Static Program Analysis

Interprocedural Analysis

Nanjing University

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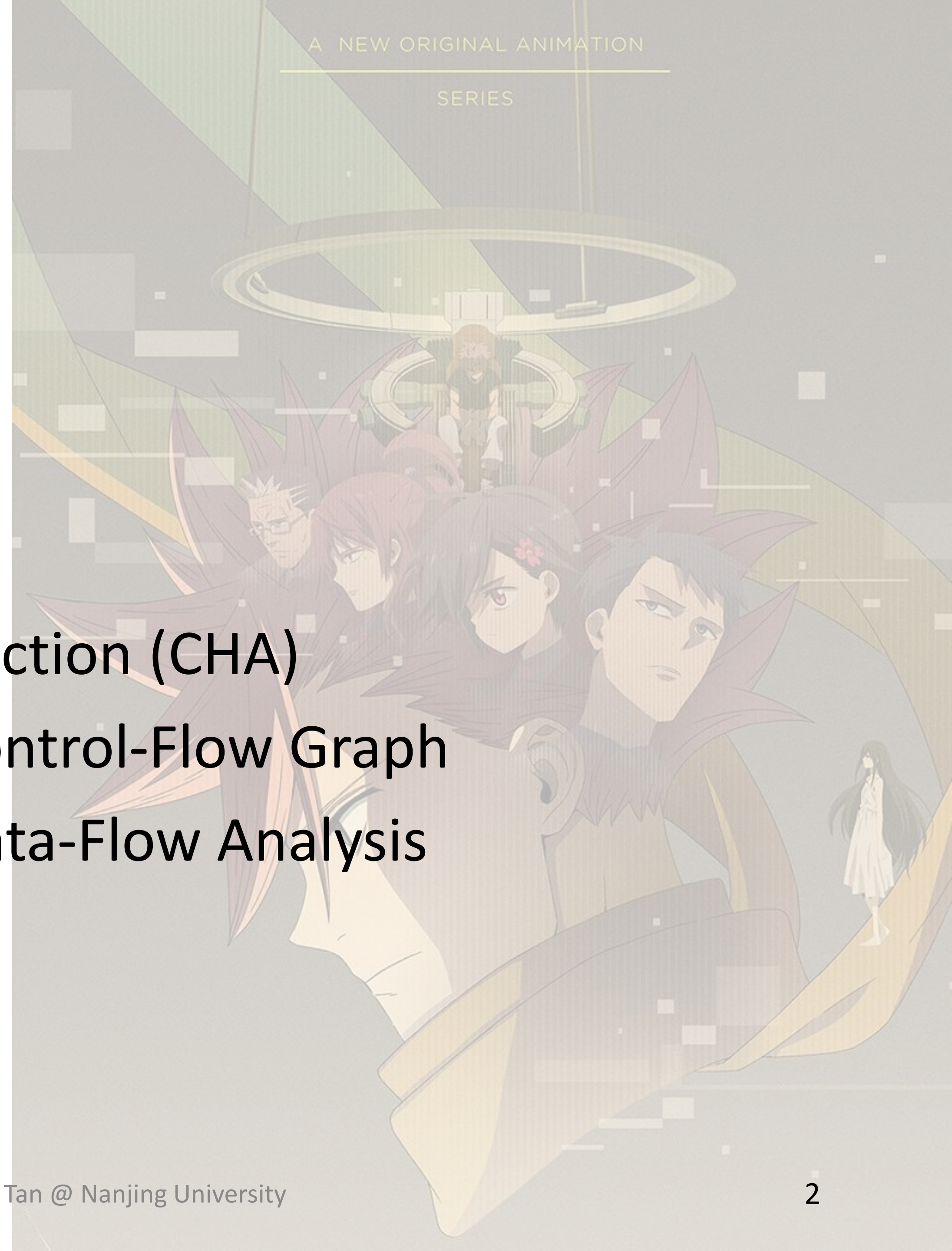
2020

Contents



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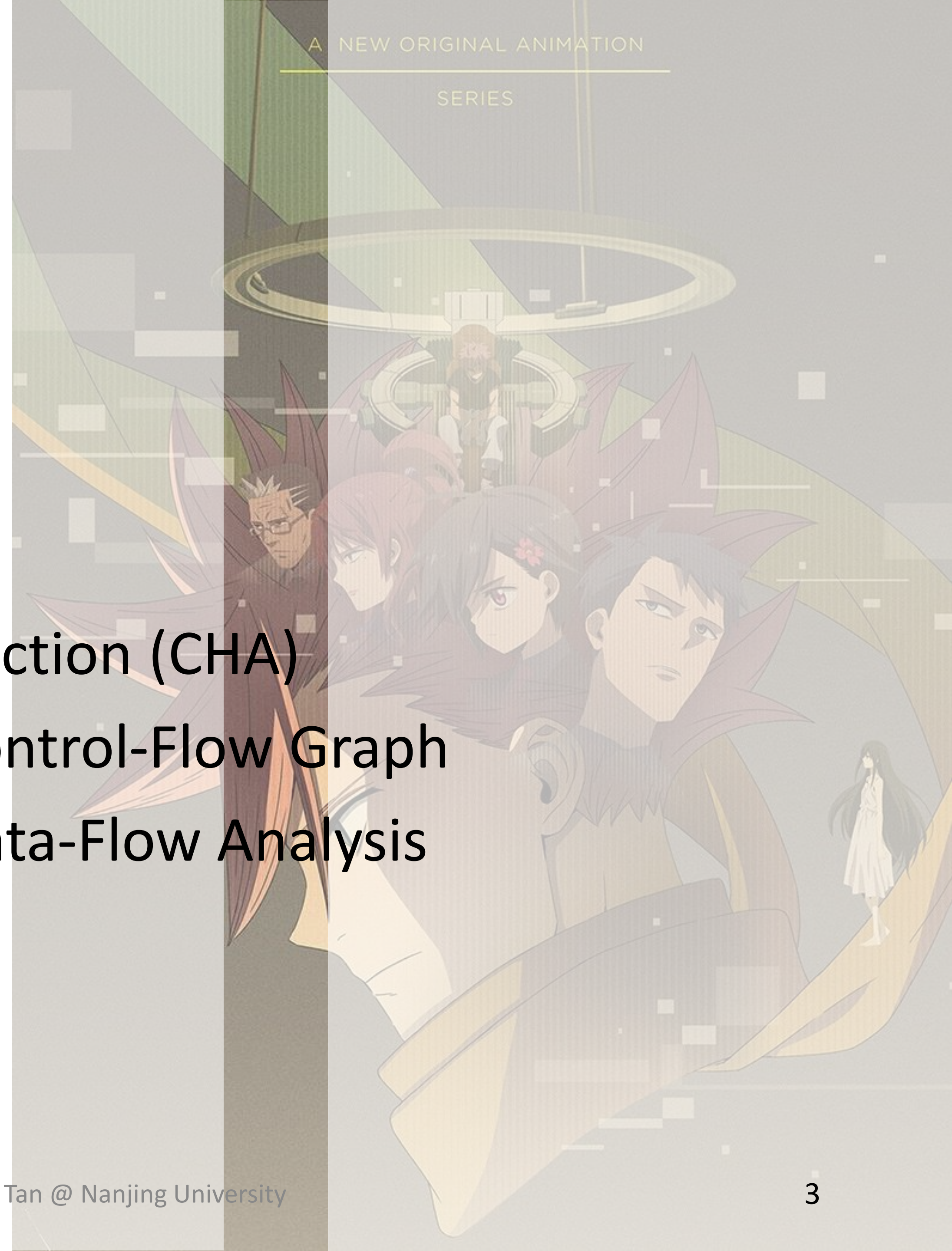

1. **Motivation**
2. Call Graph Construction (CHA)
3. Interprocedural Control-Flow Graph
4. Interprocedural Data-Flow Analysis

Motivation of Interprocedural Analysis

Constant Propagation

So far, all analyses we learnt are intraprocedural. How to deal with method calls?

```
void foo() {
    int n = bar(42);
}

int bar(int x) {
    int y = x + 1;
    return 10;
}
```

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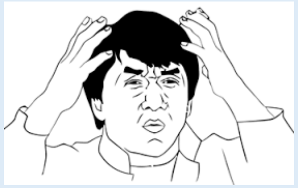
- Source of imprecision



- x = NAC, y = NAC
- n = NAC

Motivation of Interprocedural Analysis

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void foo() {
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Call edges

Return edges

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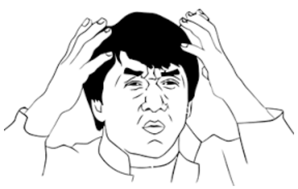

For better precision, we need Interprocedural analysis: propagate data-flow information along **interprocedural control-flow edges** (i.e., call and return edges)

Motivation of Interprocedural Analysis

Constant Propagation

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   int n = bar(42);
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Return edges

Call edges

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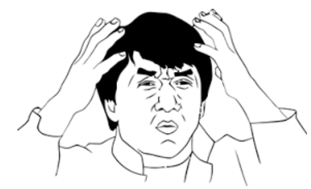

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➢ x = 42, y = 43

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Motivation of Interprocedural Analysis

Constant Propagation

```
void foo() {
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int bar(int x) {
  int y = x + 1;
  return 10;
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```

Call edges

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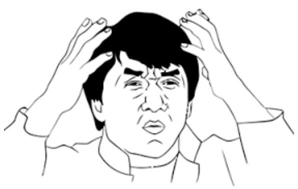

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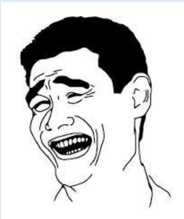
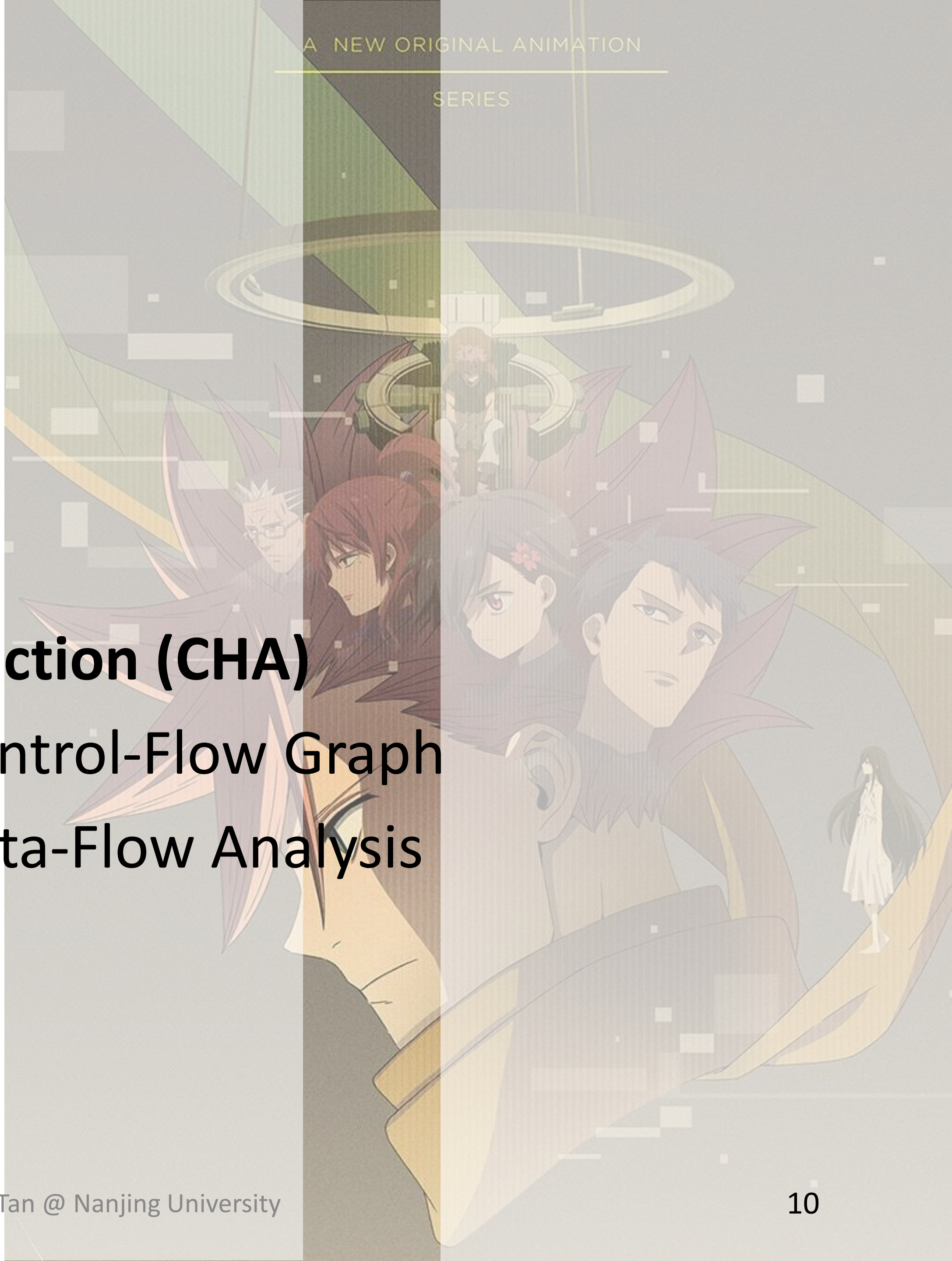


➢ x = 42, y = 43
➢ n = 10

To perform interprocedural analysis, we need **call graph**

Contents



1. Motivation
2. **Call Graph Construction (CHA)**
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4. Interprocedural Data-Flow Analysis

Call Graph

A representation of calling relationships in the program

- Essentially, a call graph is a set of call edges from call-sites to their target methods (callees)

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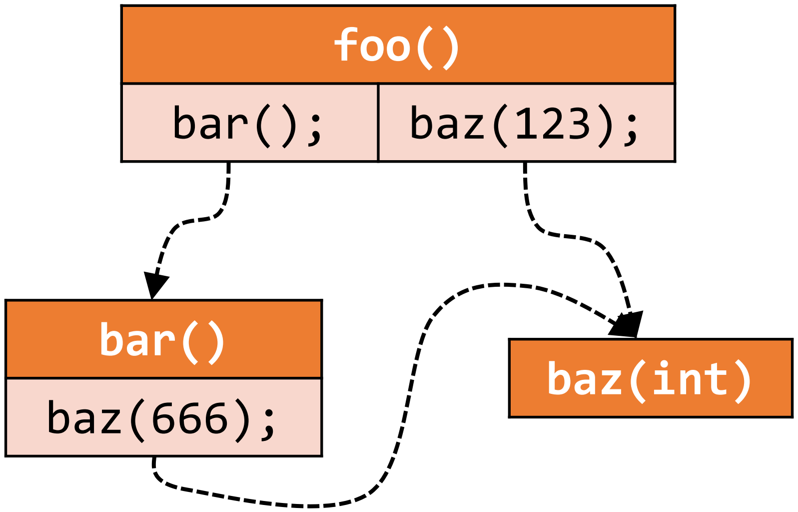
```
void foo() {
  bar();
  baz(123);
}

void bar(int x) {
  baz(666);
}

void baz() { }
```



Applications of Call Graph

- Foundation of all interprocedural analyses
- Program optimization
- Program understanding
- Program debugging
- Program testing
- And many more …

Call graph is **VERY** **important** program information

Call Graph Construction for OOPLs (focus on Java)

- Class hierarchy analysis (CHA)
- Rapid type analysis (RTA)
- Variable type analysis (VTA)
- Pointer analysis (*k*-CFA)

Call Graph Construction for OOPLs (focus on Java)

More efficient

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- Rapid type analysis (RTA)
- Variable type analysis (VTA)
- Pointer analysis (*k*-CFA)

More precise

Call Graph Construction for OOPLs (focus on Java)

this lecture

More efficient

- **Class hierarchy analysis (CHA)**
- Rapid type analysis (RTA)
- Variable type analysis (VTA)
- **Pointer analysis (*k*-CFA)**

More precise

next lectures

Method Calls (Invocations) in Java

	Static call	**Special call**	**Virtual call**
Instruction	`invokestatic`	`invokespecial`	`invokeinterface` `invokevirtual`

Method Calls (Invocations) in Java

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Target methods	• Static methods	• Constructors • Private instance methods • Superclass instance methods	• Other instance methods

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#Target methods	1	1	≥1 (**polymorphism**)
Determinacy	Compile-time	Compile-time	Run-time

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Key to call graph construction for OOPLs

Method Dispatch of Virtual Calls

During run-time, a virtual call is resolved based on

1. type of the receiver object (pointed by o)
2. method signature at the call site

```
o¹.foo(…)²;
```

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In this lecture, a signature acts as an identifier of a method

- Signature = class type + method name + descriptor
- Descriptor = return type + parameter types

Method Dispatch of Virtual Calls

During run-time, a virtual call is resolved based on

1. type of the receiver object (pointed by o)
2. method signature at the call site

$o^1.foo(\ldots)^2;$

In this lecture, a signature acts as an identifier of a method

```
class C {
  T foo(P p, Q q, R r) { … }
}
```

```
<C: T foo(P,Q,R)>
```

- Signature = class type + method name + descriptor
- Descriptor = return type + parameter types

Method Dispatch of Virtual Calls

During run-time, a virtual call is resolved based on

1. type of the receiver object (pointed by o)
2. method signature at the call site

`o`[1]`.foo(…)`[2]`;`

In this lecture, a signature acts as an identifier of a method

```
class C {
  T foo(P p, Q q, R r) { … }
}
```

<C: T foo(P,Q,R)>

C.foo(P,Q,R) for short

- Signature = class type + method name + descriptor
- Descriptor = return type + parameter types

Method Dispatch of Virtual Calls

During run-time, a virtual call is resolved based on

1. type of the receiver object (pointed by o): $\boldsymbol{c}$
2. method signature at the call site: $\boldsymbol{m}$

```
o¹.foo(…)²;
```

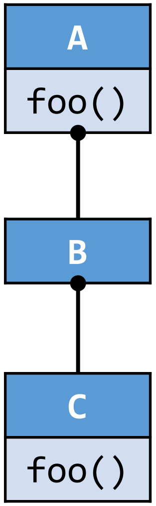
We define function Dispatch(c, m) to simulate the procedure of run-time method dispatch

$$\text{Dispatch}(c, m) = \begin{cases} m', & \textbf{if } c \text{ contains non-abstract method } m' \text{ that has the same } \underline{\text{name}} \text{ and } \underline{\text{descriptor}} \text{ as } m \\ \text{Dispatch}(c', m), & \textbf{otherwise} \end{cases}$$

where c' is superclass of c

<C: T foo(P,Q,R)>

Dispatch: An Example




```
class A {
  void foo() {…}
}

class B extends A {
}

class C extends B {
  void foo() {…}
}

void dispatch() {
  A x = new B();
  x.foo();?

  A y = new C();
  y.foo();
}
```

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$\text{Dispatch}(\texttt{B}, \texttt{A.foo()}) = ?$

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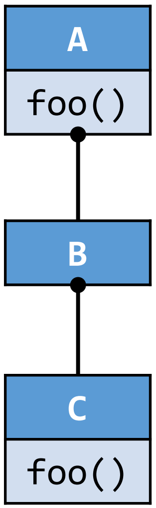


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Dispatch(B, `A.foo()`) = `A.foo()`

Dispatch(C, `A.foo()`) = ?

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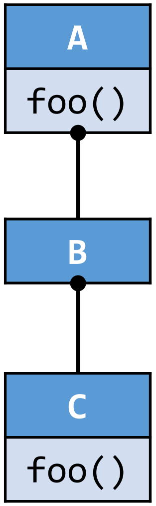


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Dispatch(`B`, `A.foo()`) = `A.foo()`

Dispatch(`C`, `A.foo()`) = `C.foo()`

Class Hierarchy Analysis* (CHA)

- Require the class hierarchy information (inheritance structure) of the whole program
- Resolve a virtual call based on the declared type of receiver variable of the call site

```
A a = …
a.foo();
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* Jeffrey Dean, David Grove, Craig Chambers, "*Optimization of Object-Oriented Programs Using Static Class Hierarchy Analysis*". ECOOP 1995.

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Call Resolution of CHA

We define function Resolve(cs) to resolve possible target methods of a call site cs by CHA

Resolve(cs)
  T = {}
  m = method signature at cs
  if cs is a static call **then**
    $T = \{ m \}$
  if cs is special call **then**
    c^m = class type of m
    T = { Dispatch(c^m, m) }
  if cs is a virtual call **then**
    c = declared type of receiver variable at cs
    foreach c' that is a subclass of c or c itself **do**
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```
class C {
  static T foo(P p, Q q)
  {…}
}

C.foo(x, y);
```

cs	`C.foo(x, y);`
m	`<C: T foo(P,Q)>`

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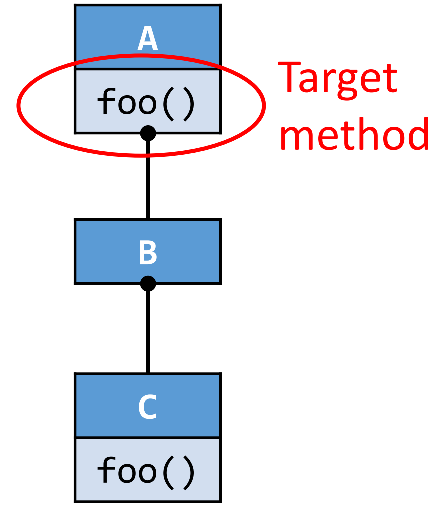
```
class C extends B {
  T foo(P p, Q q) {
    …
    super.foo(p, q);
  }
}
```

cs	`super.foo(p, q);`
m	`<B: T foo(P,Q)>`
c^m	`B`

Call Resolution of CHA



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}
```

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    c = declared type of receiver variable at cs
    foreach c' that is a subclass of c or c itself **do**
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  return T

```
class C extends B {
  T foo(P p, Q q) {
    …
    this.bar();
  }
  private T bar()
}
C c = new C();
```

Special call
- Private instance method
- Constructor
- Superclass instance method

Call Resolution of CHA

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    foreach c' that is a subclass of c or c itself **do**
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  return T

```
class A {
  T foo(P p, Q q) {…}
}
A a = …
a.foo(x, y);
```

cs	`a.foo(x, y);`
m	`<A: T foo(P,Q)>`
c	`A`

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        foreach c' that is a subclass of c or c itself **do**
            add $\text{Dispatch}(c', m)$ to T
    return T

```
class A {
  T foo(P p, Q q) {…}
}
A a = …
a.foo(x, y);
```

cs	`a.foo(x, y);`
m	`<A: T foo(P,Q)>`
c	`A`

Subclasses includes all **direct** and **indirect** subclasses of c

CHA: An Example

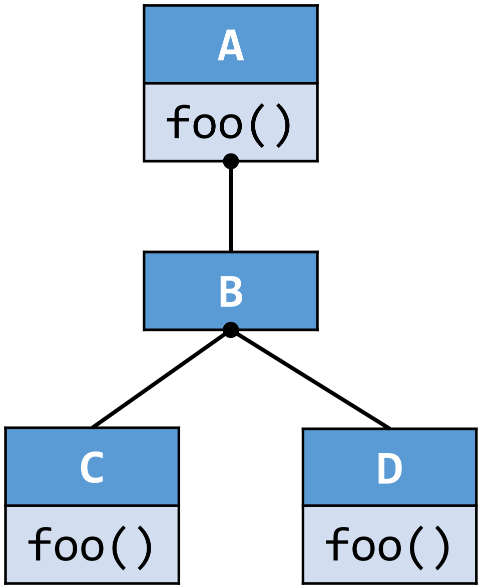
```
class A {
  void foo() {…}
}
class B extends A {}

class C extends B {
  void foo() {…}
}
class D extends B {
  void foo() {…}
}

void resolve() {
  C c = …
  c.foo();

  A a = …
  a.foo();

  B b = …
  b.foo();
}
```



CHA: An Example

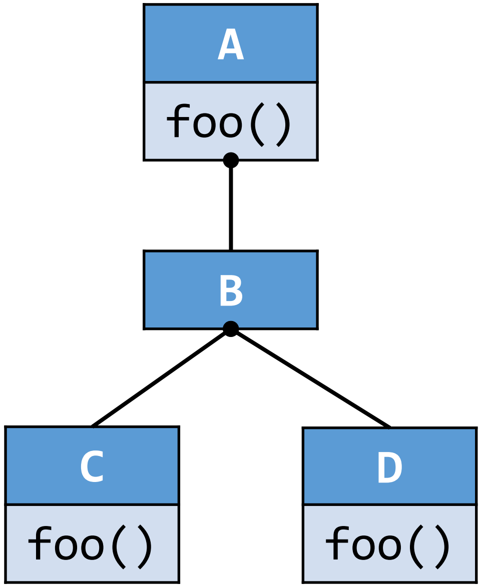
```
class A {
  void foo() {…}
}
class B extends A {}

class C extends B {
  void foo() {…}
}
class D extends B {
  void foo() {…}
}

void resolve() {
  C c = …
  c.foo(); ?

  A a = …
  a.foo();

  B b = …
  b.foo();
}
```



Resolve(c.foo()) = ?

CHA: An Example

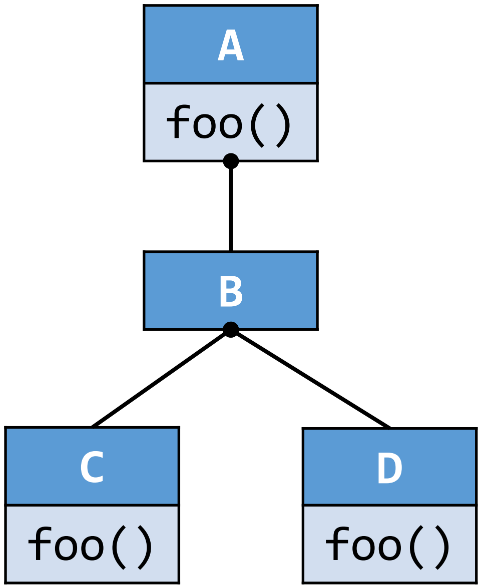
```
class A {
  void foo() {…}
}
class B extends A {}

class C extends B {
  void foo() {…}
}
class D extends B {
  void foo() {…}
}

void resolve() {
  C c = …
  c.foo();

  A a = …
  a.foo();?

  B b = …
  b.foo();
}
```



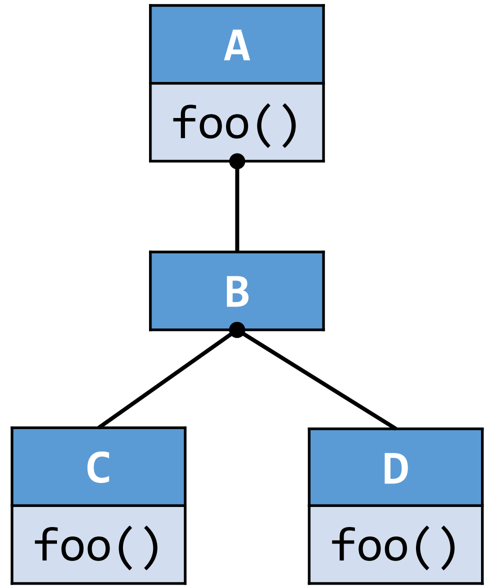
Resolve(c.foo()) = {C.foo()}

Resolve(a.foo()) = ?

CHA: An Example

```
class A {
  void foo() {…}
}
class B extends A {}

class C extends B {
  void foo() {…}
}
class D extends B {
  void foo() {…}
}
```




```
void resolve() {
  C c = …
  c.foo();

  A a = …
  a.foo();

  B b = …
  b.foo(); ?
}
```

Resolve(c.foo()) = {C.foo()}

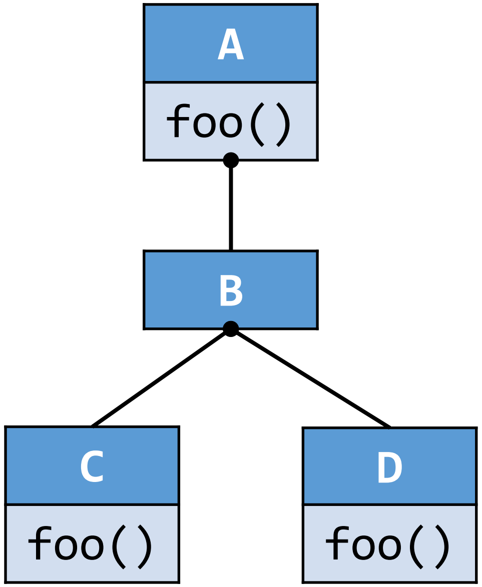
Resolve(a.foo()) = {A.foo(), C.foo(), D.foo()}

Resolve(b.foo()) = ?

CHA: An Example

```
class A {
  void foo() {…}
}
class B extends A {}

class C extends B {
  void foo() {…}
}
class D extends B {
  void foo() {…}
}
```




```
void resolve() {
  C c = …
  c.foo();              Resolve(c.foo()) = {C.foo()}

  A a = …
  a.foo();              Resolve(a.foo()) = {A.foo(), C.foo(), D.foo()}

  B b = …
  b.foo();              Resolve(b.foo()) = {A.foo(), C.foo(), D.foo()}
}
```

CHA: An Example

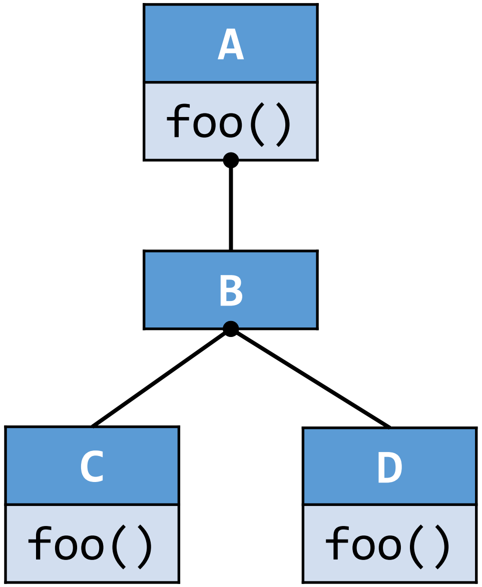
```
class A {
  void foo() {…}
}
class B extends A {}

class C extends B {
  void foo() {…}
}
class D extends B {
  void foo() {…}
}

void resolve() {
  C c = …
  c.foo();

  A a = …
  a.foo();

  B b = new B();
  b.foo(); ?
}
```



Resolve(c.foo()) = {C.foo()}

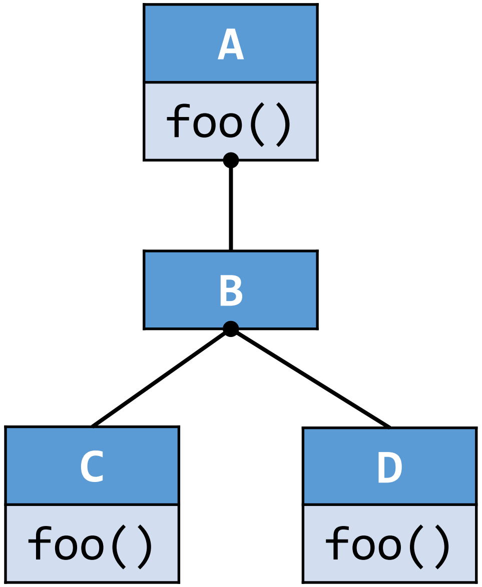
Resolve(a.foo()) = {A.foo(), C.foo(), D.foo()}

Resolve(b.foo()) = ?

CHA: An Example

```
class A {
  void foo() {…}
}
class B extends A {}

class C extends B {
  void foo() {…}
}
class D extends B {
  void foo() {…}
}
```




```
void resolve() {
  C c = …
  c.foo();

  A a = …
  a.foo();

  B b = new B();
  b.foo();
}
```

Resolve(`c.foo()`) = {`C.foo()`}

Resolve(`a.foo()`) = {`A.foo()`, `C.foo()`, `D.foo()`}

Resolve(`b.foo()`) = {`A.foo()`, `C.foo()`, `D.foo()`}

Spurious call targets

Features of CHA

- Advantage: fast
  - Only consider the declared type of receiver variable at the call-site, and its inheritance hierarchy
  - Ignore data- and control-flow information

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  - Addressed in next lectures

Common usage: IDE

CHA in IDE (IntelliJ IDEA)

TestCHA.java

```java
public class TestCHA {
    void test() {
        B b = new B();
        b.foo();
    }
}
class A {
    void foo() {}
}
class B extends A {}
class C extends B {
    void foo() {}
}
class D extends B {
    void foo() {}
}
```

Hierarchy: Callees of foo

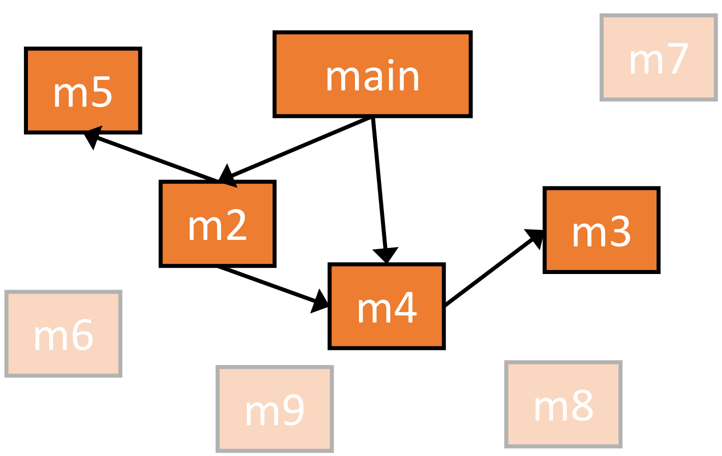
Scope: All

- A.foo() ()
  - C.foo() ()
  - D.foo() ()

Call Graph Construction

Build call graph for whole program via CHA

- Start from entry methods (focus on main method)
- For each reachable method m, resolve target methods for each call site cs in m via CHA ($\text{Resolve}(cs)$)
- Repeat until no new method is discovered



Call Graph Construction: Algorithm

BuildCallGraph(m^{entry})
    WL = [m^{entry}], CG = {}, RM = {}
    while WL is not empty **do**
        remove m from WL
        if $m \notin RM$ **then**
            add m to RM
            foreach call site cs in m **do**
                T = Resolve(cs)
                foreach target method m' in T **do**
                    add $cs \rightarrow m'$ to CG
                    add m' to WL
    return CG

WL	Work list, containing the methods to be processed
CG	Call graph, a set of call edges
RM	A set of reachable methods

Call Graph Construction: Algorithm

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BuildCallGraph(m^entry)
  WL = [m^entry], CG = {}, RM = {}
  while WL is not empty do
    remove m from WL
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        T = Resolve(cs)
        foreach target method m' in T do
          add cs → m' to CG
          add m' to WL
  return CG
```

Initialize the algorithm

WL	Work list, containing the methods to be processed
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```

Initialize the algorithm

Resolve target methods via CHA

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                foreach target method m' in T do
                    add cs → m' to CG
                    add m' to WL
    return CG
```

Initialize the algorithm

Resolve target methods via CHA

Add call edges to call graph

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                foreach target method m' in T do
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                    add m' to WL
    return CG
```

Initialize the algorithm

Resolve target methods via CHA

Add call edges to call graph

May discover new method, add it to work list

WL	Work list, containing the methods to be processed
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Call Graph Construction: An Example

```
class A {
  static void main() {
    A.foo();
  }
  static void foo() {
    A a = new A();
    a.bar();
  }
  void bar() {
    C c = new C();
    c.bar();
  }
}
class B extends A {
  void bar() {} }
class C extends A {
  void bar() {
    if (…) A.foo();
  }
  void m() {}
}
```

A.main()
A.foo();

A.foo()
a.bar();

A.bar()
c.bar();

B.Bar()

C.bar()
A.foo();

C.m()

Initialization with main method

WL = [A.main()]

Call Graph Construction: An Example

```
class A {
  static void main() {
    A.foo();
  }
  static void foo() {
    A a = new A();
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  }
  void bar() {
    C c = new C();
    c.bar();
  }
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class C extends A {
  void bar() {
    if (…) A.foo();
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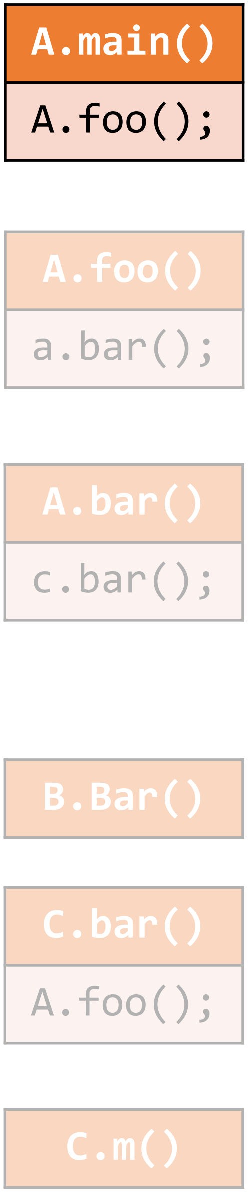
```



$WL = [\ ]$

Resolve(A.foo()) = ?

Call Graph Construction: An Example

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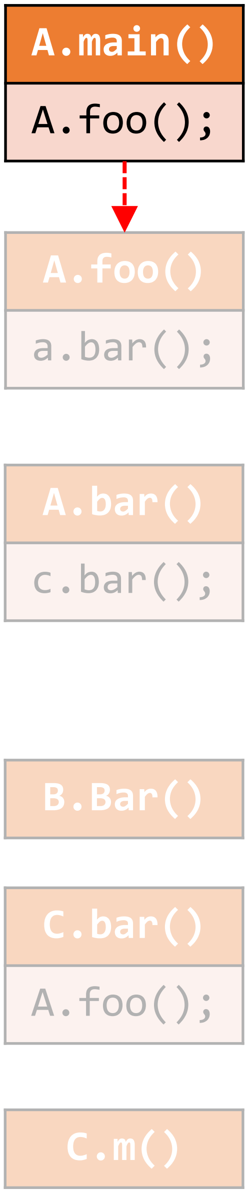

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Resolve(`A.foo()`) = { `A.foo()` }

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  }
  static void foo() {
    A a = new A();
    a.bar();
  }
  void bar() {
    C c = new C();
    c.bar();
  }
}
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    if (…) A.foo();
  }
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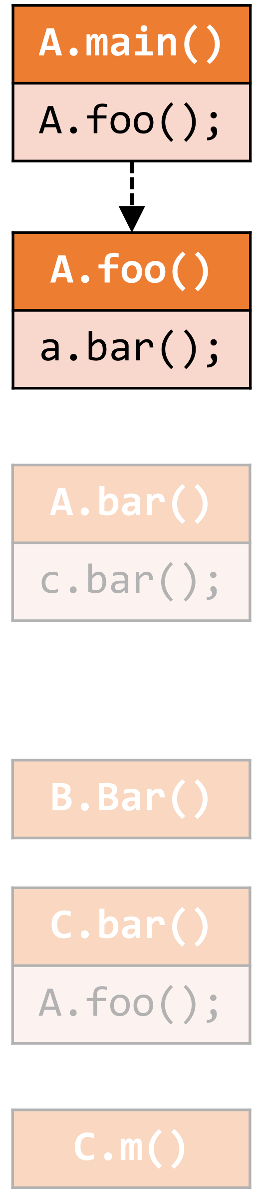
}
```



$WL = [\ \ ]$

Call Graph Construction: An Example

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    A.foo();
  }
  static void foo() {
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    c.bar();
  }
}
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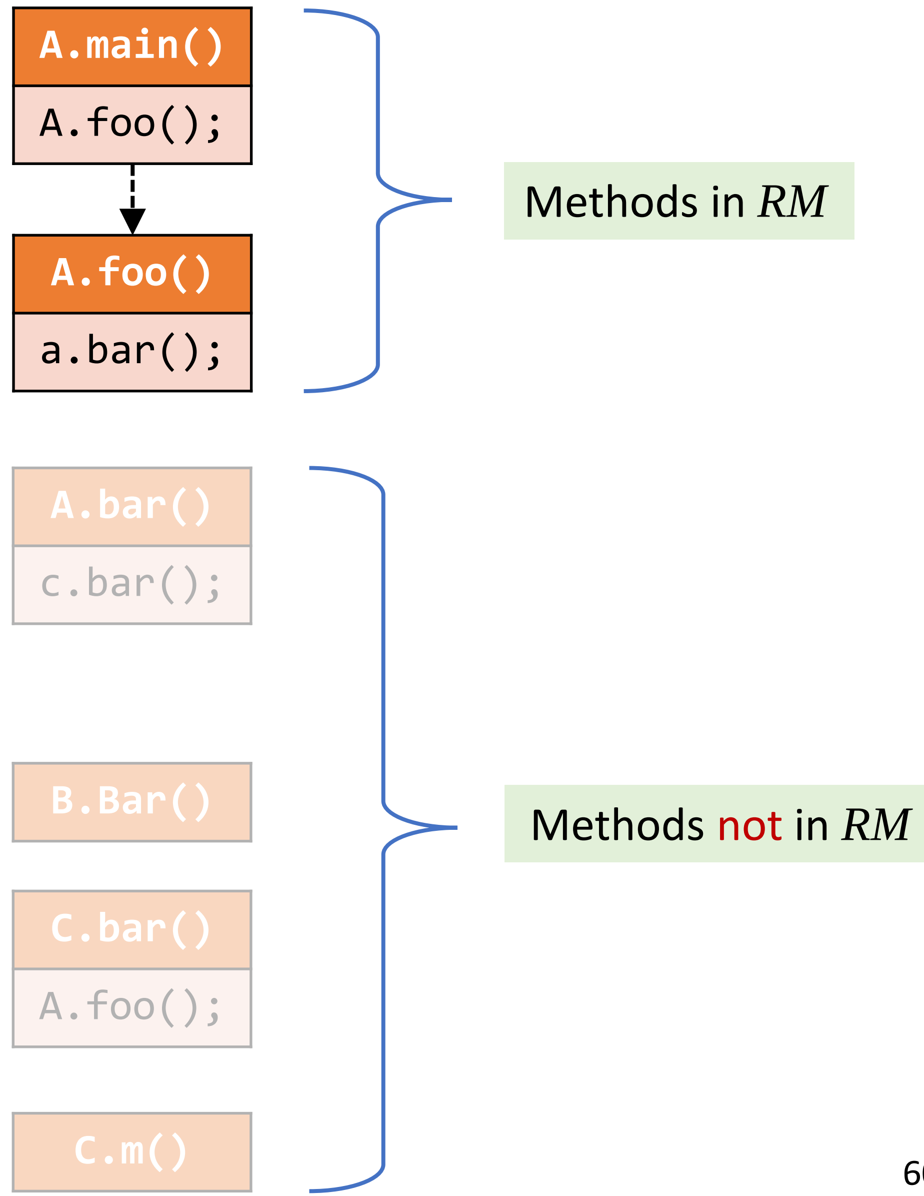
  void bar() {} }
class C extends A {
  void bar() {
    if (…) A.foo();
  }
  void m() {}
}
```



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  }
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}
class B extends A {
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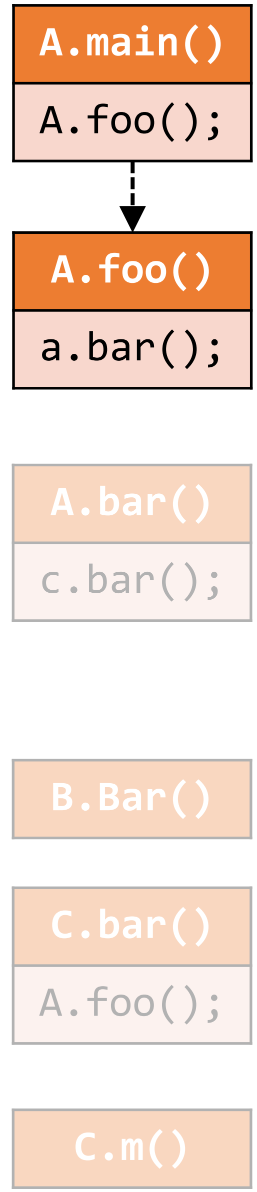
  void m() {}
}
```



$WL = [\ \ ]$

Resolve(a.bar()) = ?

Call Graph Construction: An Example

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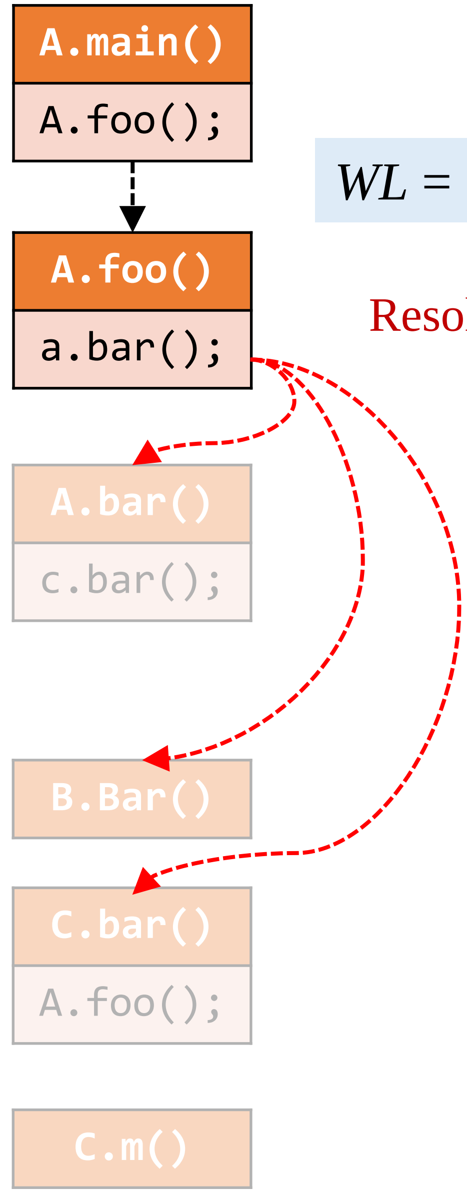
```



WL = [`A.bar()`, `B.bar()`, `C.bar()`]

Resolve(`a.bar()`) = { `A.bar()`, `B.bar()`, `C.bar()` }

Call Graph Construction: An Example

```
class A {
  static void main() {
    A.foo();
  }
  static void foo() {
    A a = new A();
    a.bar();
  }
  void bar() {
    C c = new C();
    c.bar();
  }
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class B extends A {
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}
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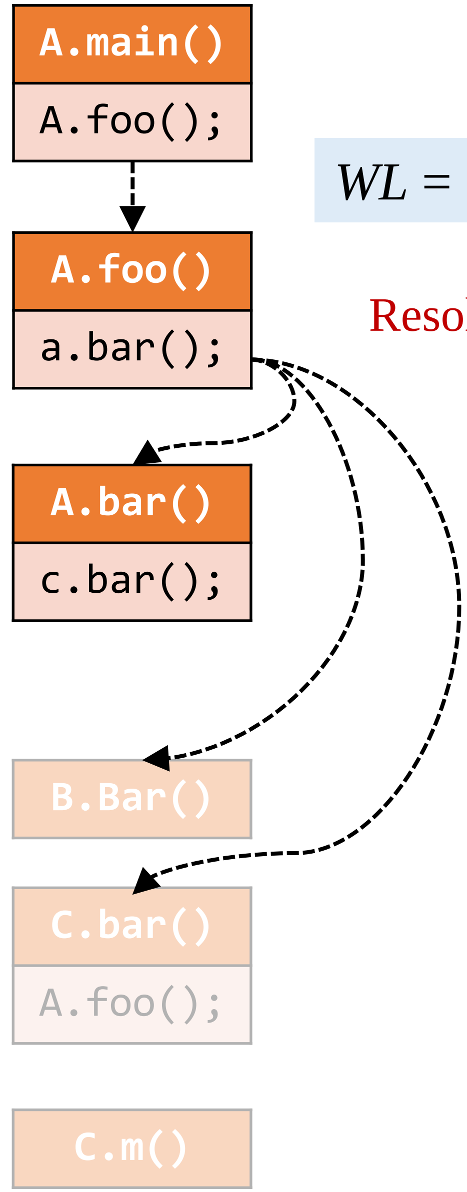

WL = [`B.bar()`, `C.bar()`]

Resolve(`c.bar()`) = ?

Call Graph Construction: An Example

```
class A {
  static void main() {
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  }
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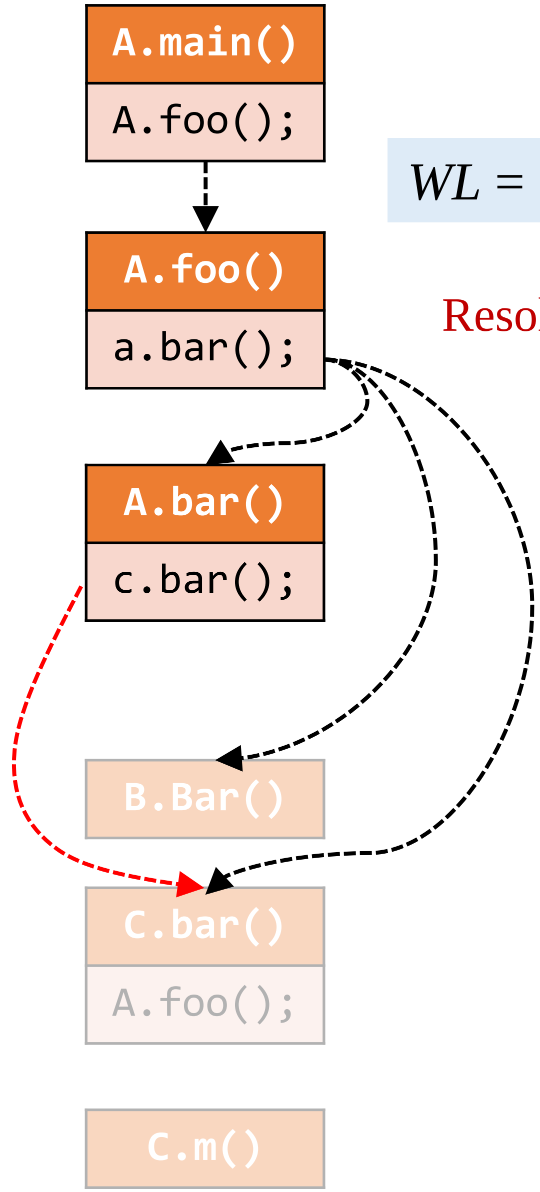

WL = [B.bar(), C.bar(), C.bar()]

Resolve(c.bar()) = { C.bar() }

Call Graph Construction: An Example

```
class A {
  static void main() {
    A.foo();
  }
  static void foo() {
    A a = new A();
    a.bar();
  }
  void bar() {
    C c = new C();
    c.bar();
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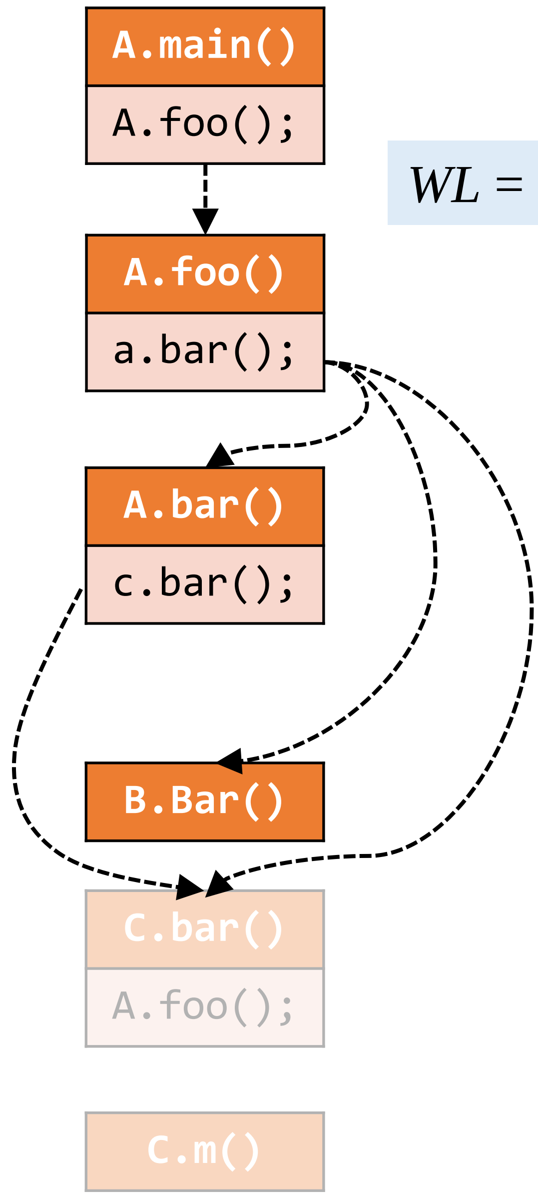

$WL = [$C.bar(),C.bar()$]$

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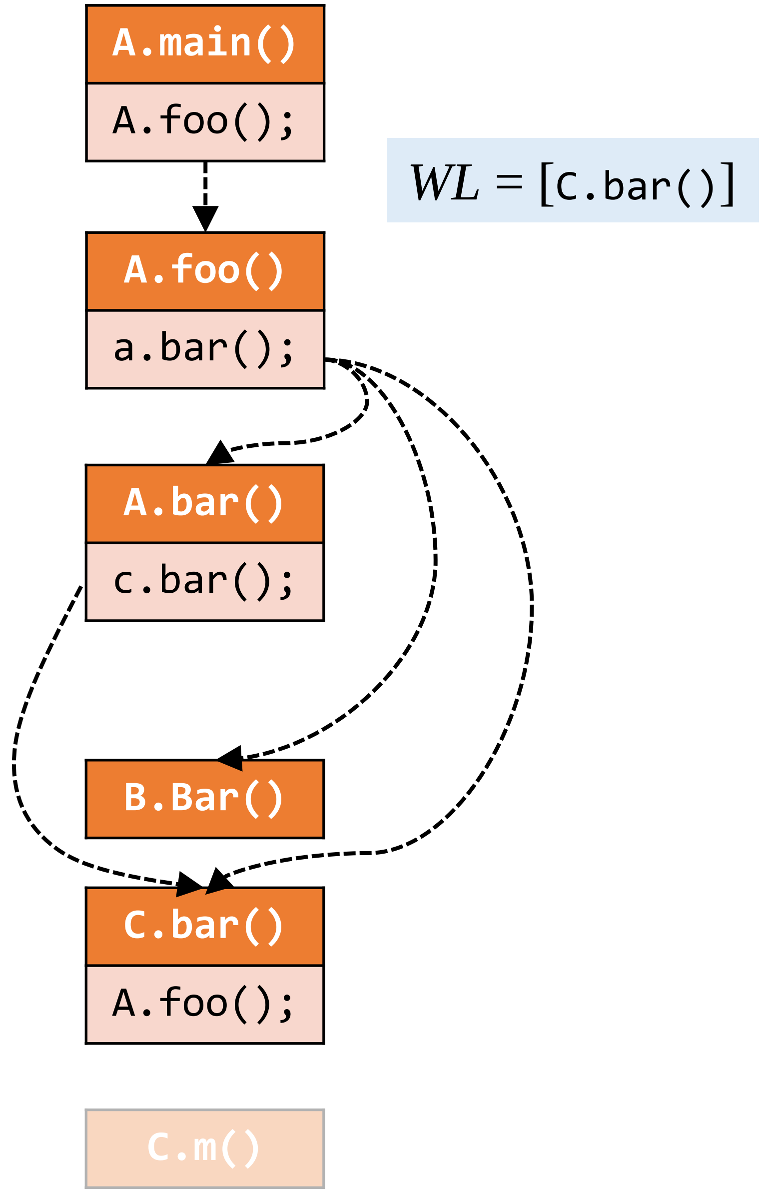

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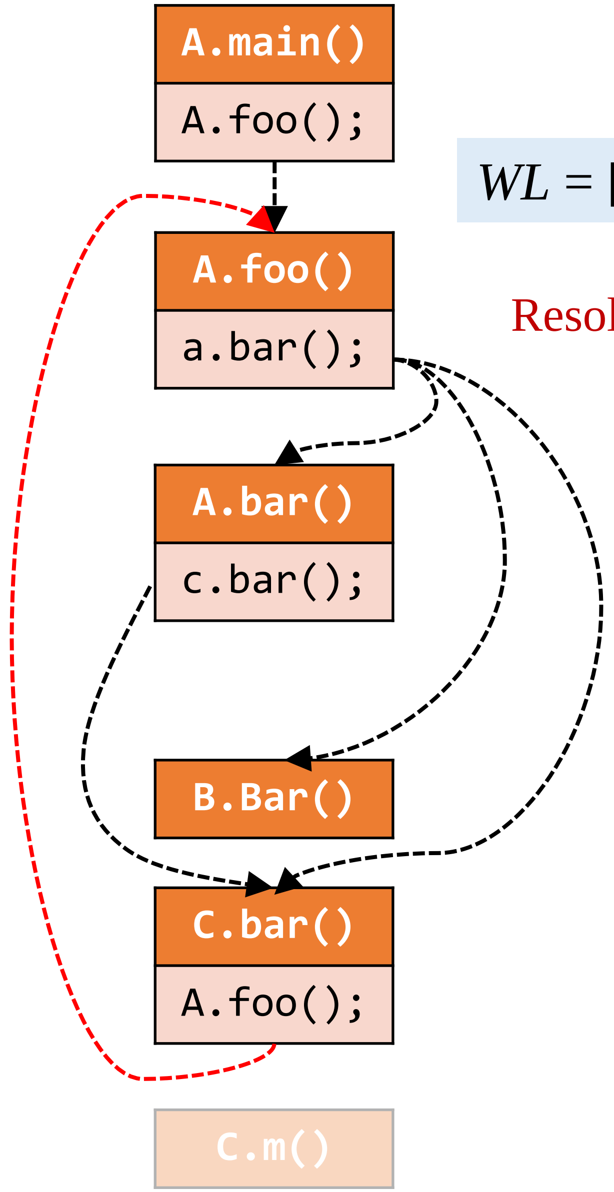

WL = [C.bar(),A.foo()]

Resolve(A.foo()) = { A.foo() }

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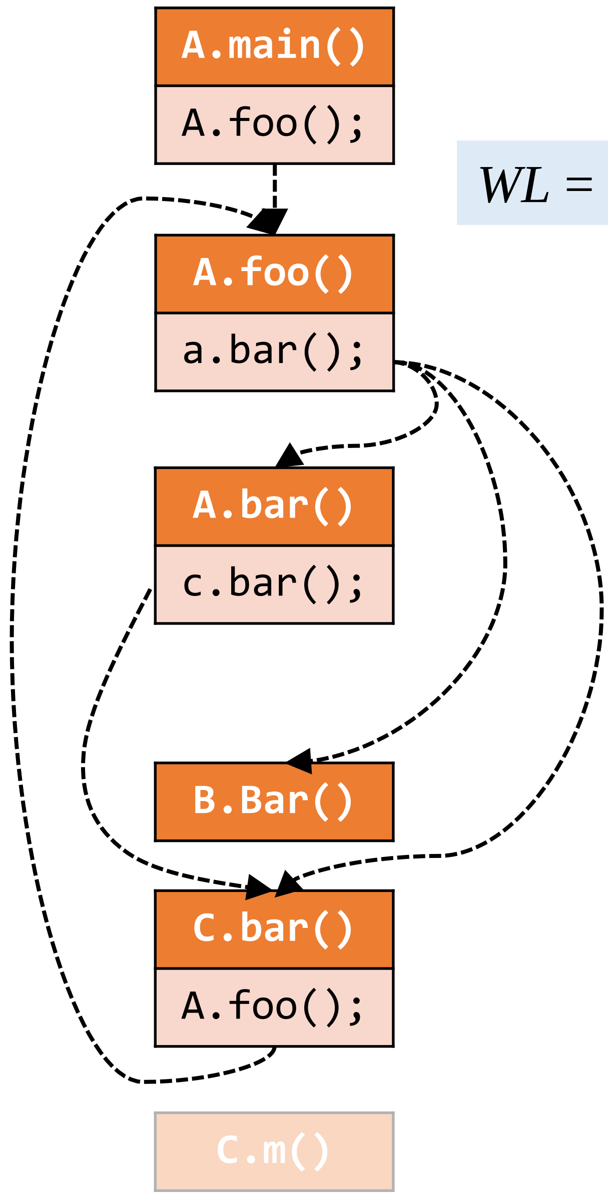

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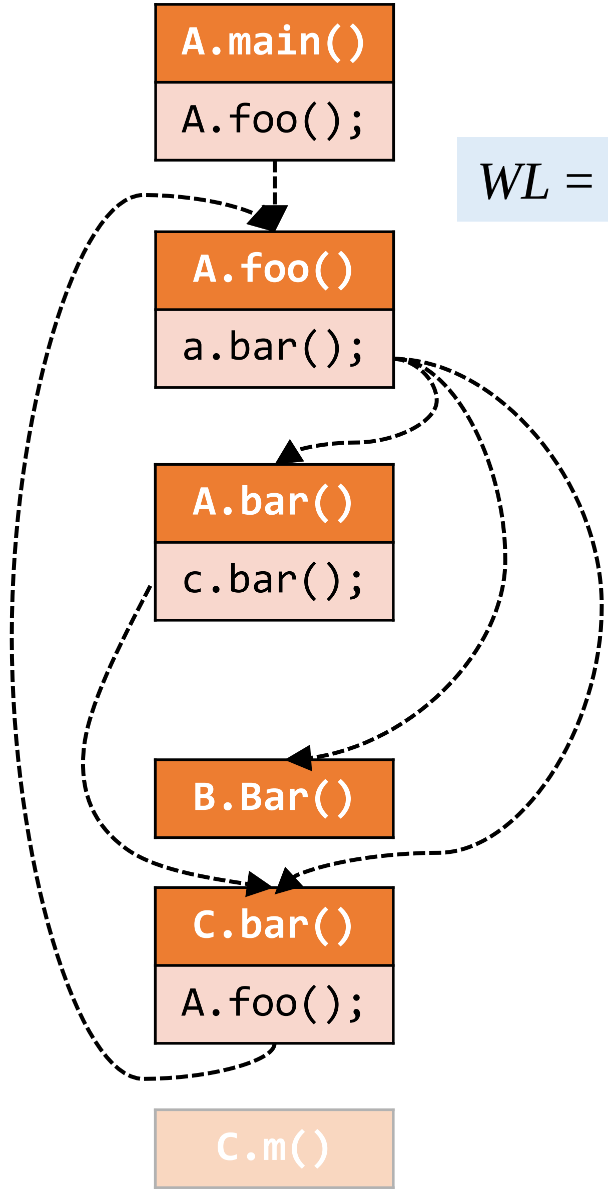

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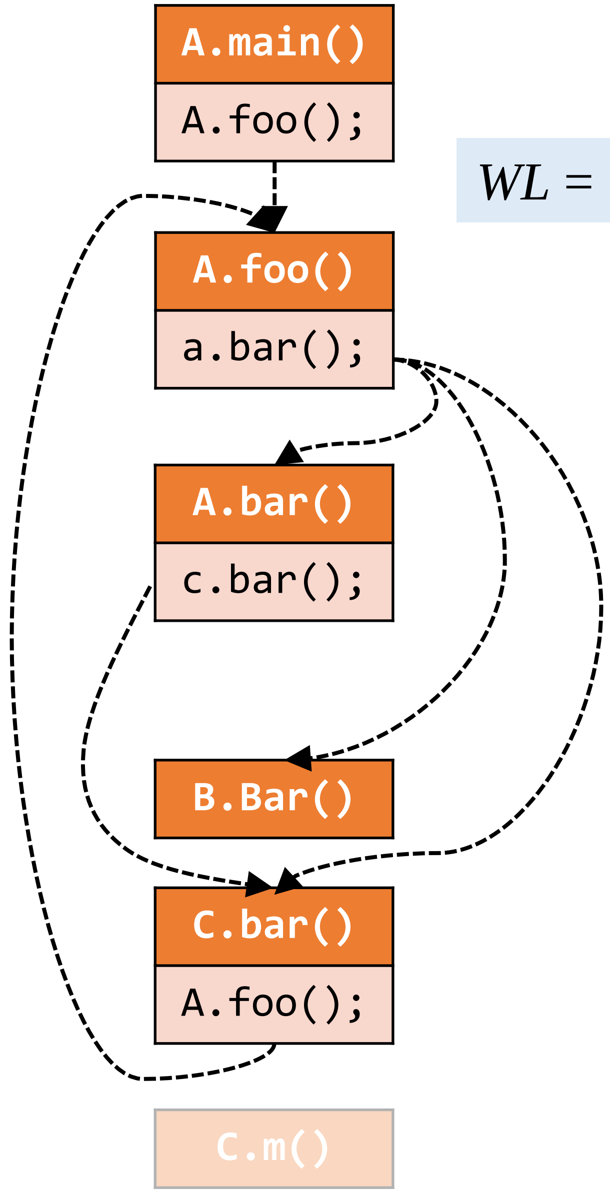

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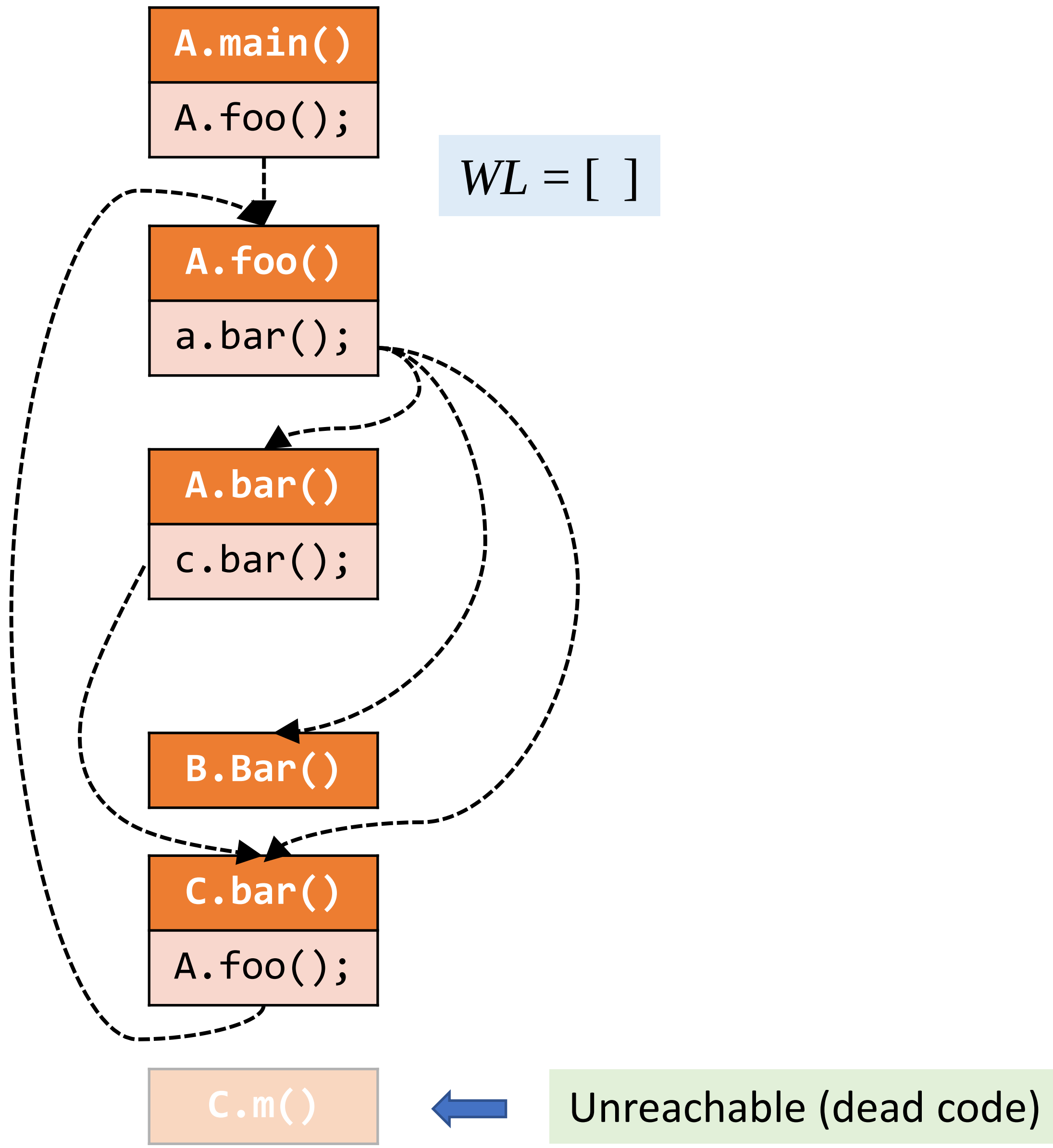
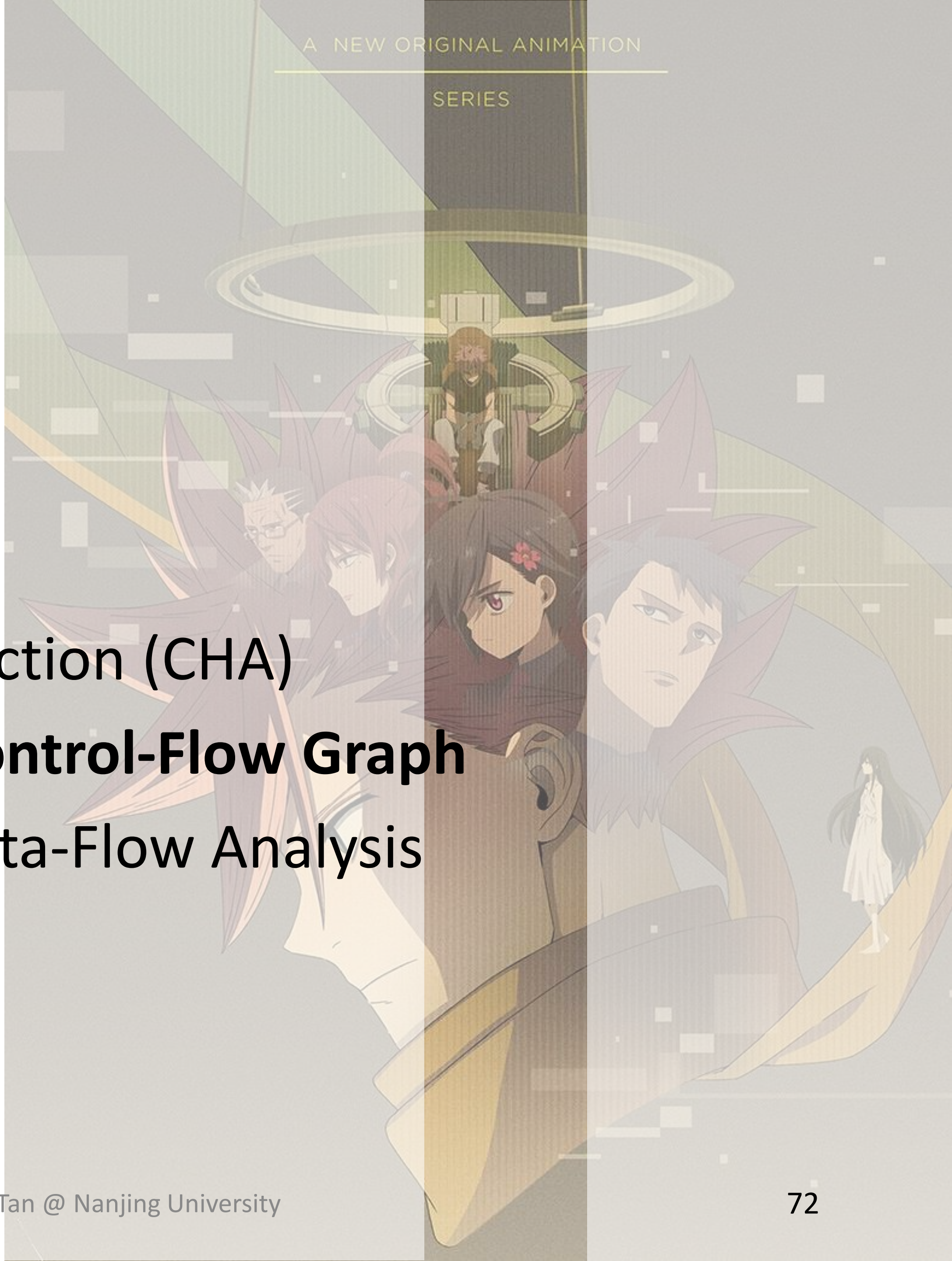


Contents



Interprocedural Control-Flow Graph

- CFG represents structure of an individual method
- ICFG represents structure of the whole program
  - With ICFG, we can perform interprocedural analysis

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- An ICFG of a program consists of CFGs of the methods in the program, plus two kinds of additional edges:
  - ➢ Call edges: from call sites to the entry nodes of their callees
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```
void foo() {
  bar(…);     // call site
  int n = 3; // return site
}
```

Interprocedural Control-Flow Graph

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ICFG = CFGs + call & return edges

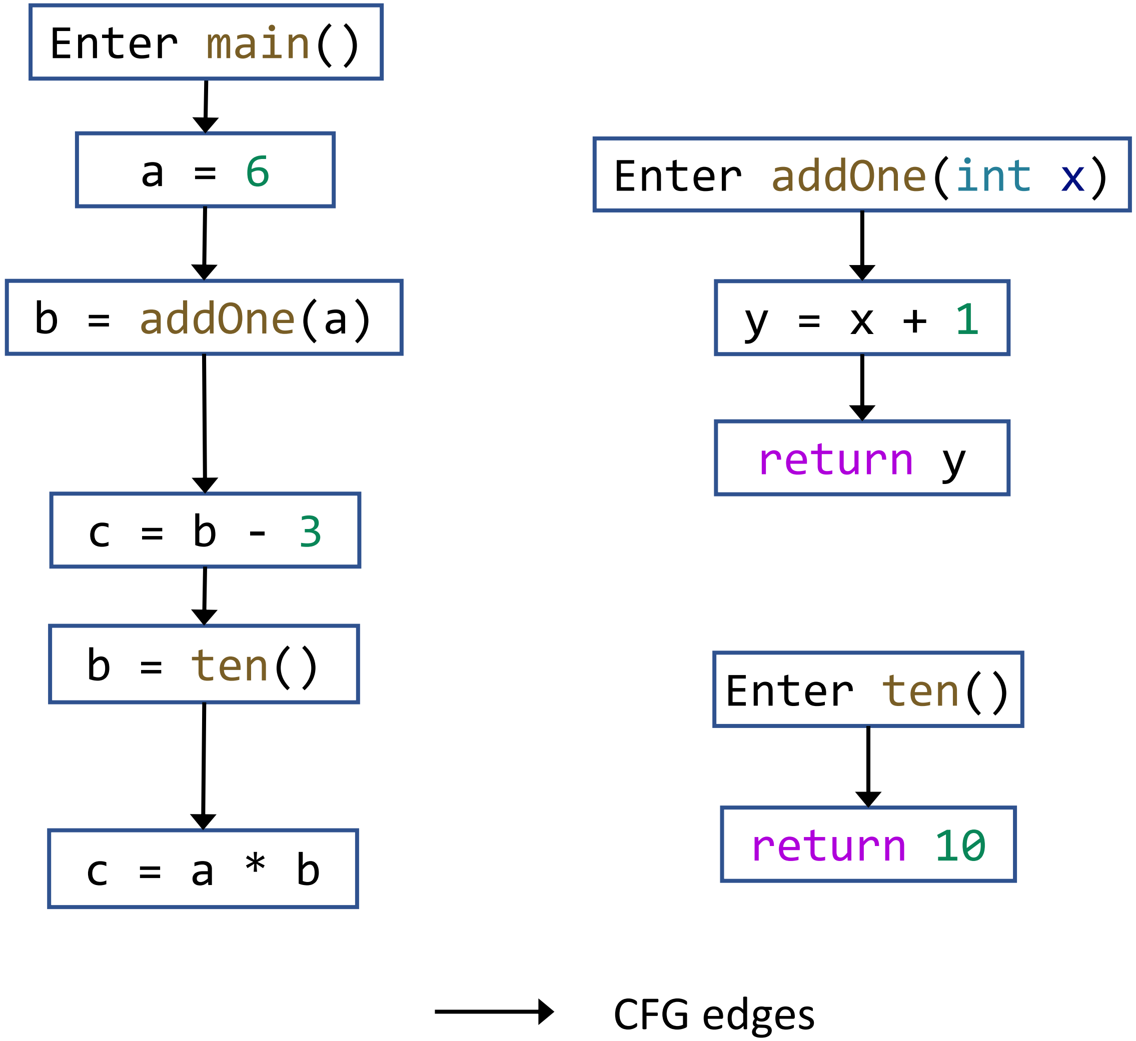
The information for connecting these two kinds of edges comes from call graph

ICFG: An Example

```
static void main() {
  int a, b, c;
  a = 6;
  b = addOne(a);
  c = b - 3;
  b = ten();
  c = a * b;
}

int addOne(int x) {
  int y = x + 1;
  return y;
}

int ten() {
  return 10;
}
```



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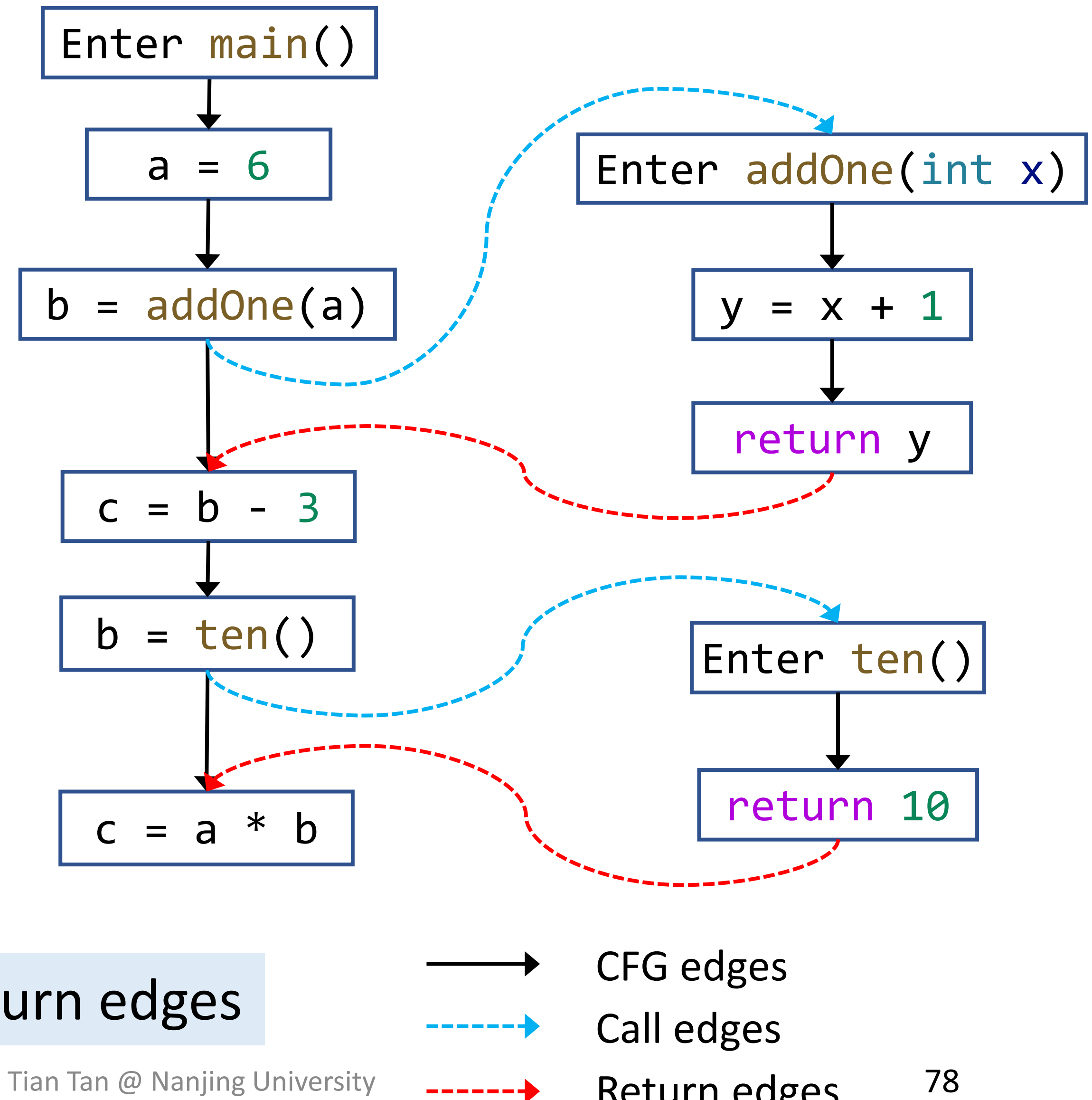

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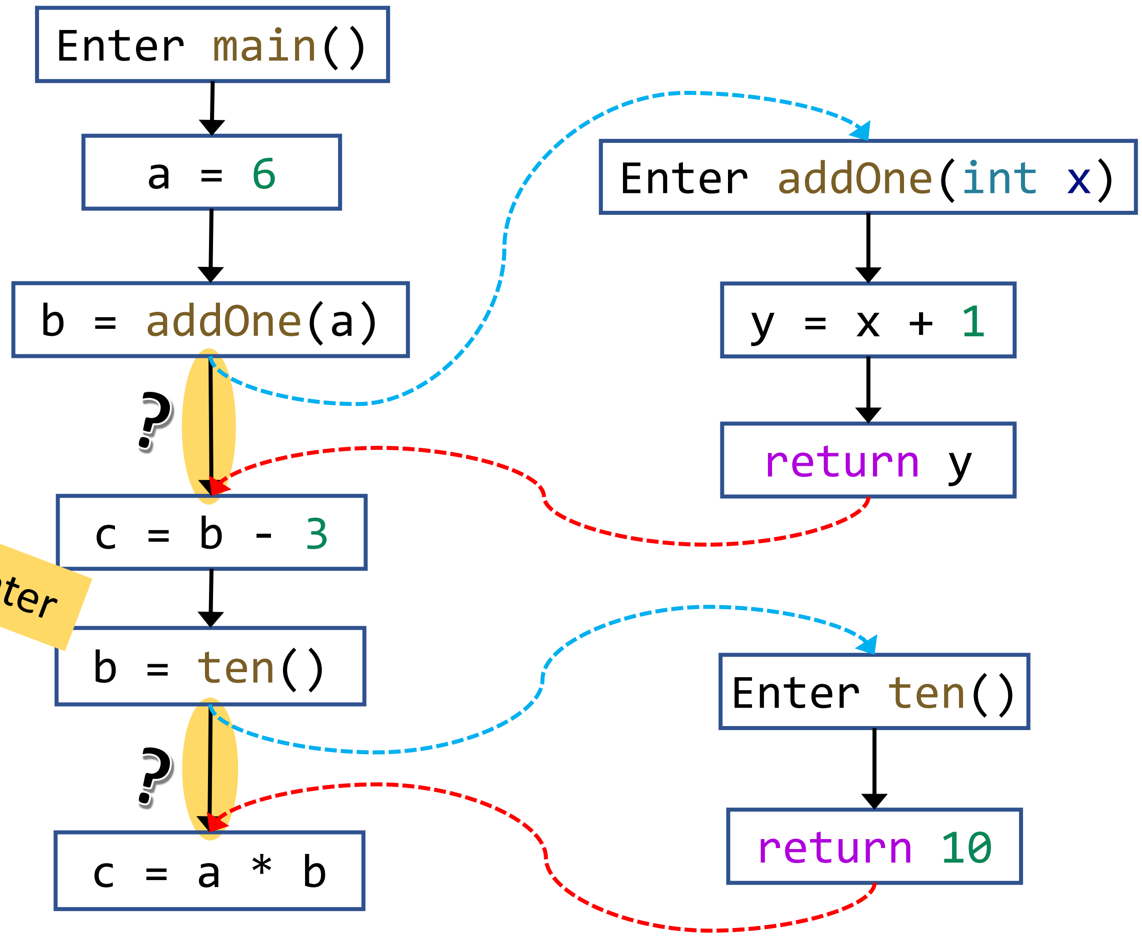
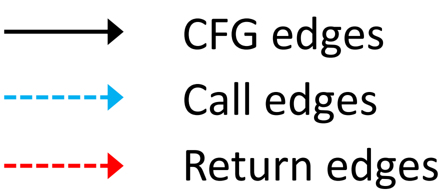
Will be explained later



ICFG = CFGs + call & return edges



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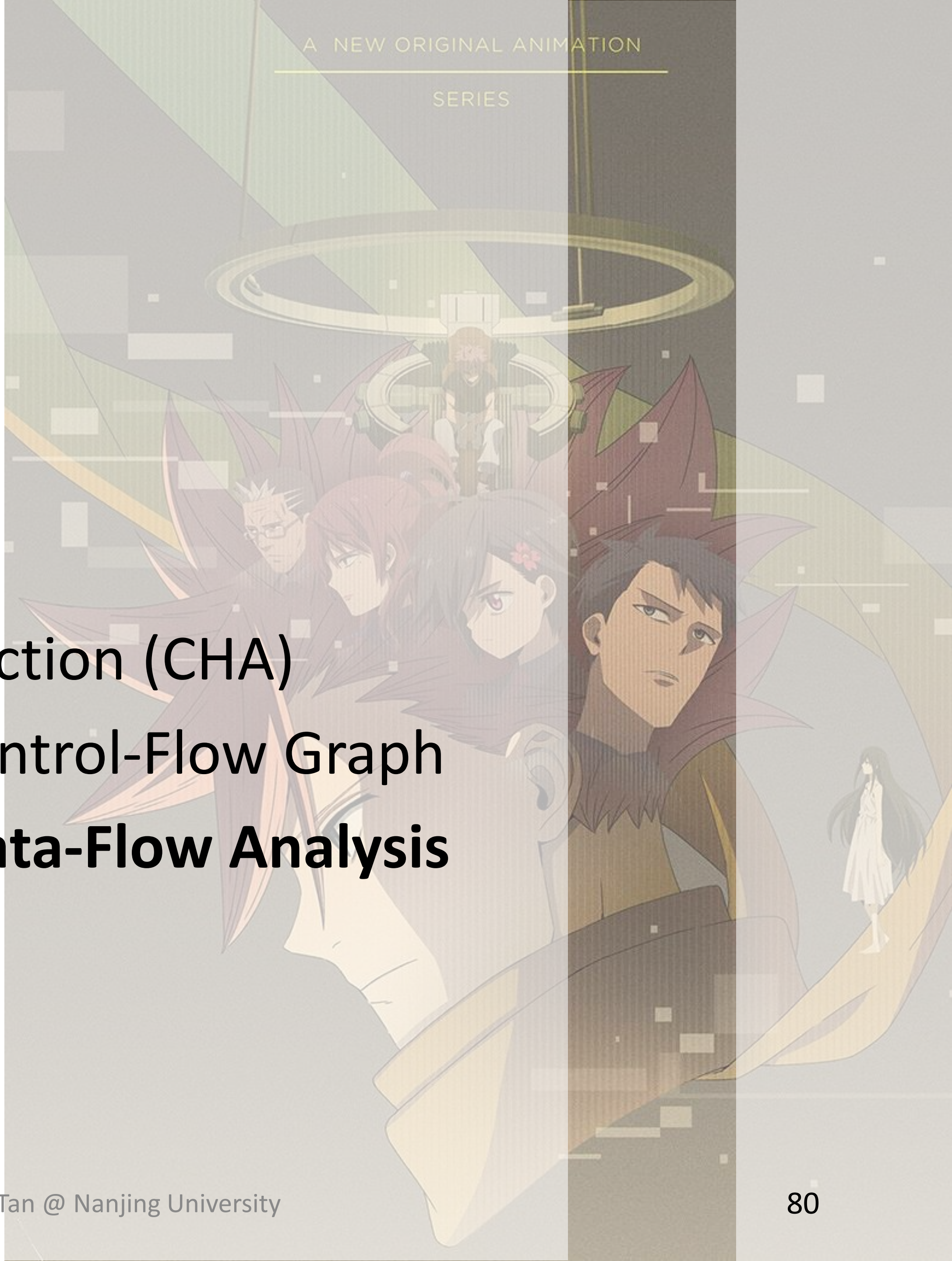

1. Motivation
2. Call Graph Construction (CHA)
3. Interprocedural Control-Flow Graph
4. **Interprocedural Data-Flow Analysis**

Interprocedural Data-Flow Analysis

Analyzing the whole program with method calls based on interprocedural control-flow graph (ICFG)

	*Intra*procedural	*Inter*procecdural
Program representation	CFG	ICFG = CFGs + call & return edges

Interprocedural Data-Flow Analysis

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Transfer functions	Node transfer	Node transfer + edge transfer

Interprocedural Data-Flow Analysis

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	*Intra*procedural	*Inter*procecdural
Program representation	CFG	ICFG = CFGs + call & return edges
Transfer functions	Node transfer	Node transfer + edge transfer

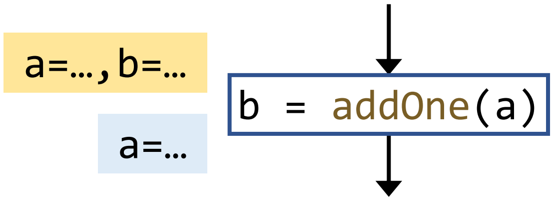
Edge transfer

- Call edge transfer: transfer data flow from call node to the entry node of callee (along call edges)
- Return edge transfer: transfer data flow from return node of the callee to the return site (along return edges)

Interprocedural Constant Propagation

- Call edge transfer: pass argument values
- Return edge transfer: pass return values

- Node transfer: same as intra-procedural constant propagation, plus that
  - For each call node, kill data-flow value for the LHS variable. Its value will flow to return site along the return edges



Interprocedural Constant Propagation: An Example

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static void main() {
  int a, b, c;
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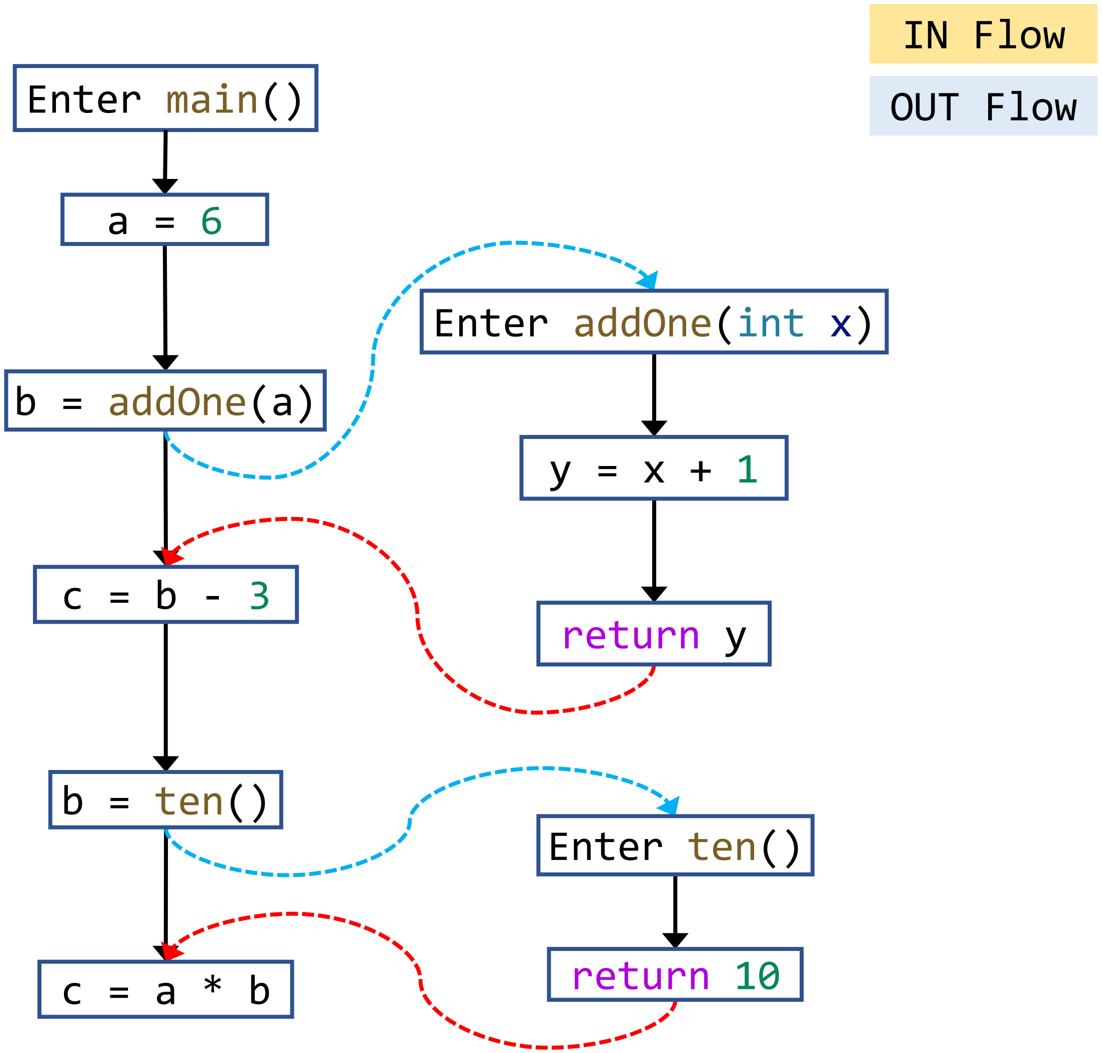

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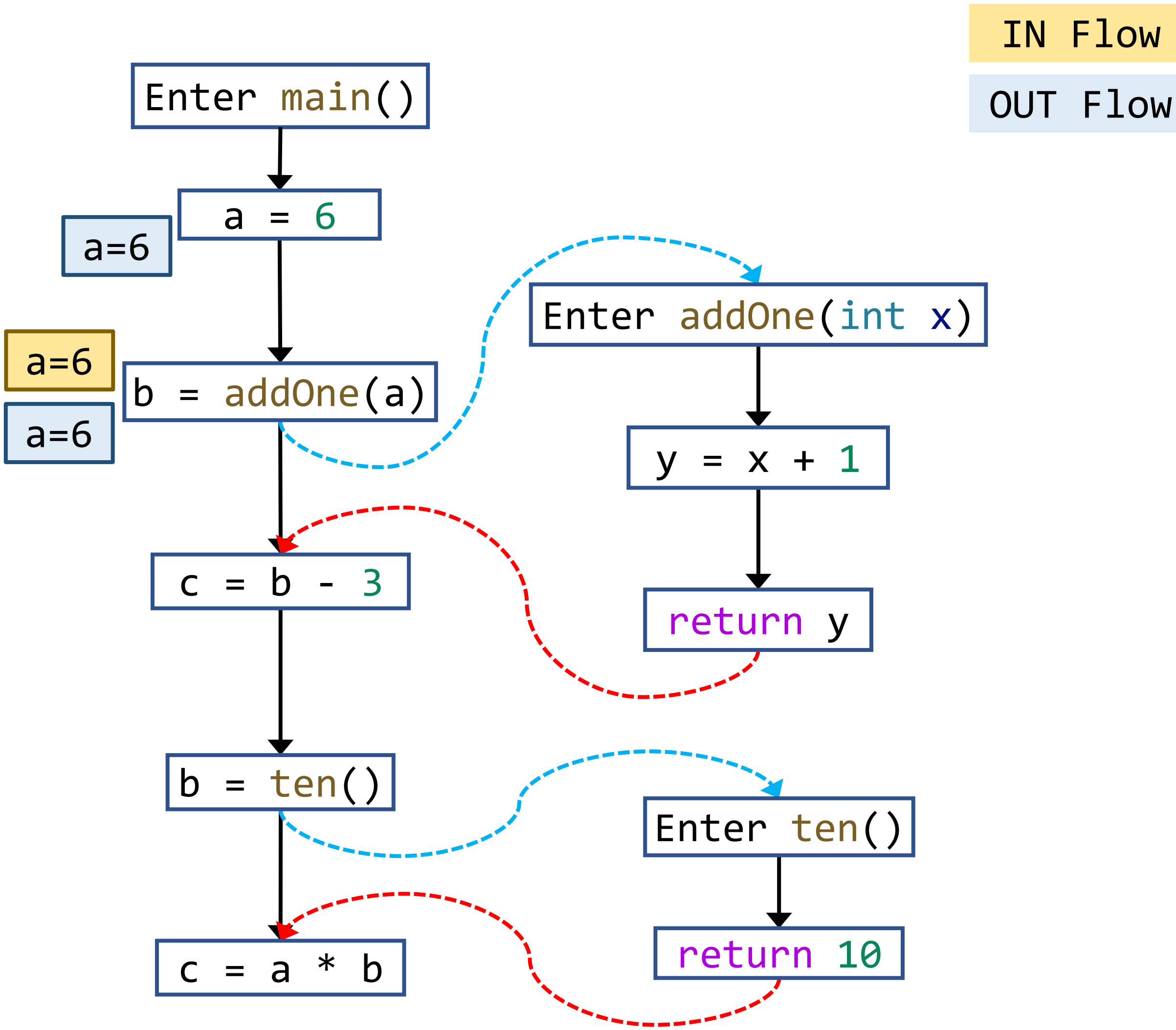

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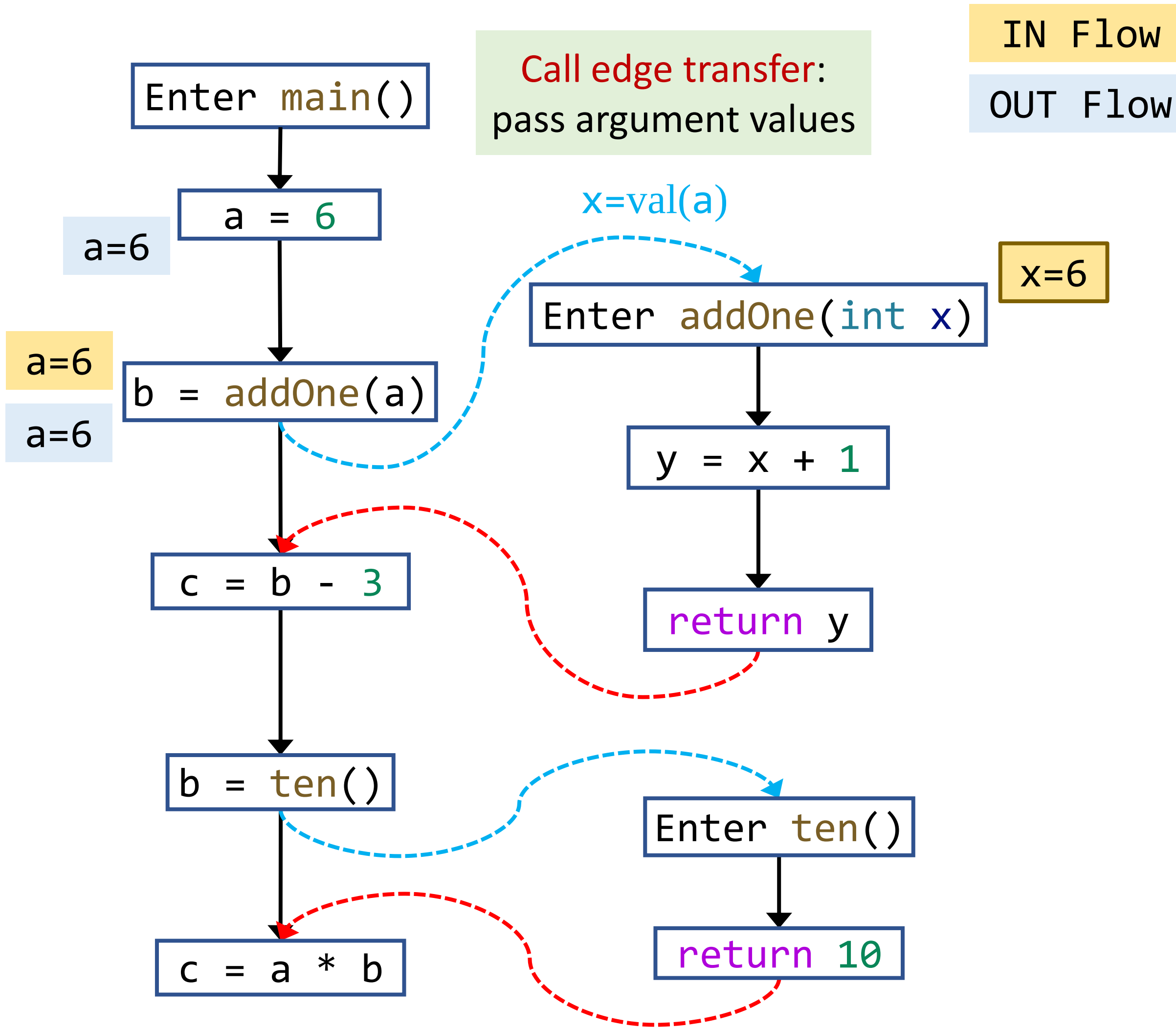

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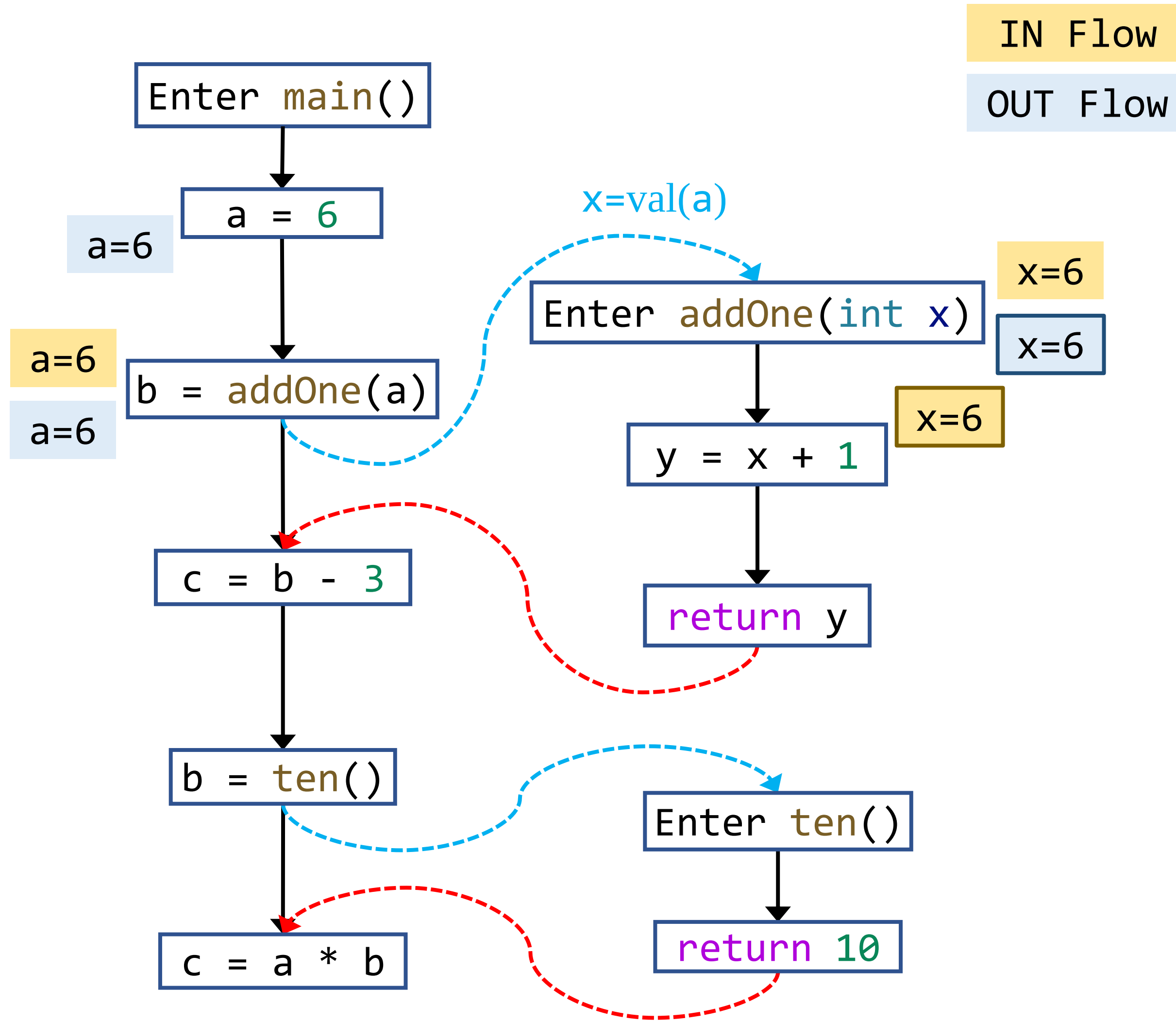

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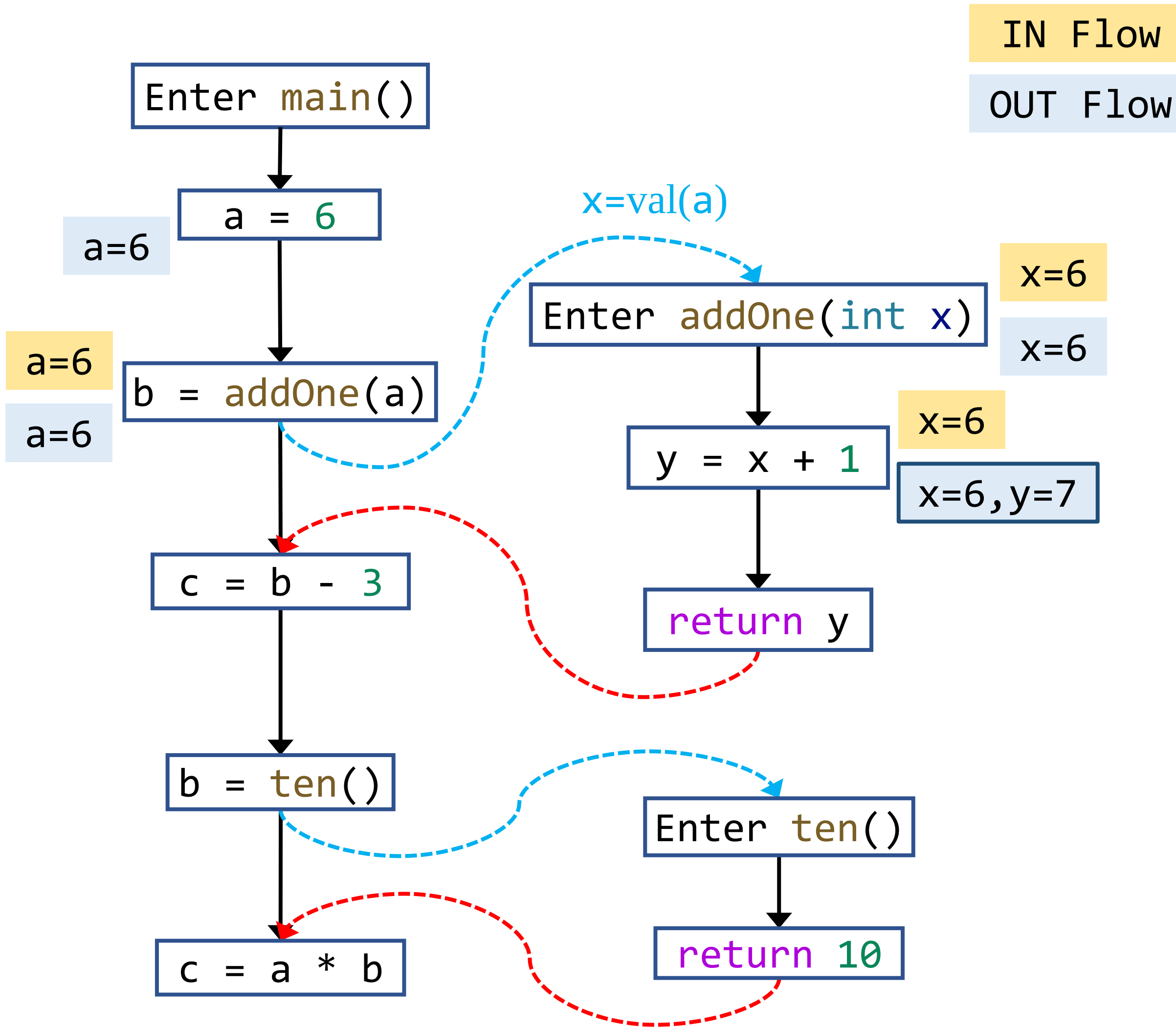

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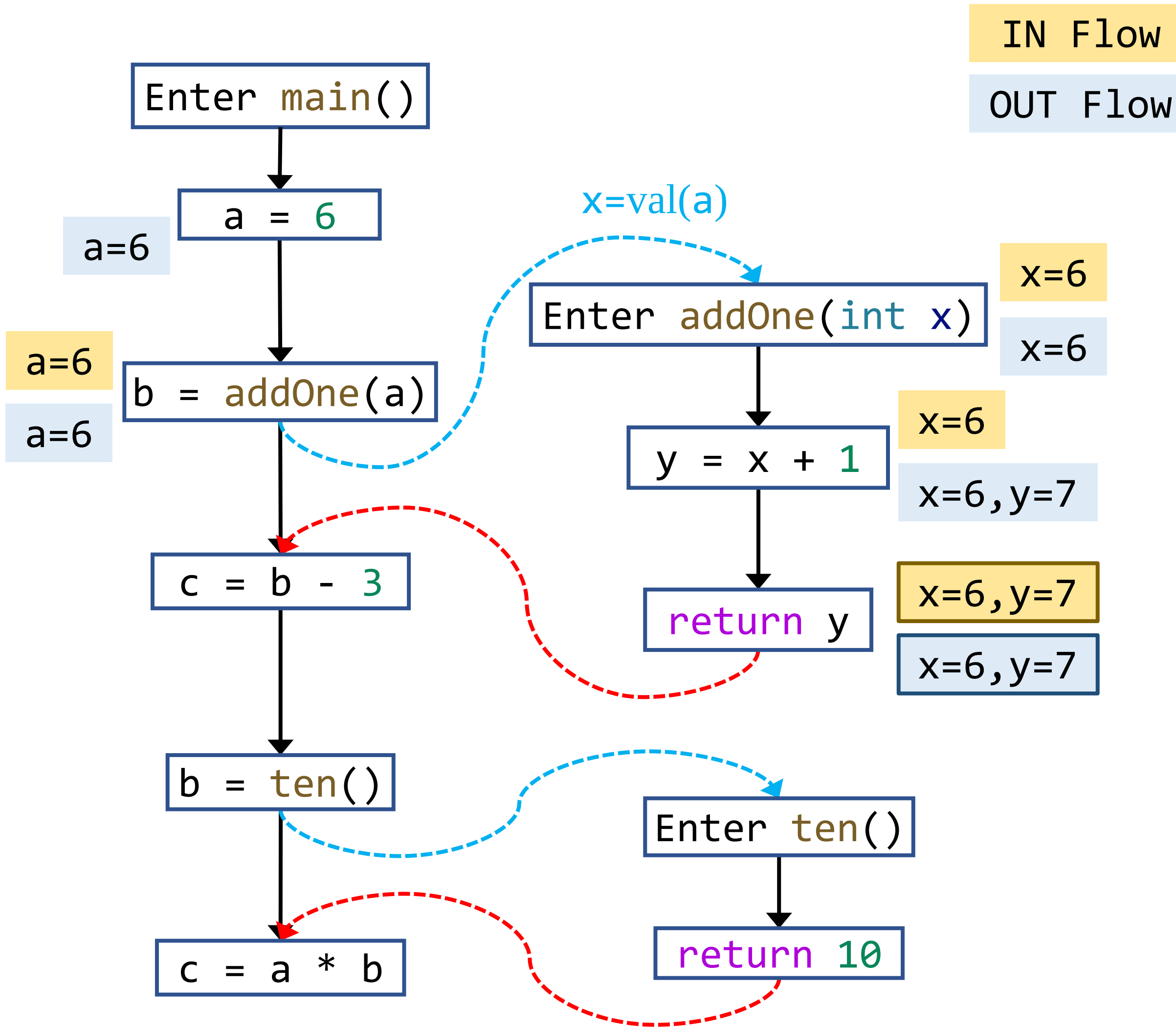

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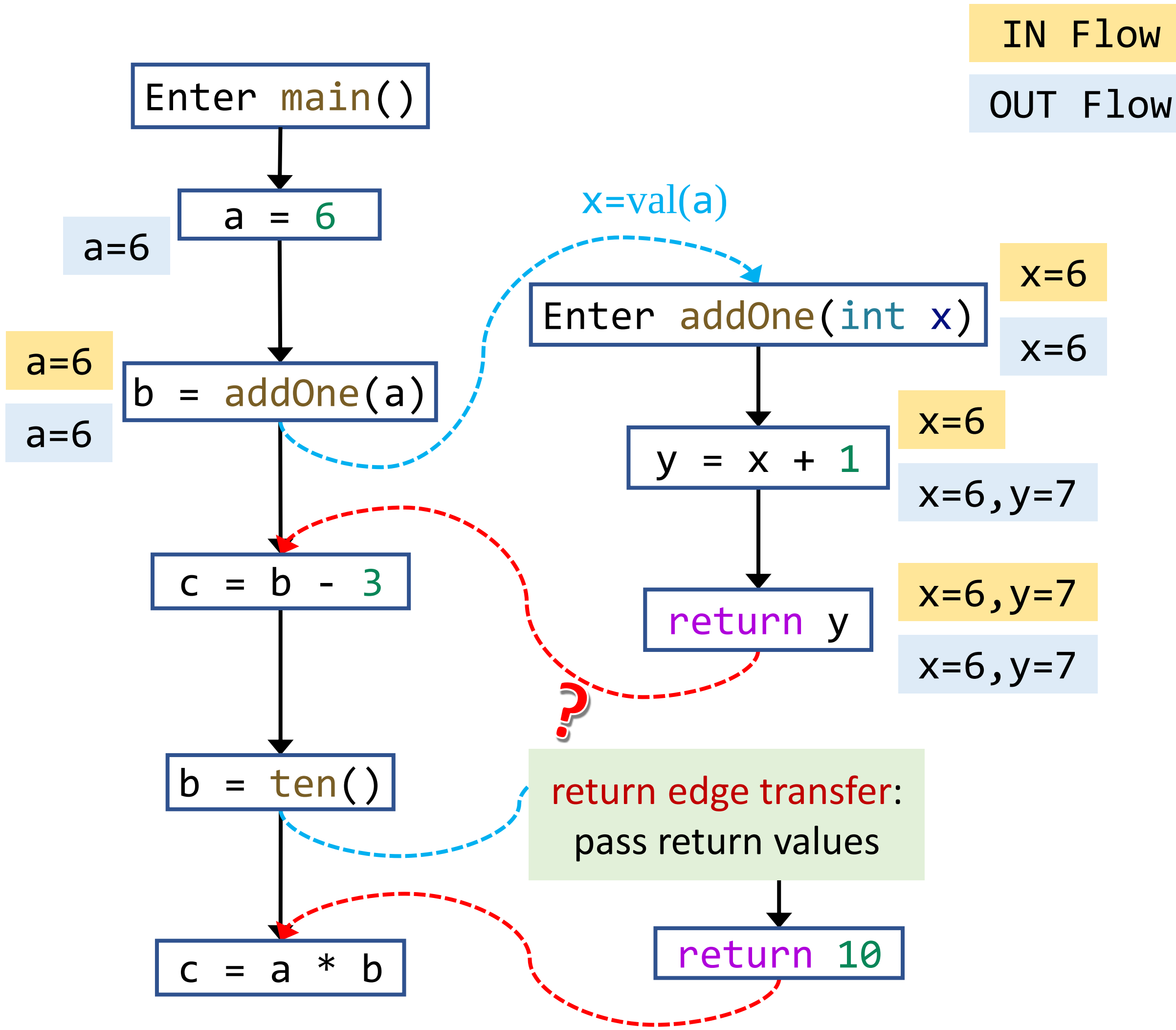

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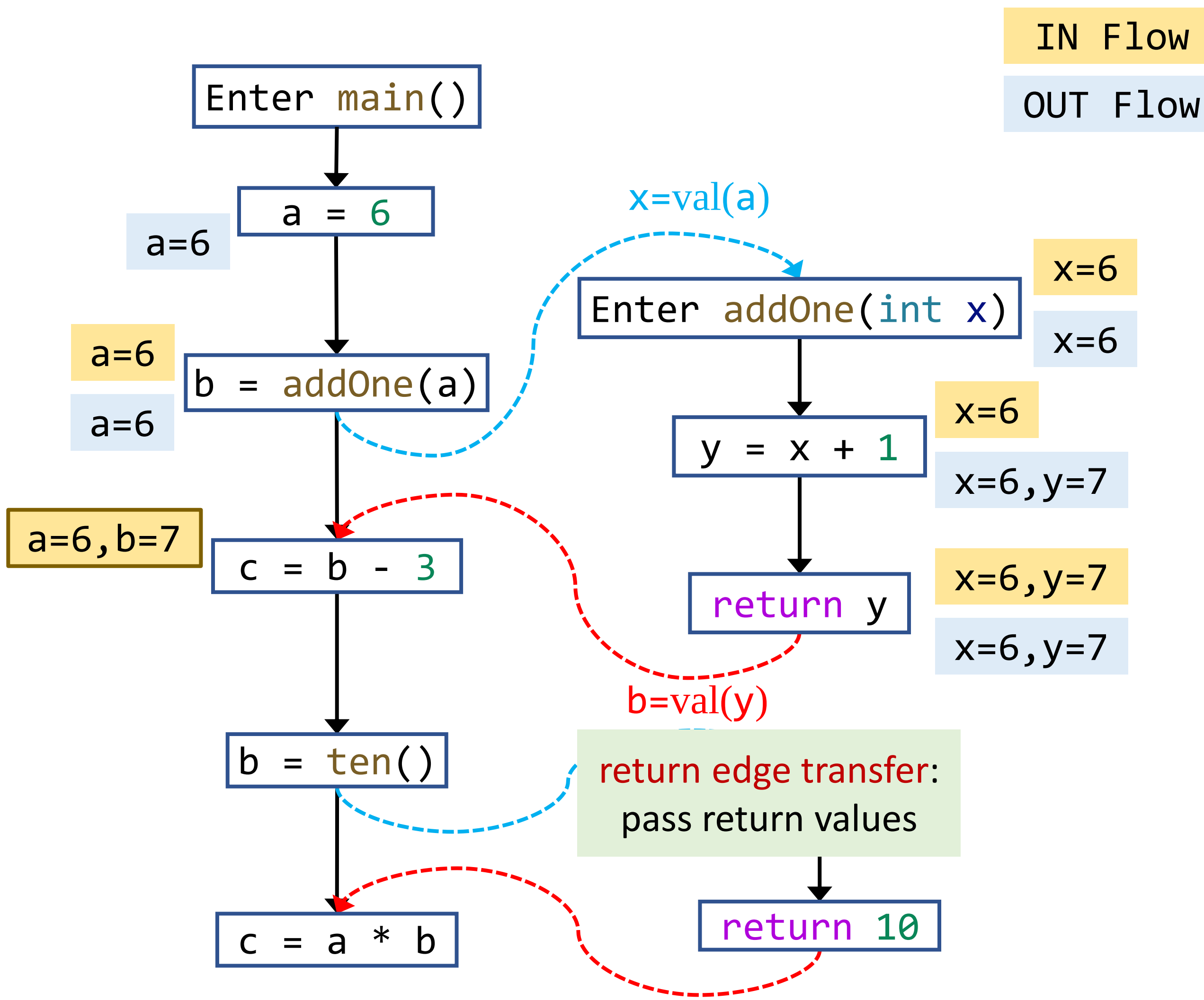

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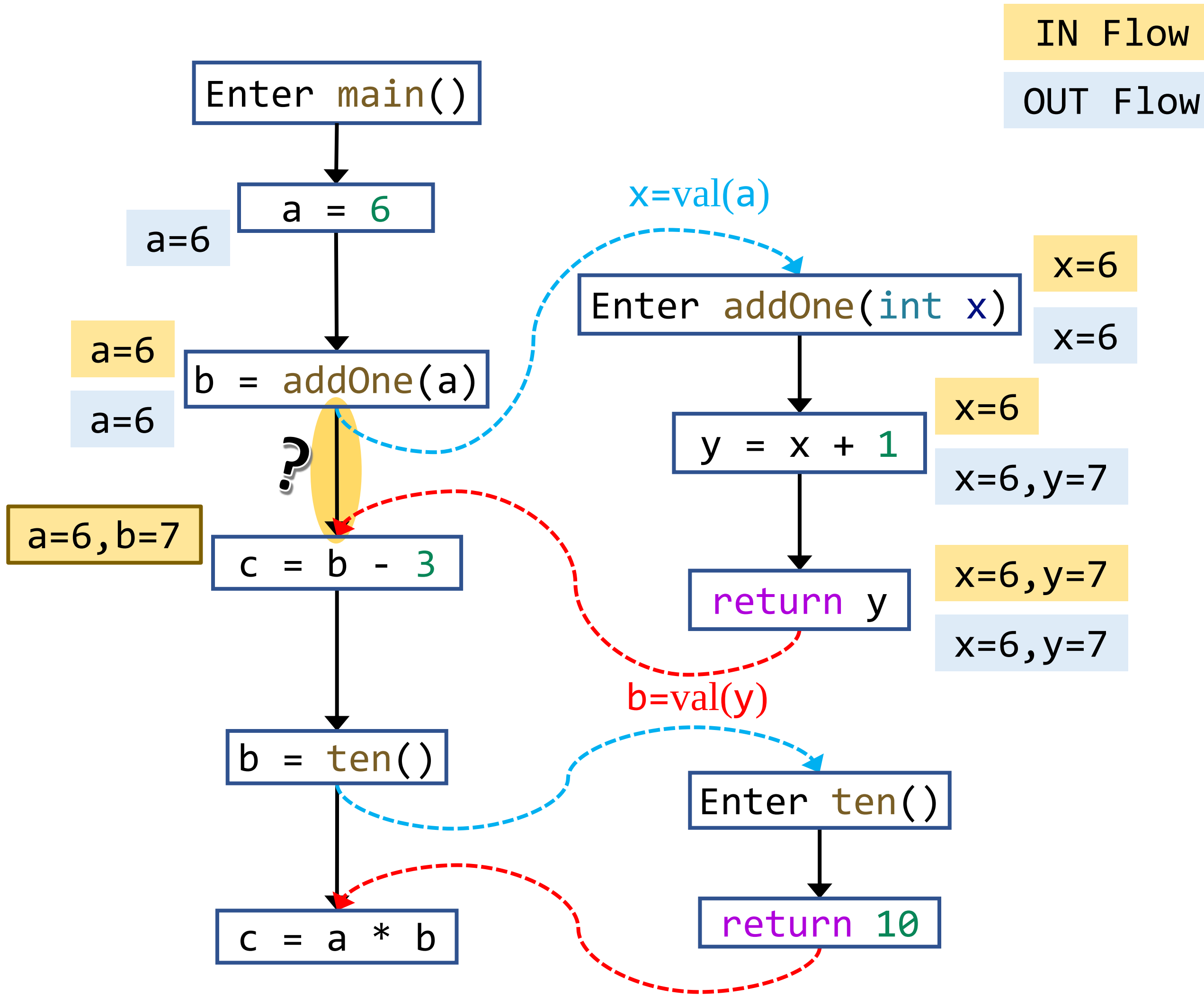

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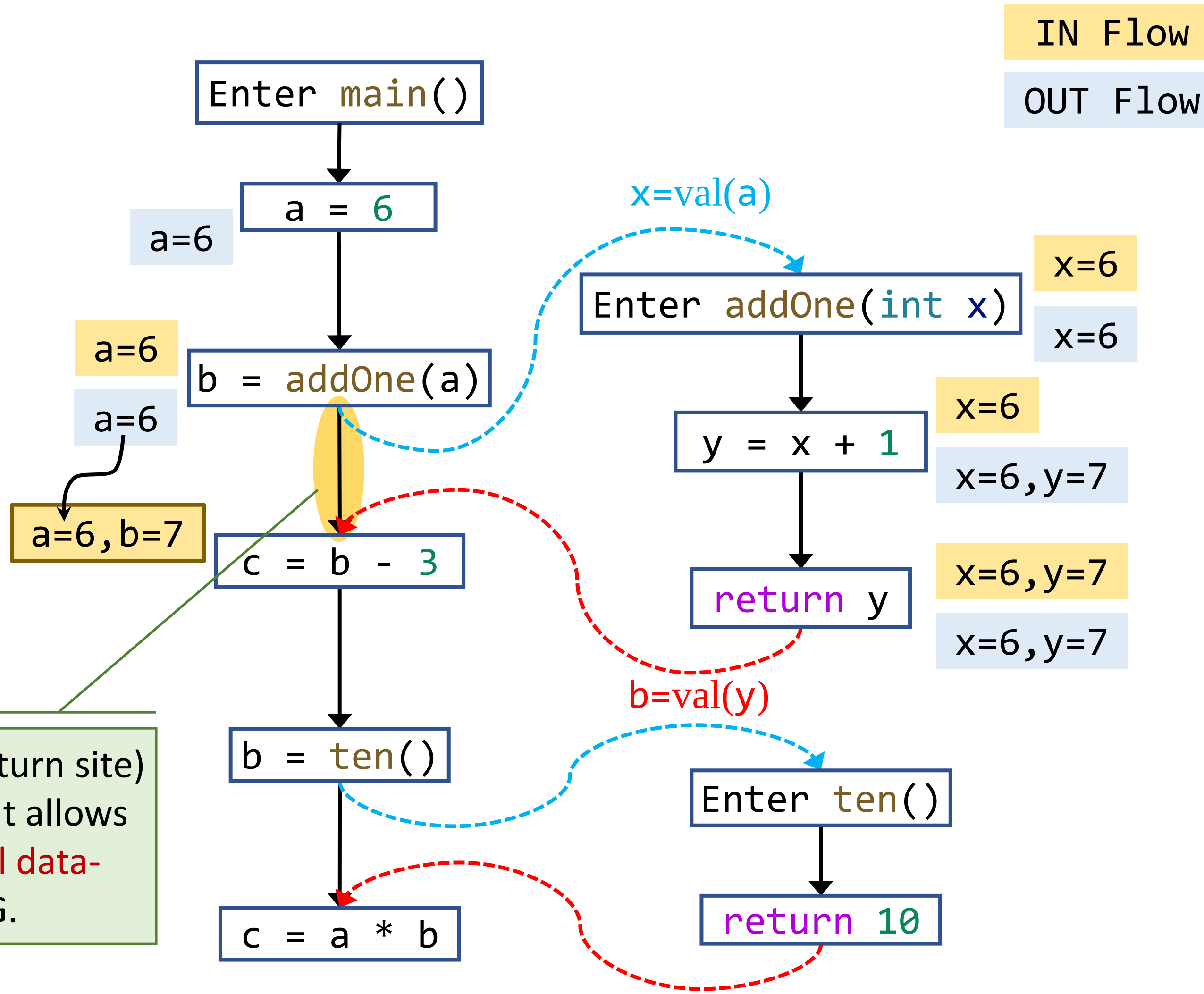

Such edge (from call site to return site) is named *call-to-return edge*. It allows the analysis to propagate local data-flow (a=6 in this case) on ICFG.

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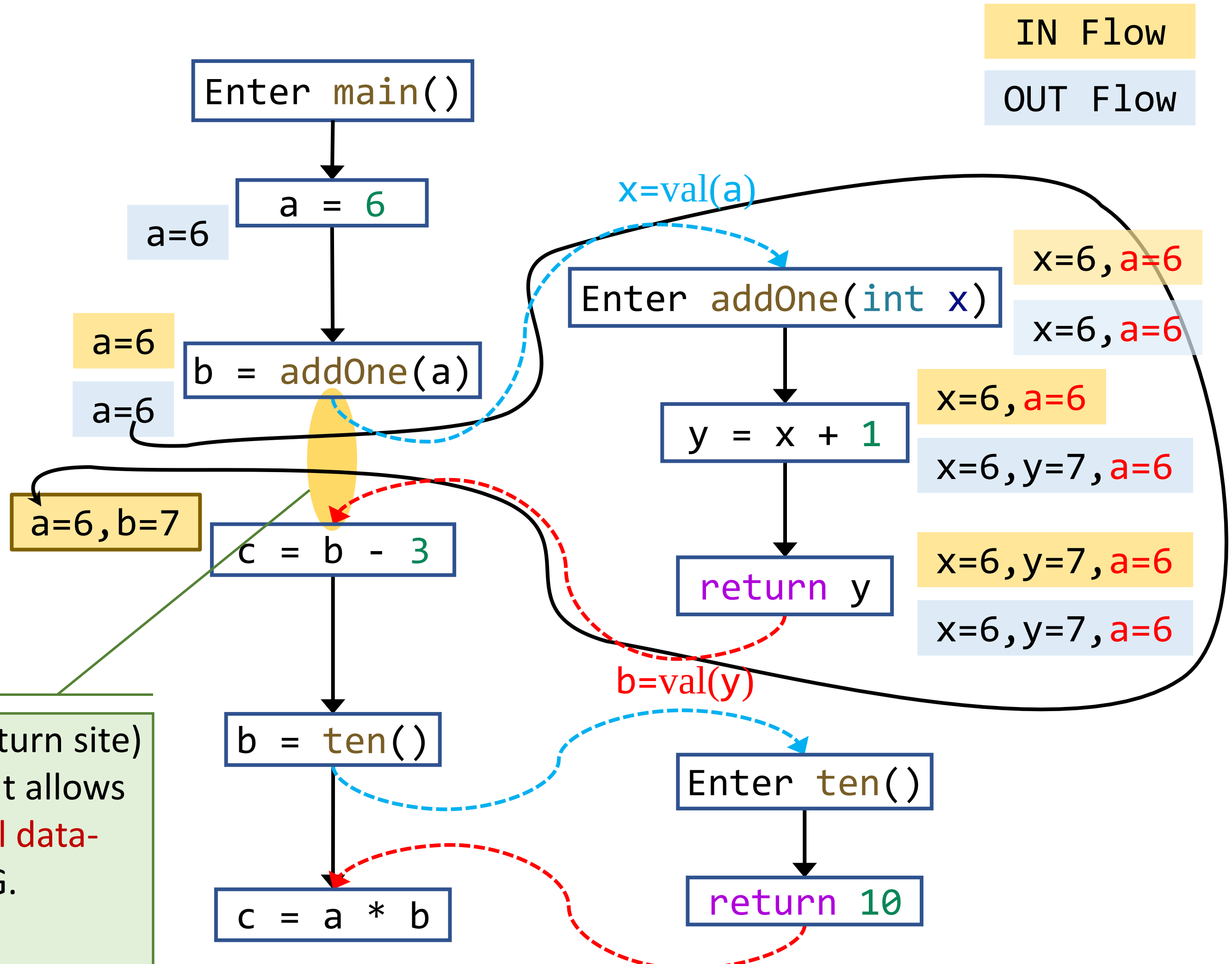

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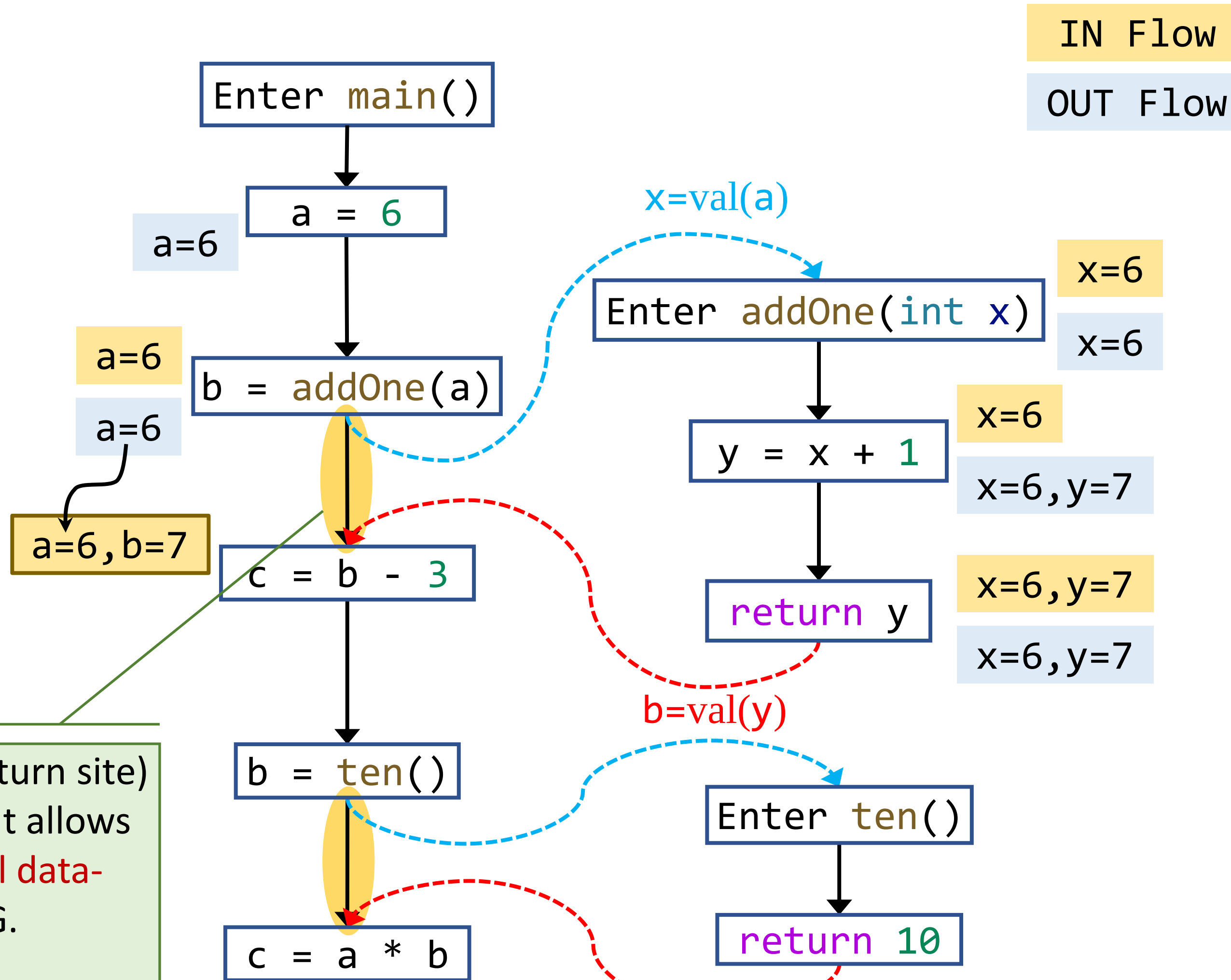

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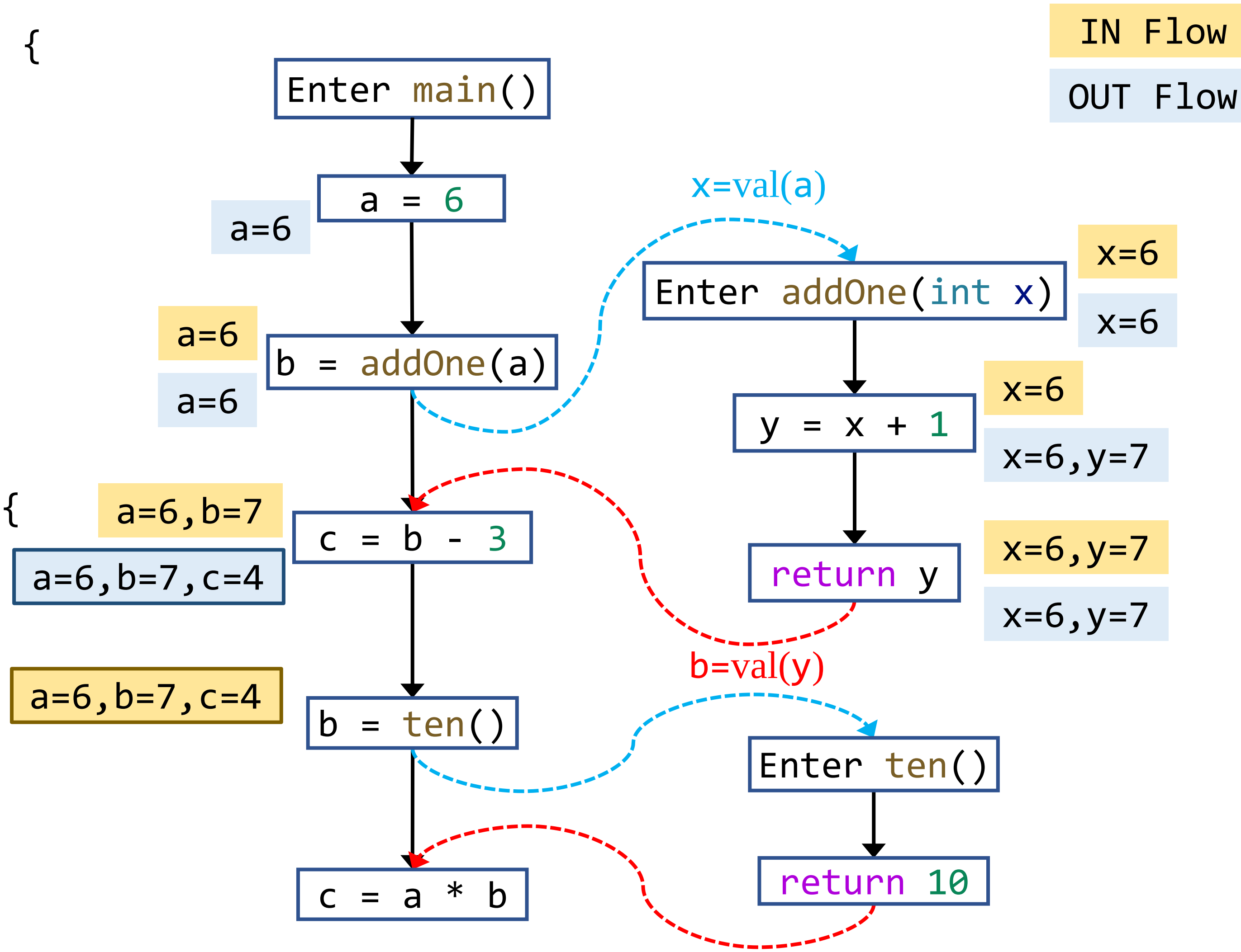

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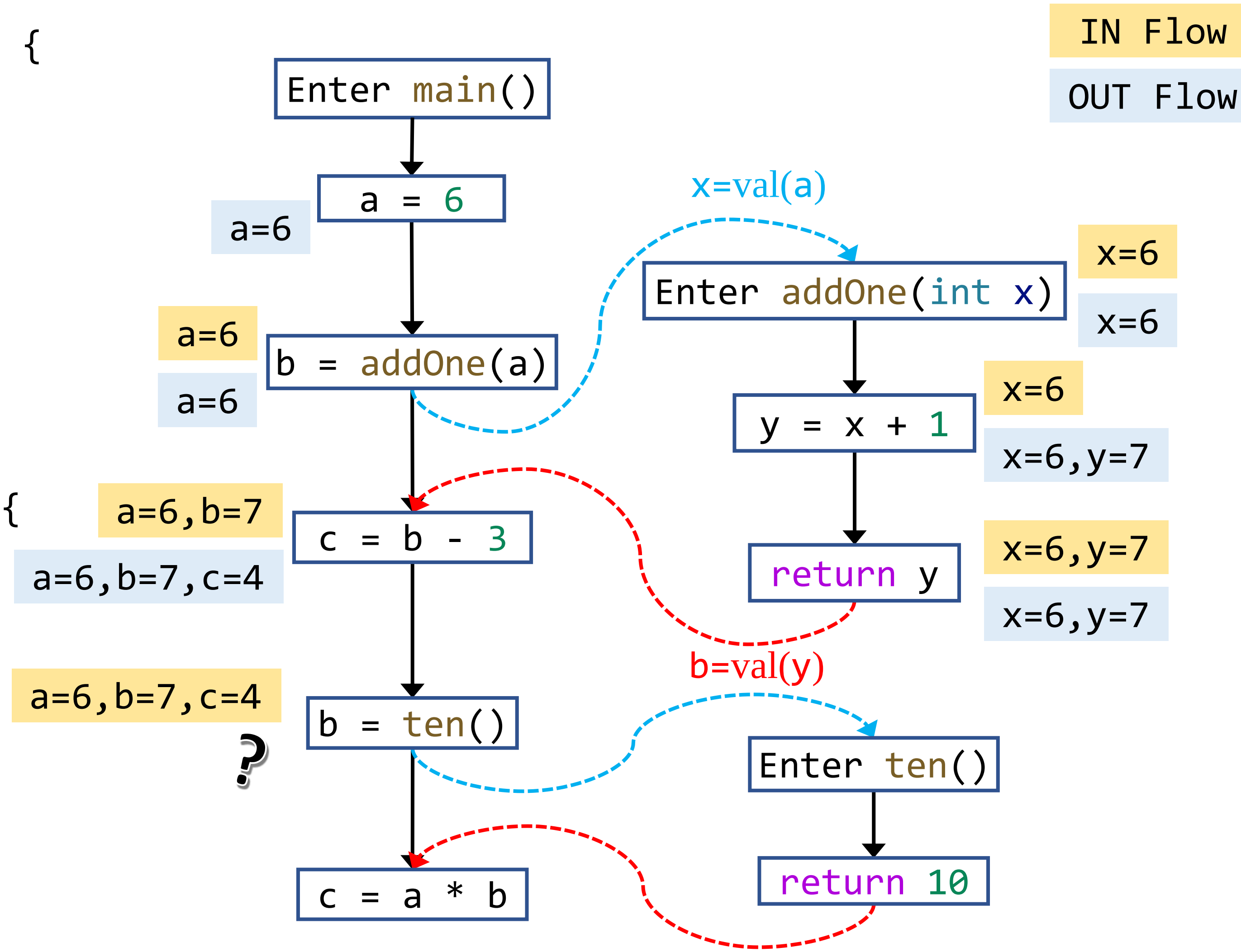

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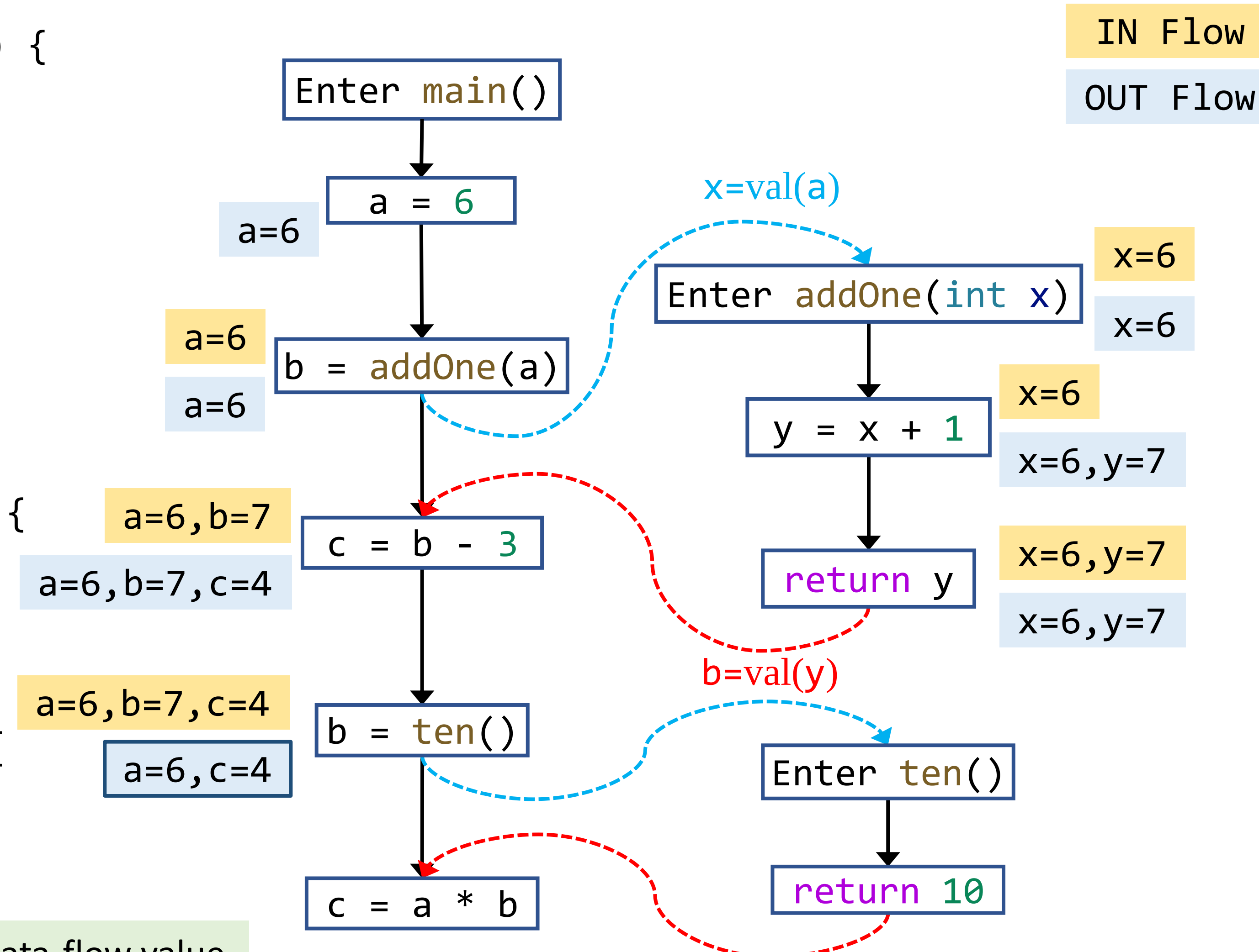

For each call node, kill data-flow value of the LHS variable. Its value will flow. to return site along the return edges.

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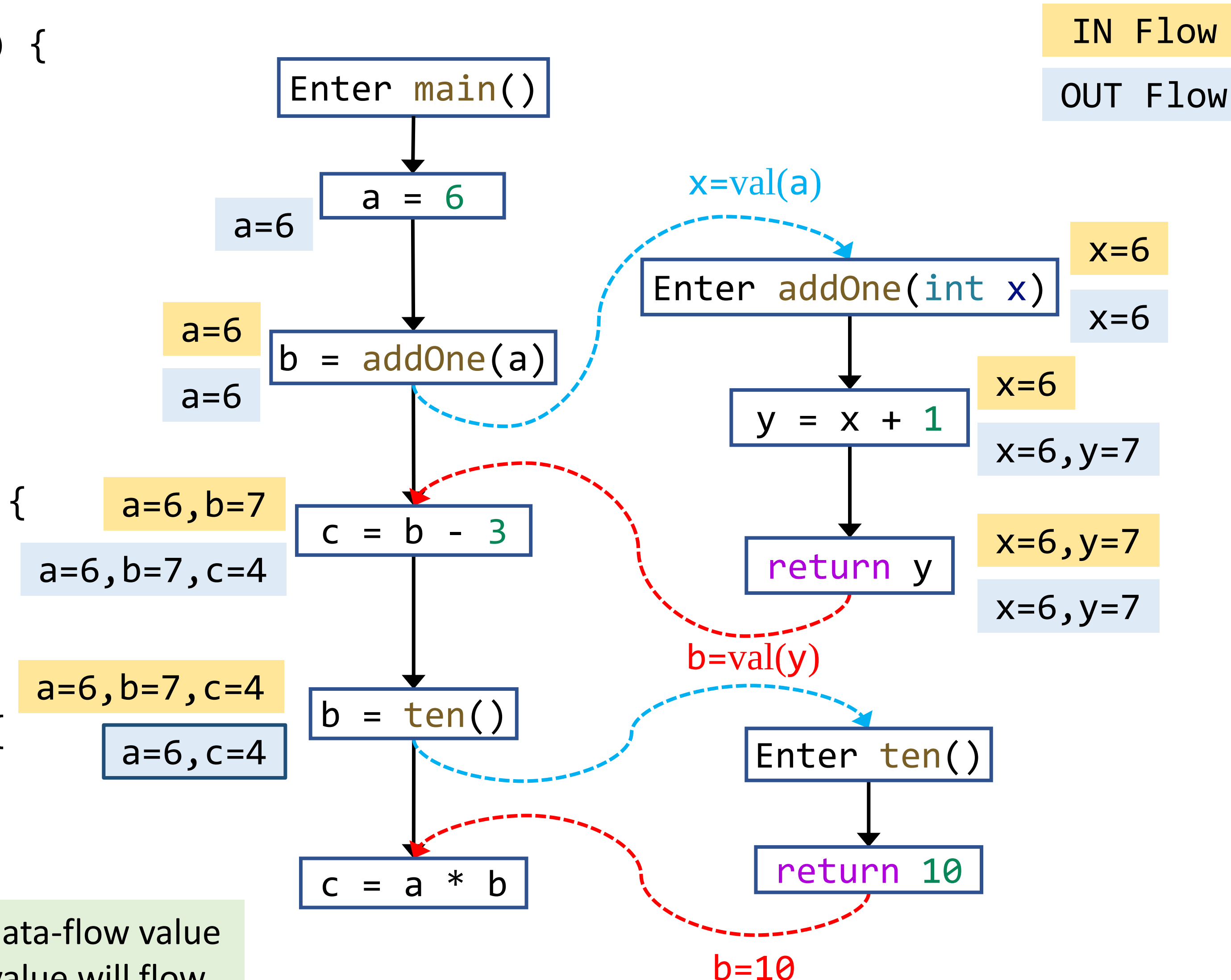

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Return edge transfer: pass return values

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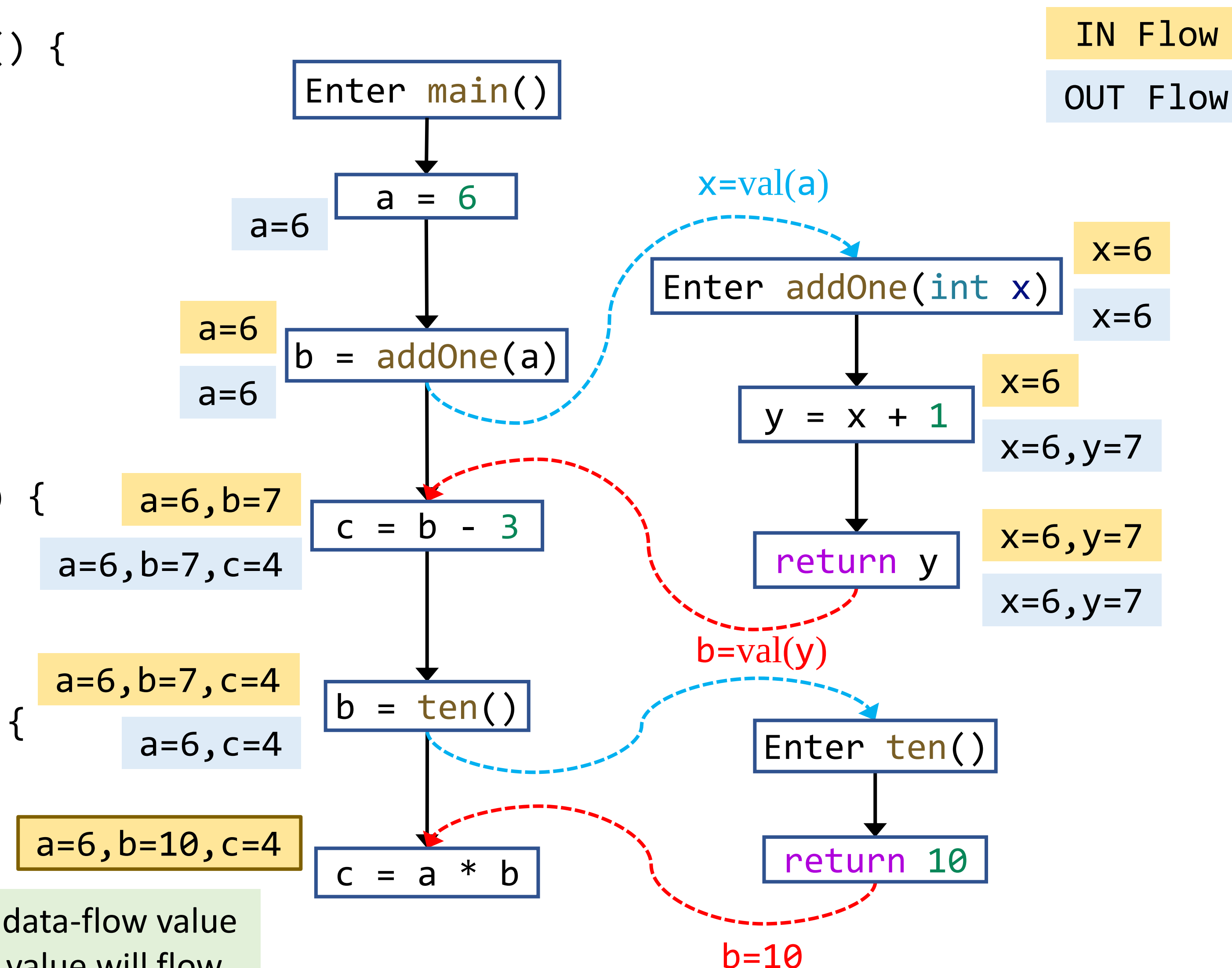

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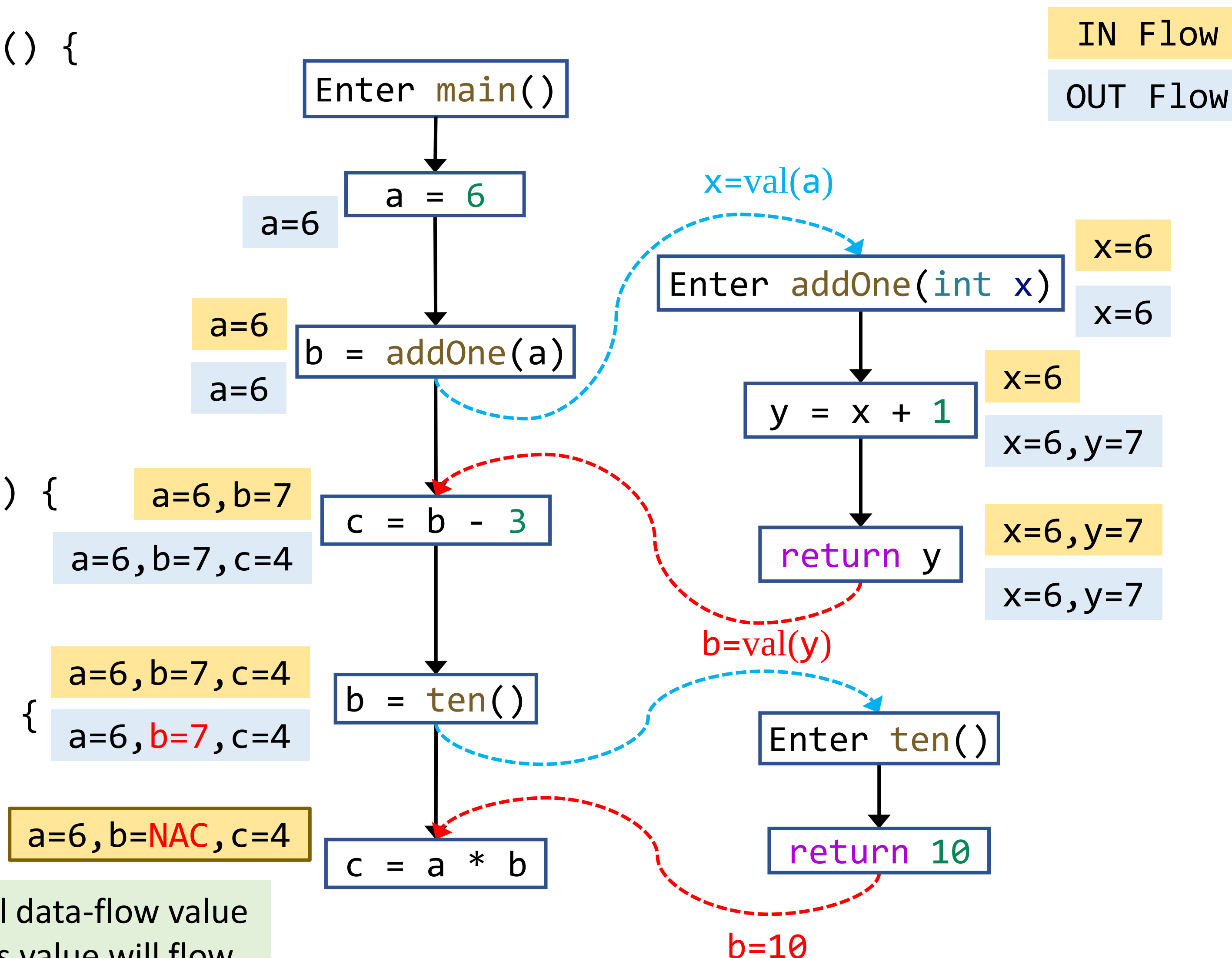

For each call node, kill data-flow value of the LHS variable. Its value will flow. to return site along the return edges. **Otherwise, it may cause imprecision.**

Return edge transfer: pass return values

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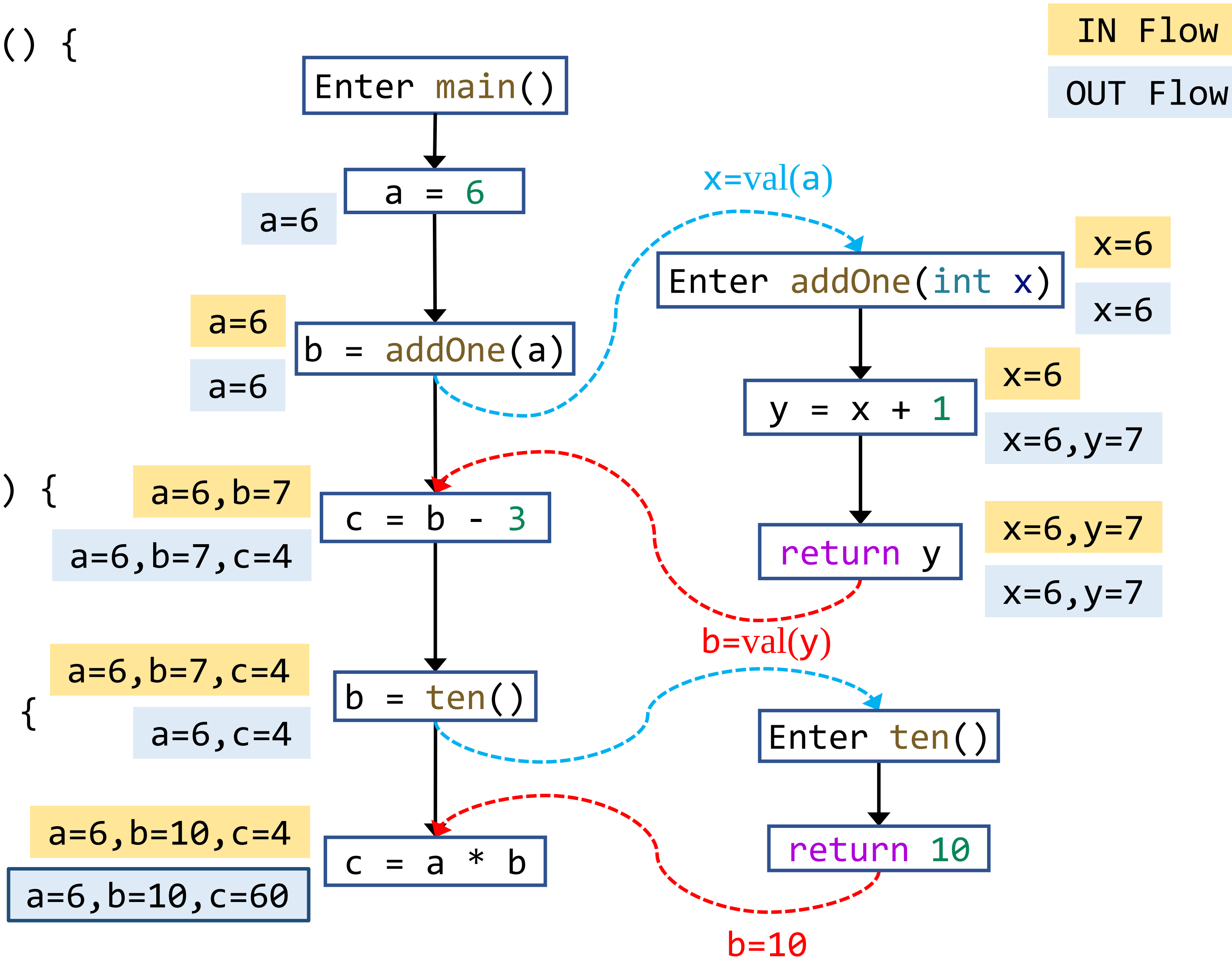

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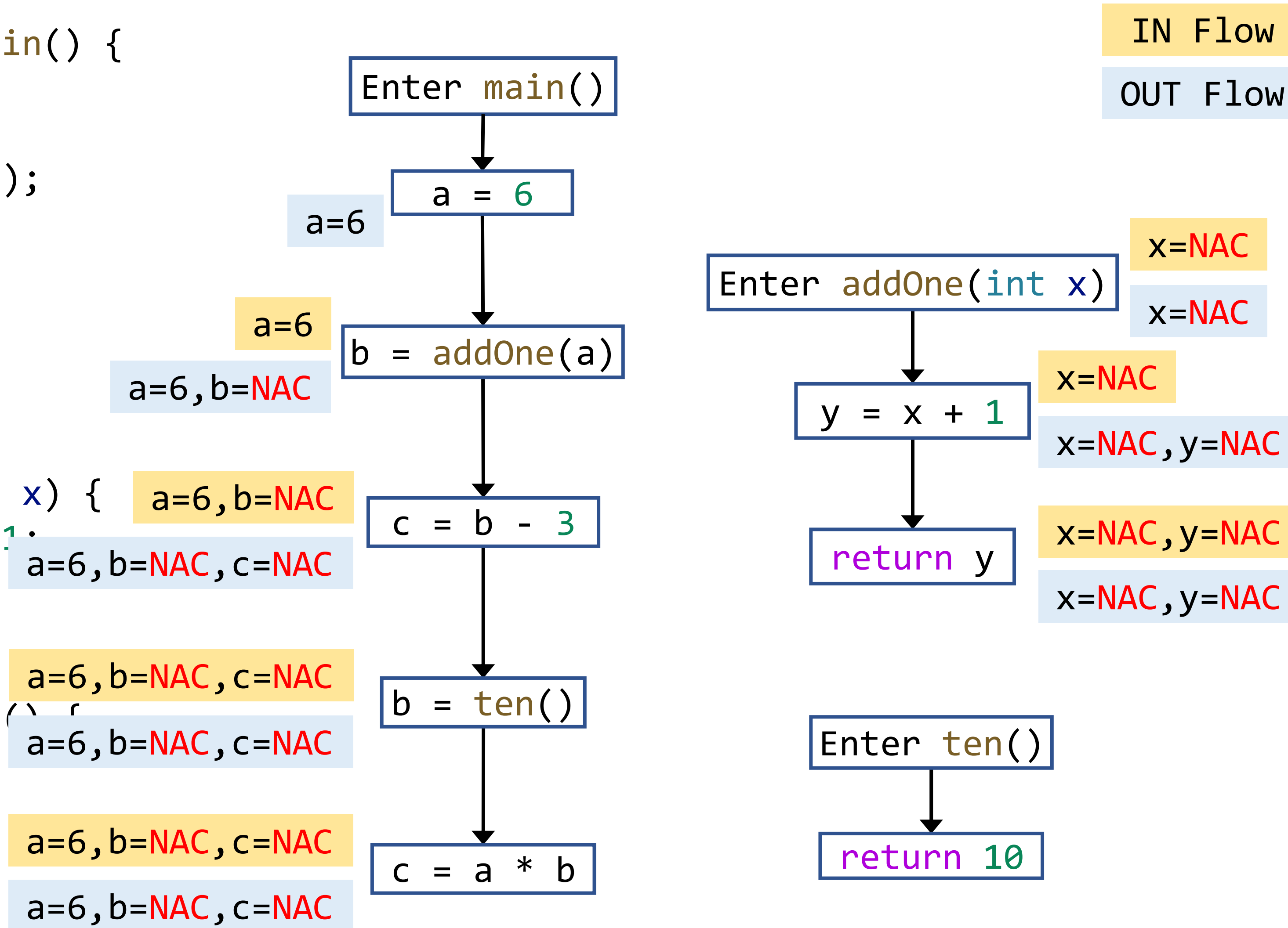

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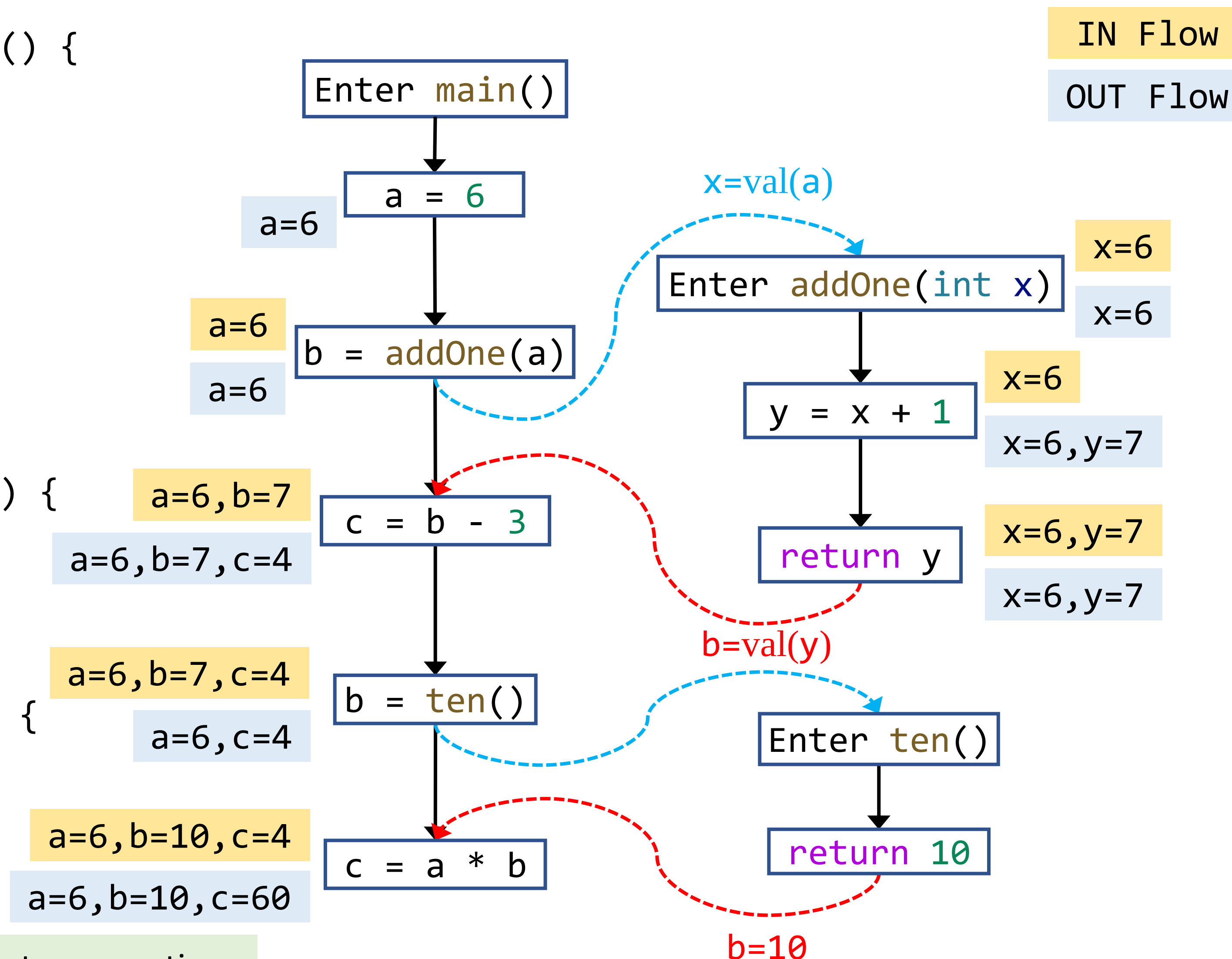

Interprocedural constant propagation
is more precise than
Intraprocedural constant propagation

The X You Need To Understand in This Lecture

- How to build call graph via class hierarchy analysis
- Concept of interprocedural control-flow graph
- Concept of interprocedural data-flow analysis
- Interprocedural constant propagation