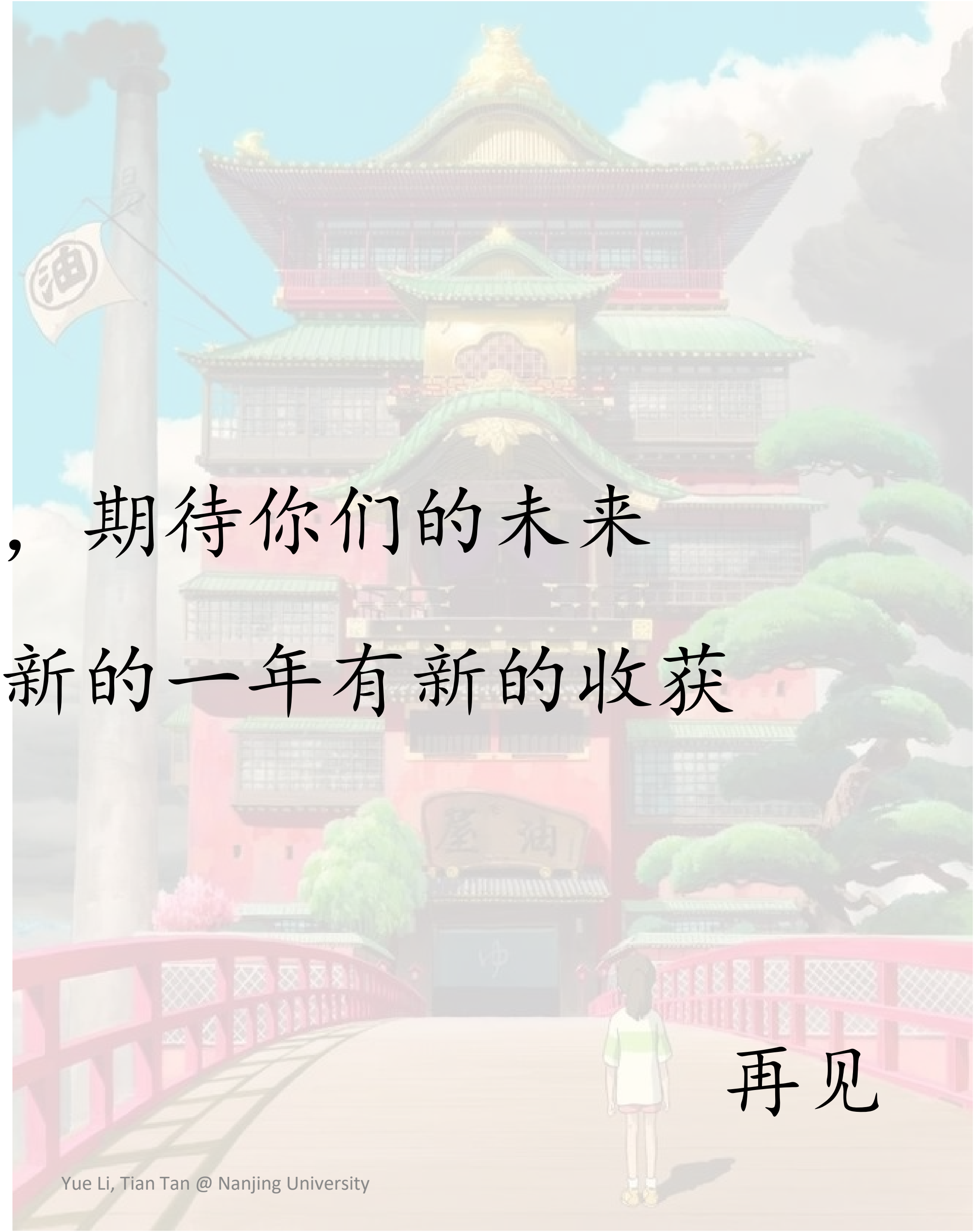


Contents

1. Feasible and Realizable Paths
2. CFL-Reachability
3. Overview of IFDS
4. Supergraph and Flow Functions
5. Exploded Supergraph and Tabulation Algorithm
6. Understanding the Distributivity of IFDS

The X You Need To Understand in This Lecture

- Understand CFL-Reachability
- Understand the basic idea of IFDS
- Understand what problems can be solved by IFDS



感谢陪伴，期待你们的未来

祝同学们在新的一年有新的收获

再见

软件分析

南京大学

计算机科学与技术系

程序设计语言与
静态分析研究组

李樾 谭添