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

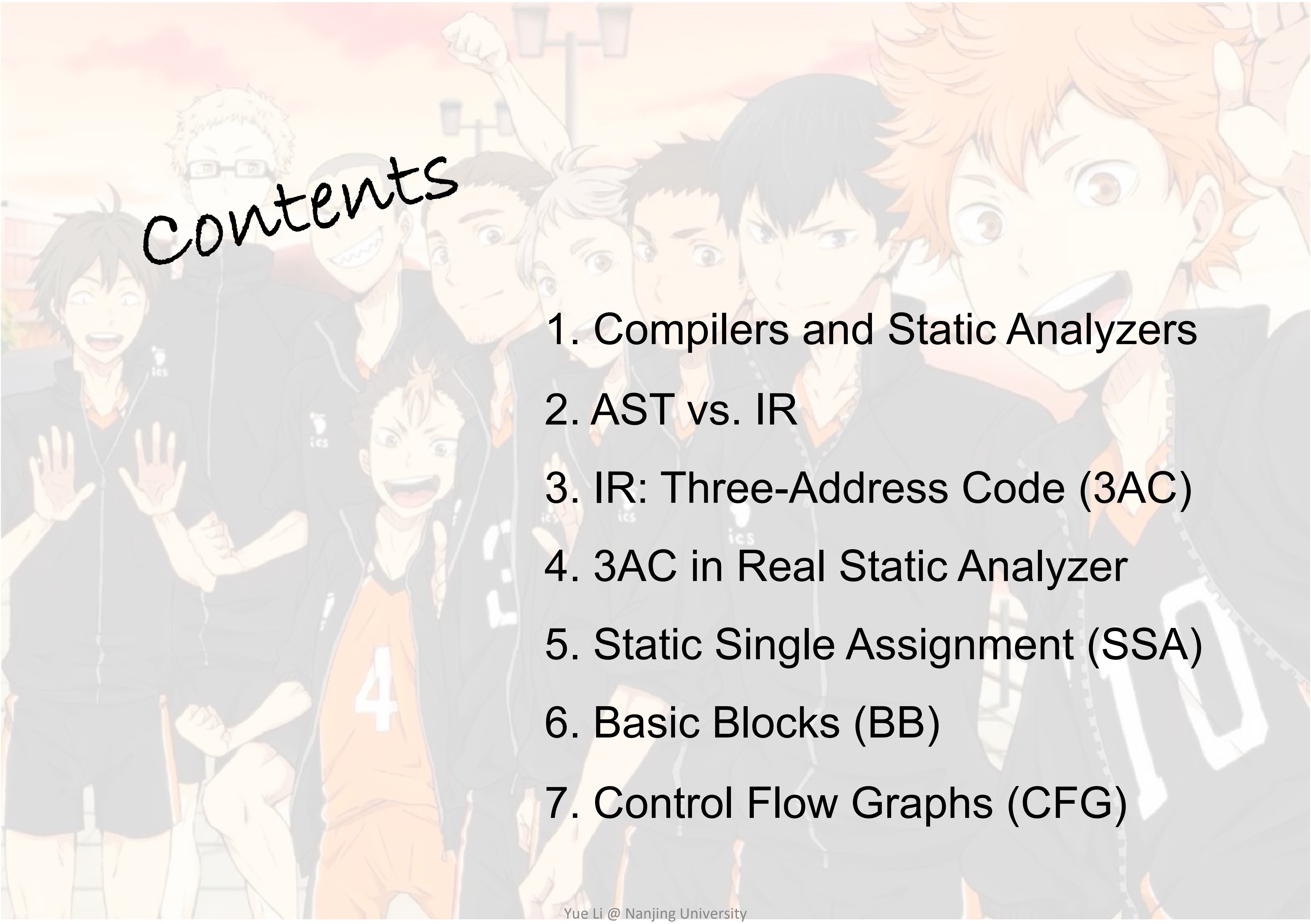
Static Program Analysis

Intermediate Representation

Nanjing University

Yue Li

Fall 2022



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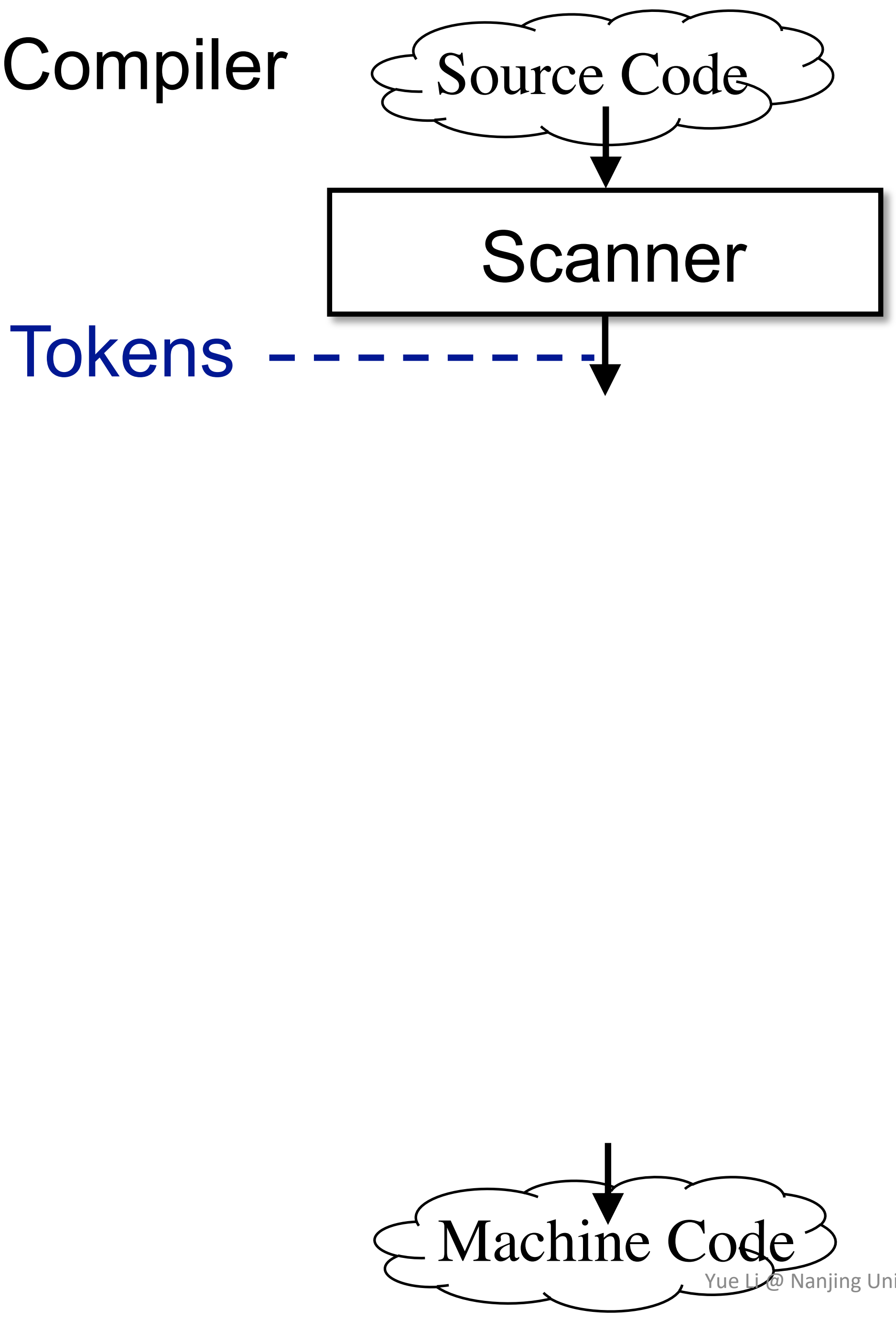
Machine Code

Compiler

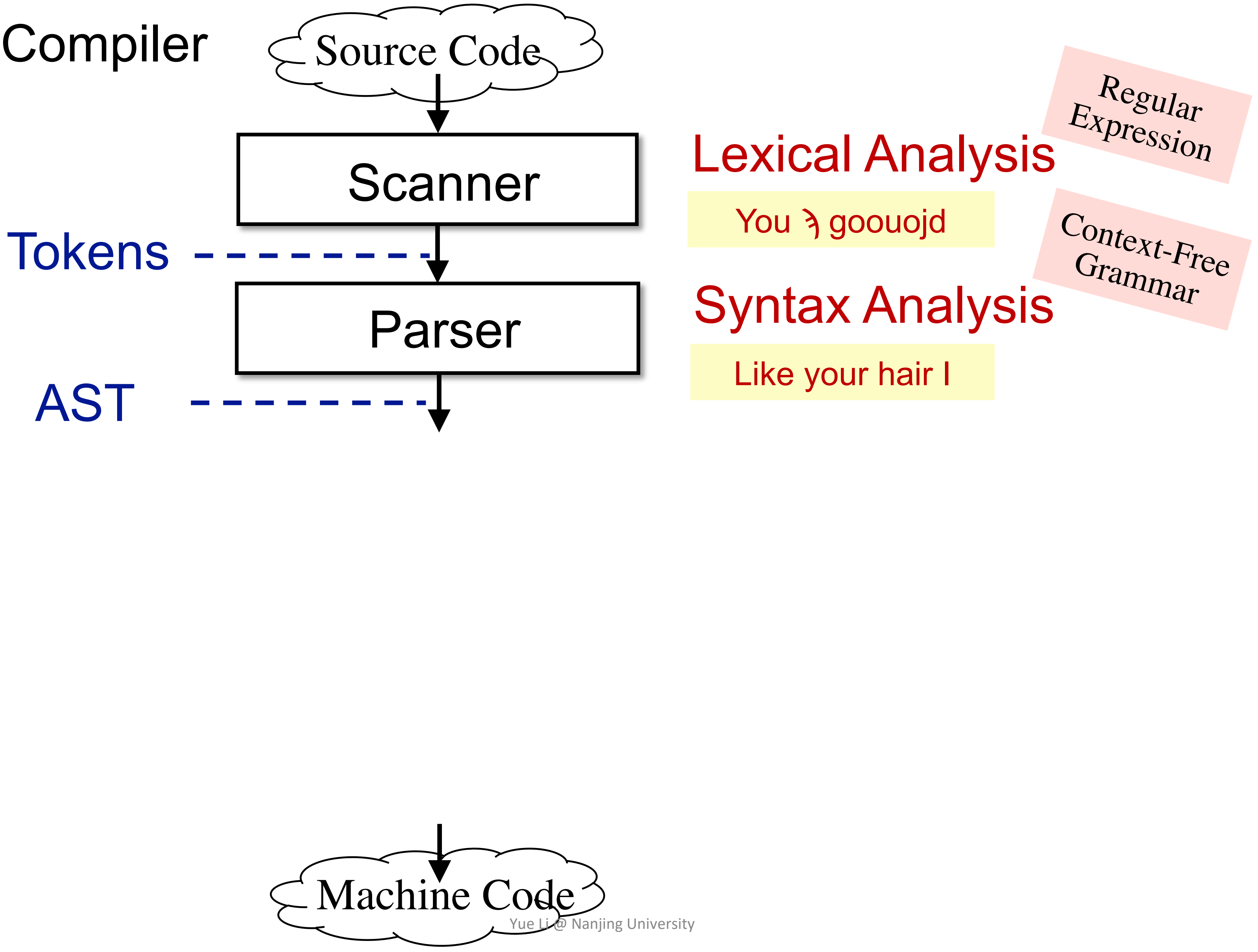


Lexical Analysis

You [illegible] goouojd

Regular Expression

Compiler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You [illegible] goouojd
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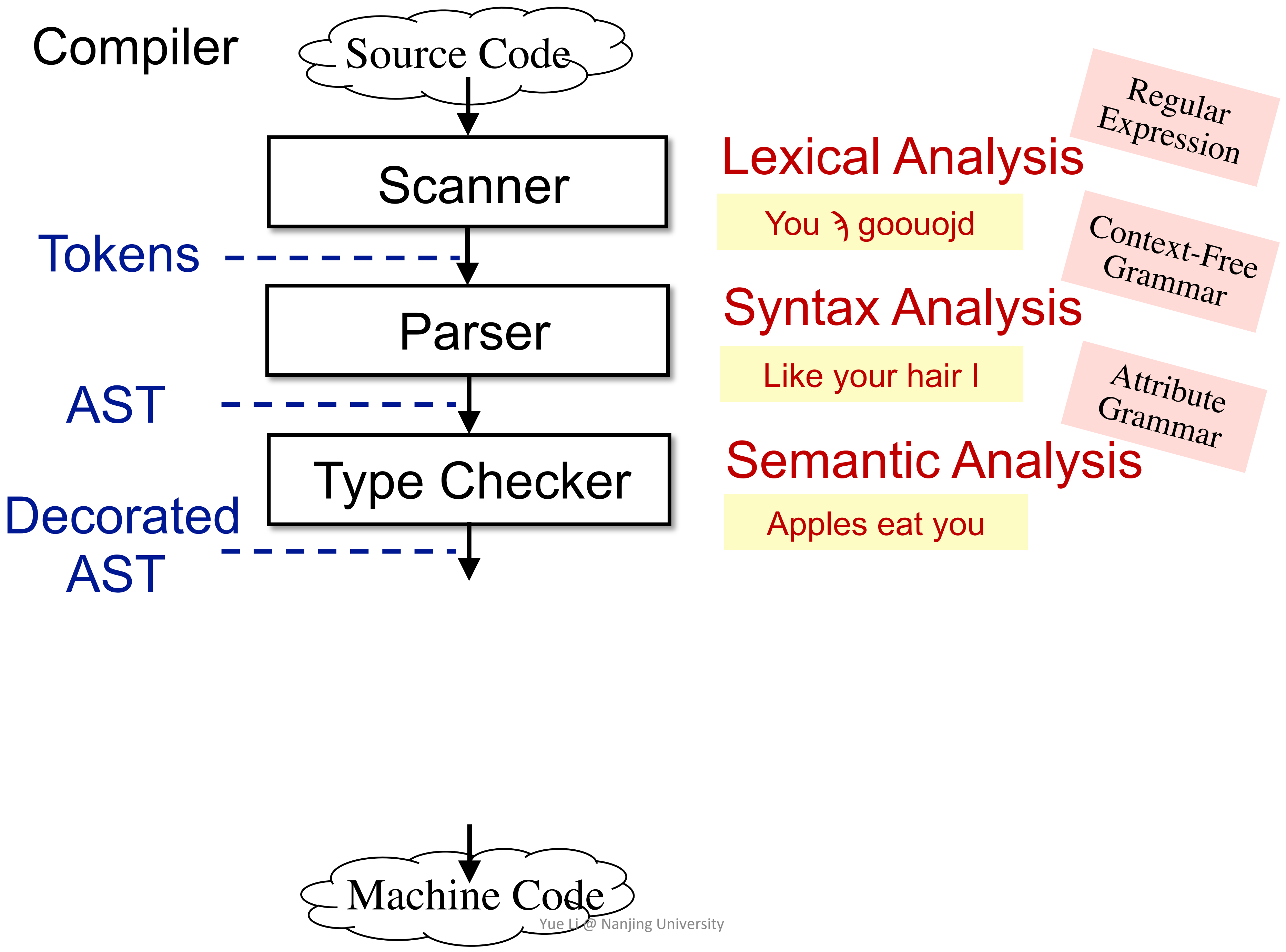
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Regular Expression
Context-Free Grammar
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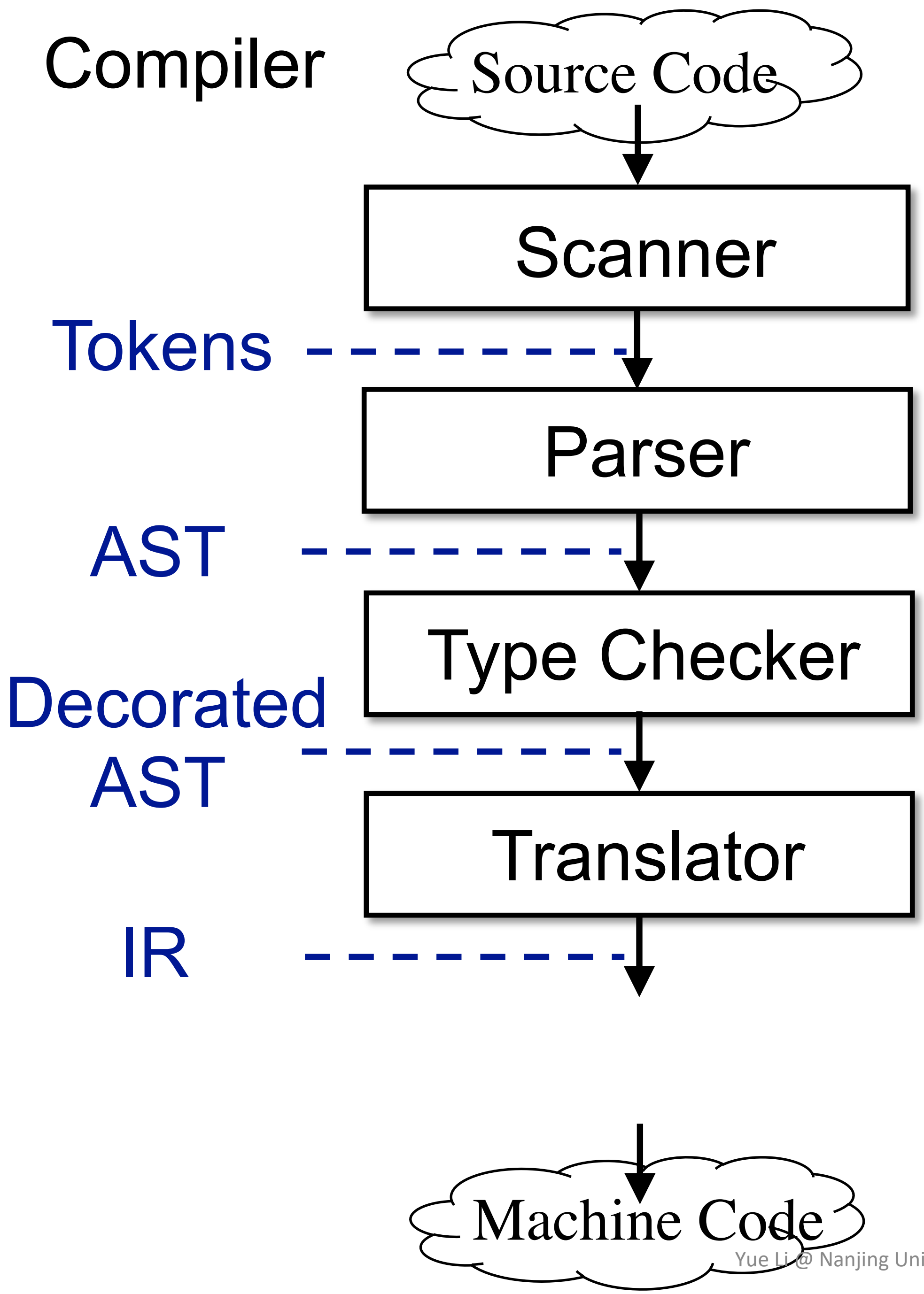
Compiler



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Semantic Analysis

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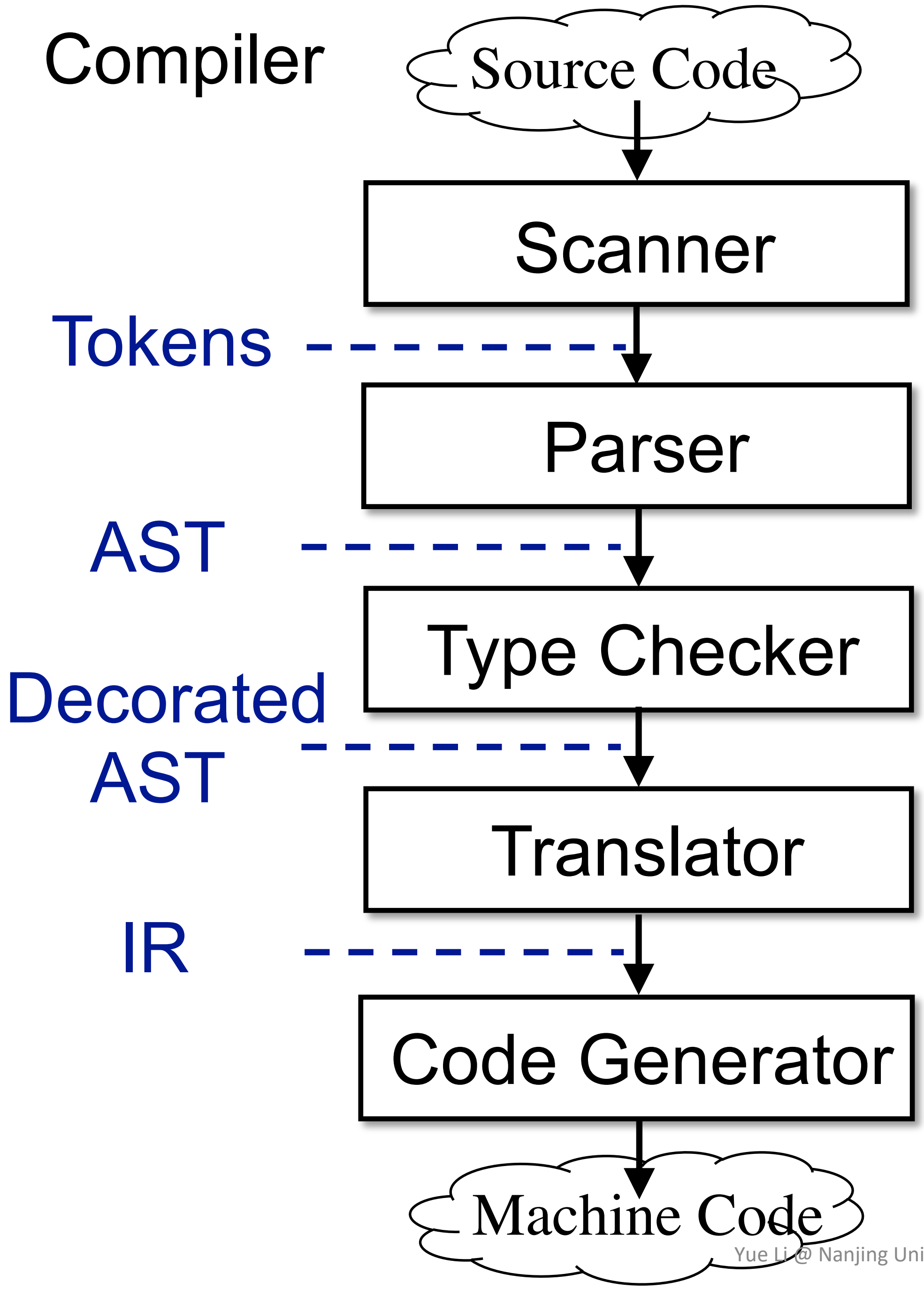

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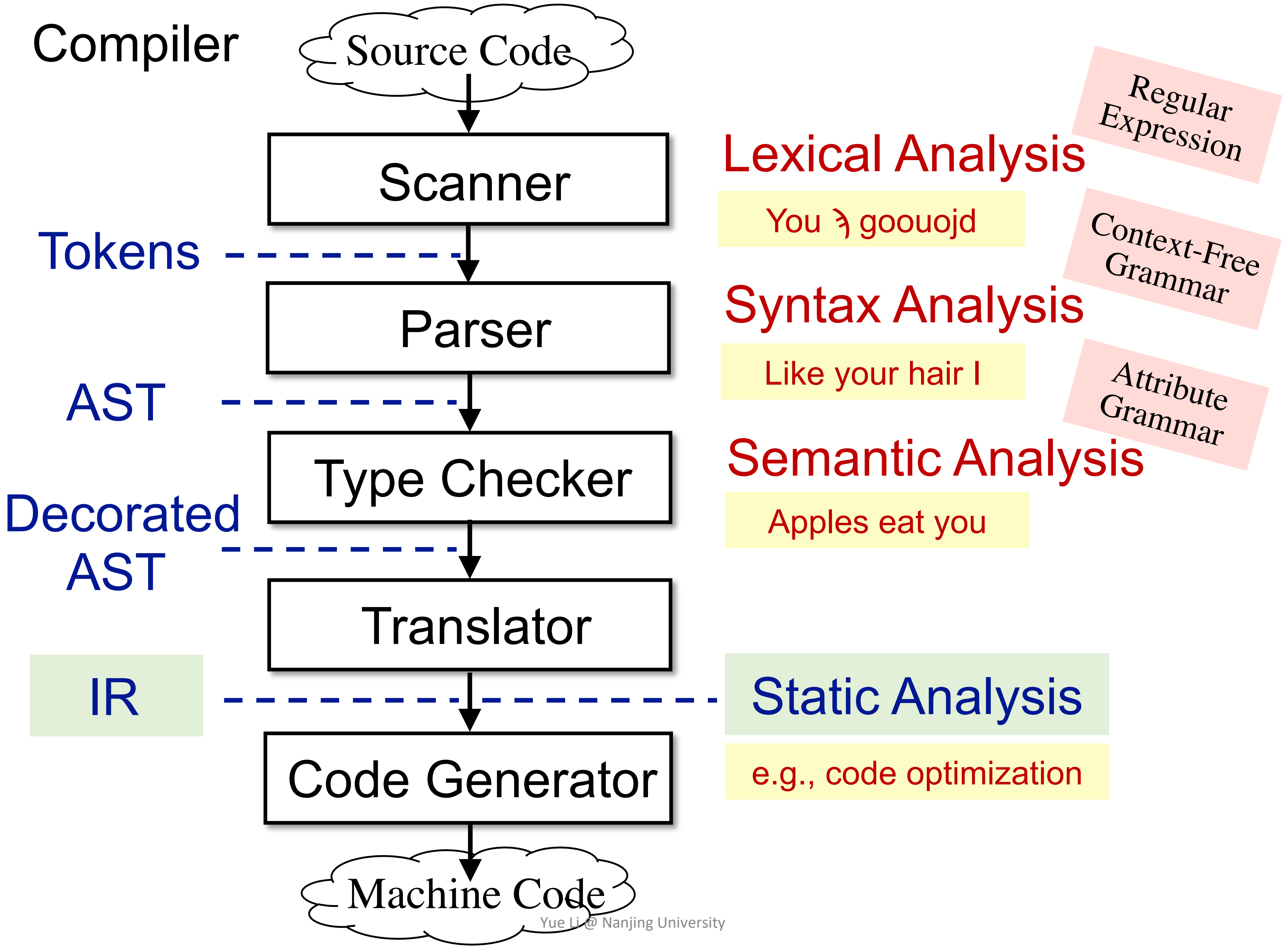
Source Code
Scanner
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Translator
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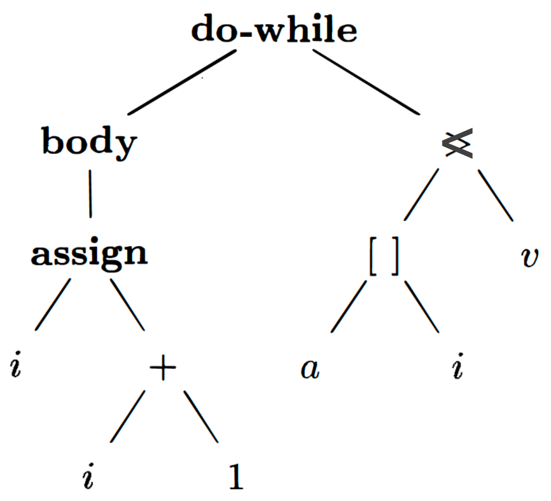
Attribute Grammar
Static Analysis
e.g., code optimization

AST vs. IR

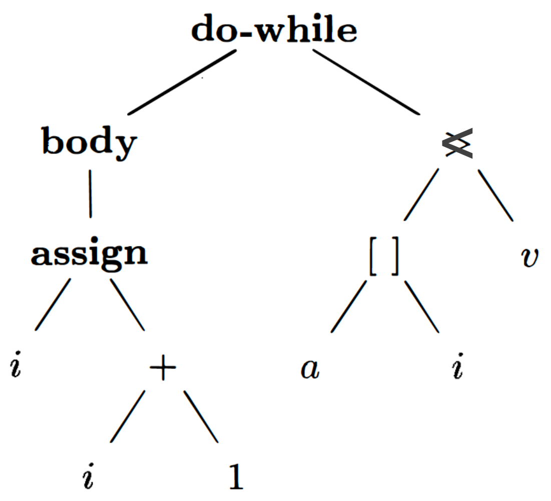
AST



“do i = i + 1; while (a[i] < v);”

AST vs. IR

AST



```
"do i=i+1; while (a[i] < v);"
```

IR

```
1: i = i + 1
2: t1 = a [ i ]
3: if t1 < v goto 1
```

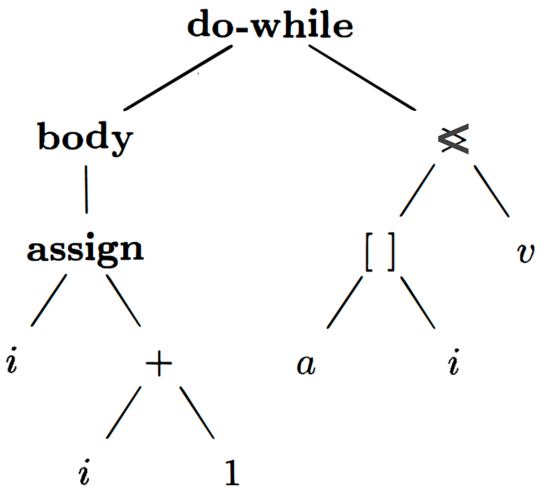
("3-address" form)

AST vs. IR

AST
- high-level and closed to grammar structure
- usually language dependent
- suitable for fast type checking
- lack of control flow information

IR
- low-level and closed to machine code
- usually language independent
- compact and uniform
- contains control flow information
- usually considered as the basis for static analysis

AST



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"do i=i+1; while(a[i]<v);"
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IR

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("3-address" form)

Intermediate Representation (IR)

- 3-Address Code (3AC)

  There is at most one operator on the right side of an instruction.

$$c = a + b + 3 \quad \Rightarrow \quad \begin{array}{l} t1 = a + b \\ c \;\; = t1 + 3 \end{array}$$

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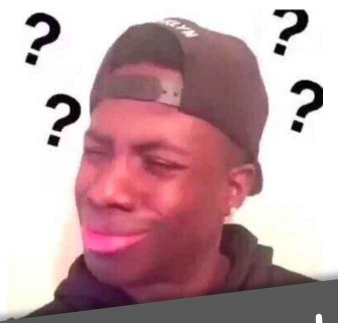
Each 3AC contains at most 3 addresses



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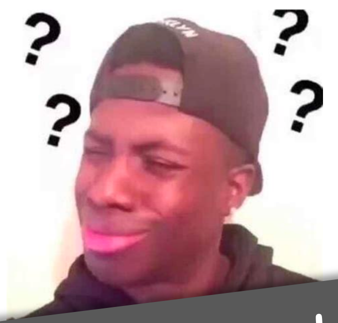

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Address can be one of the following:

- Name: a, b, c
- Constant: 3
- Compiler-generated temporary: t1

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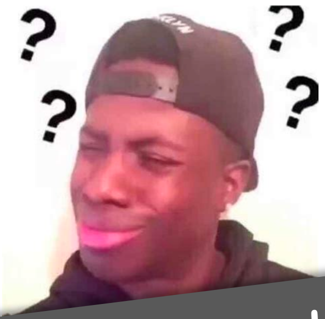

Why called 3-address?

Address can be one of the following:

- Name: a, b, c
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Each type of instructions has its own 3AC form

Some Common 3AC Forms

- x = y *bop* z
- x = *uop* y
- x = y
- goto L
- if x goto L
- if x *rop* y goto L

x, y, z: addresses
bop: binary arithmetic or logical operation
uop: unary operation (minus, negation, casting)
L: a label to represent a program location
rop: relational operator (>, <, ==, >=, <=, etc.)
goto L: unconditional jump
if … goto L: conditional jump

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Let's see some more real-world complicated forms

Soot and Its IR: Jimple

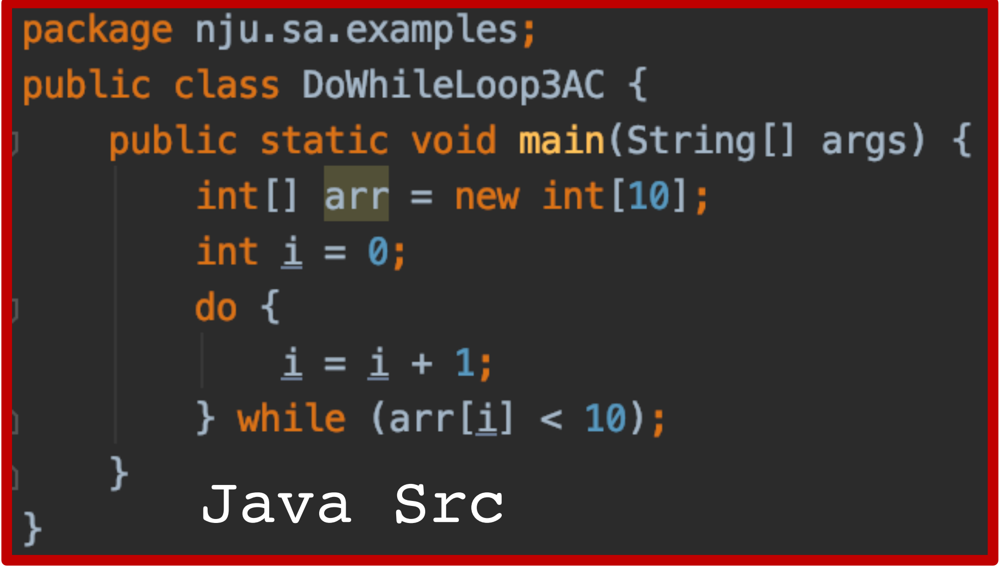
- Soot

  Most popular static analysis framework for Java

  https://github.com/Sable/soot

  https://github.com/Sable/soot/wiki/Tutorials

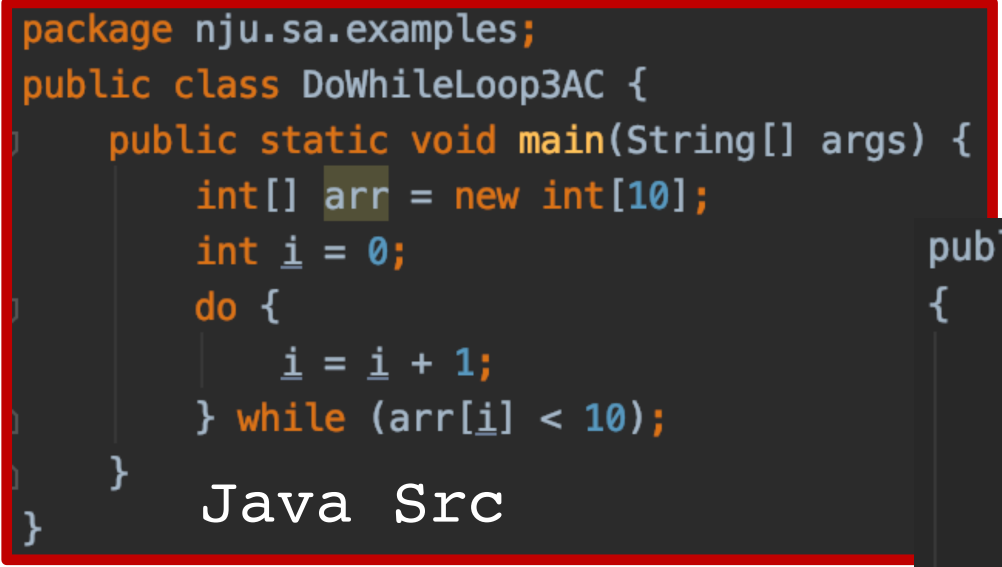
  Soot’s IR is Jimple: typed 3-address code



```
package nju.sa.examples;
public class DoWhileLoop3AC {
    public static void main(String[] args) {
        int[] arr = new int[10];
        int i = 0;
        do {
            i = i + 1;
        } while (arr[i] < 10);
    }
}
```

Java Src

Do-While Loop



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Java Src

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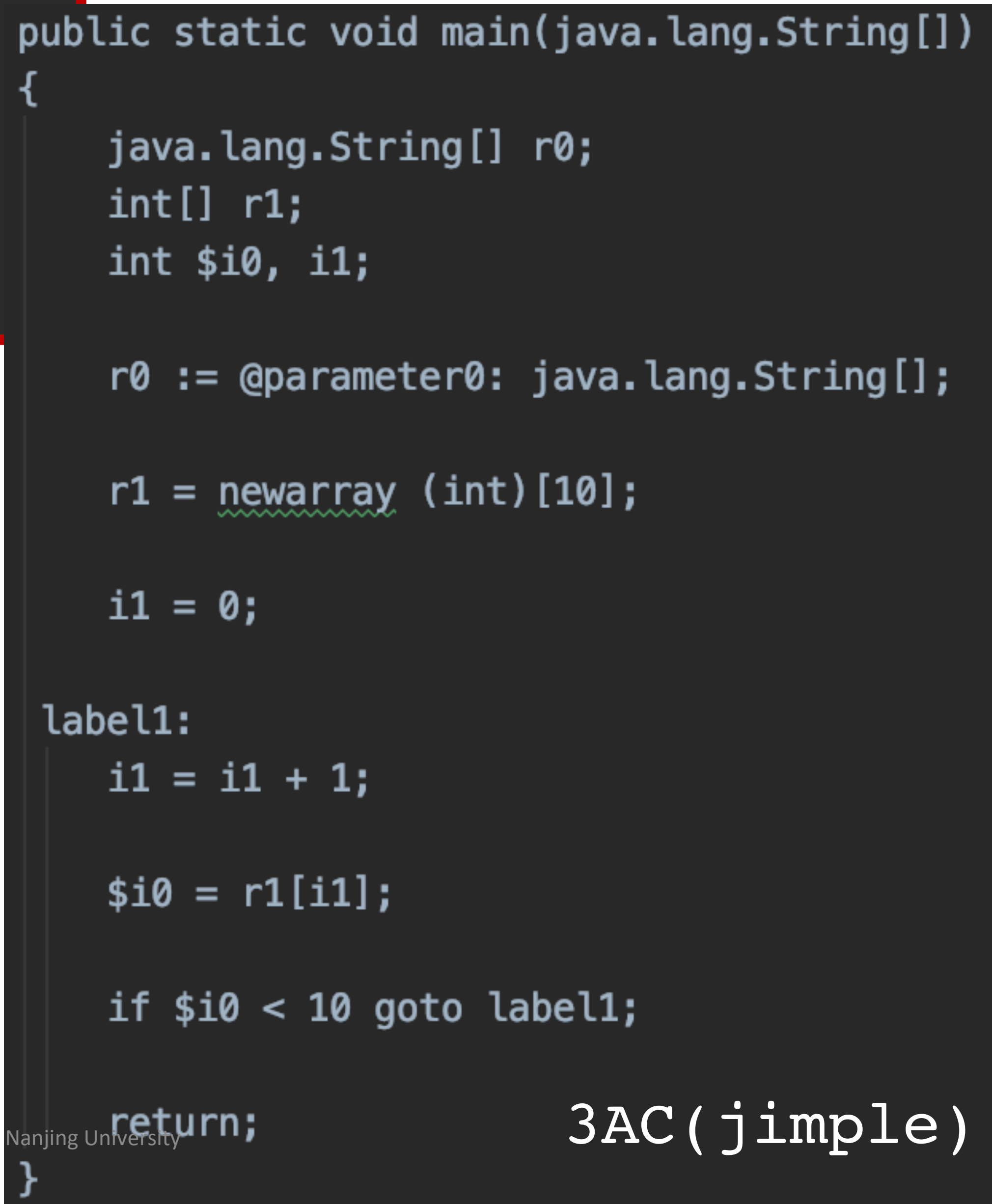
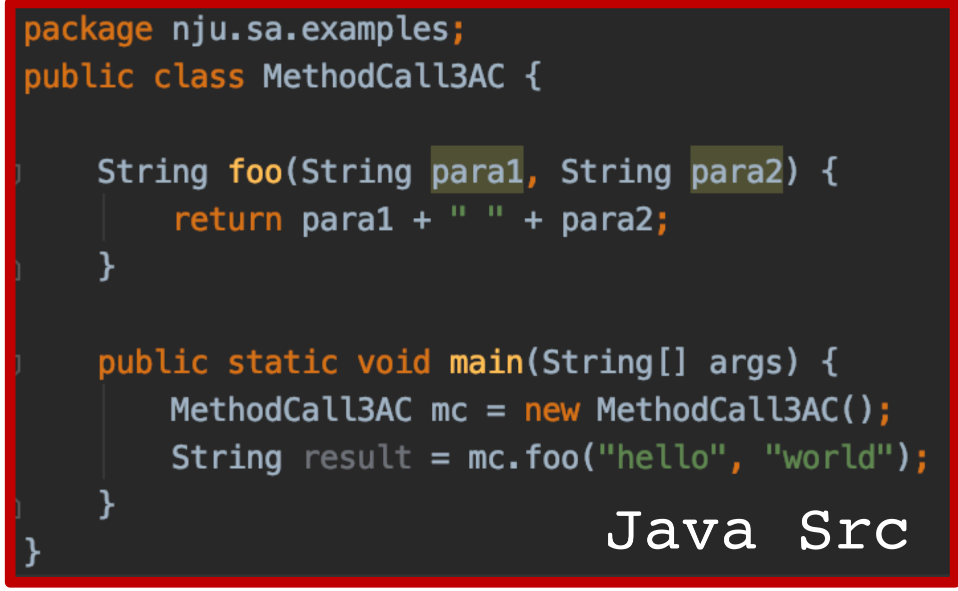


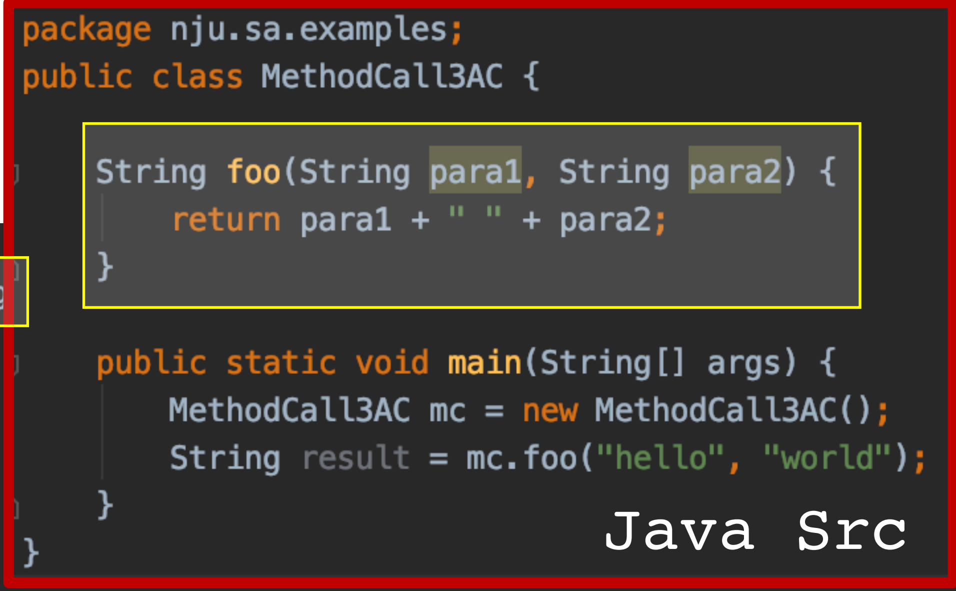
```
public static void main(java.lang.String[])
{
    java.lang.String[] r0;
    int[] r1;
    int $i0, i1;

    r0 := @parameter0: java.lang.String[];

    r1 = newarray (int)[10];

    i1 = 0;

  label1:
    i1 = i1 + 1;

    $i0 = r1[i1];

    if $i0 < 10 goto label1;

    return;
}
```

3AC(jimple)



```java
package nju.sa.examples;
public class MethodCall3AC {

    String foo(String para1, String para2) {
        return para1 + " " + para2;
    }

    public static void main(String[] args) {
        MethodCall3AC mc = new MethodCall3AC();
        String result = mc.foo("hello", "world");
    }
}
```

Method Call



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Java Src

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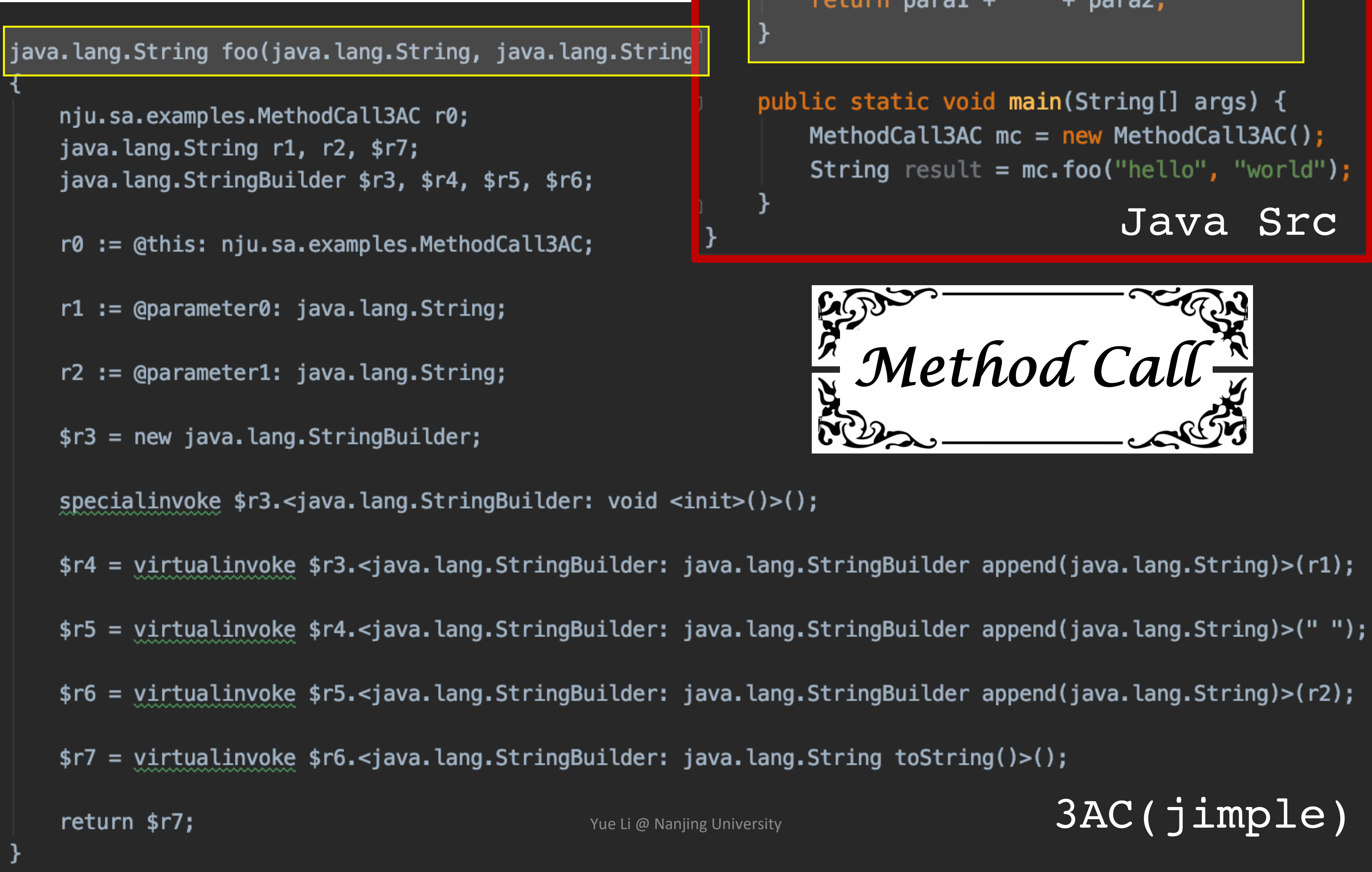
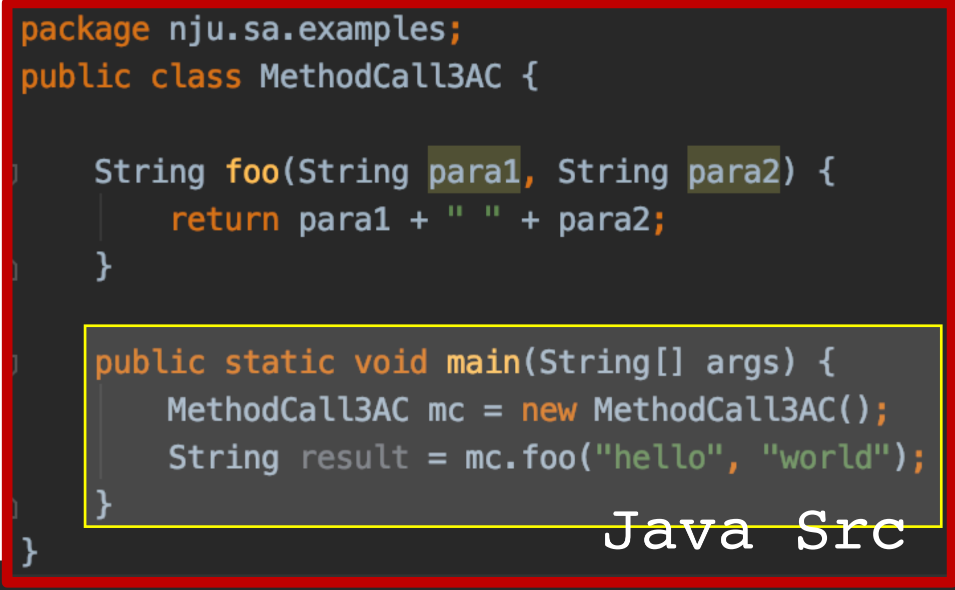


```
java.lang.String foo(java.lang.String, java.lang.String
{
    nju.sa.examples.MethodCall3AC r0;
    java.lang.String r1, r2, $r7;
    java.lang.StringBuilder $r3, $r4, $r5, $r6;

    r0 := @this: nju.sa.examples.MethodCall3AC;

    r1 := @parameter0: java.lang.String;

    r2 := @parameter1: java.lang.String;

    $r3 = new java.lang.StringBuilder;

    specialinvoke $r3.<java.lang.StringBuilder: void <init>()>();

    $r4 = virtualinvoke $r3.<java.lang.StringBuilder: java.lang.StringBuilder append(java.lang.String)>(r1);

    $r5 = virtualinvoke $r4.<java.lang.StringBuilder: java.lang.StringBuilder append(java.lang.String)>(" ");

    $r6 = virtualinvoke $r5.<java.lang.StringBuilder: java.lang.StringBuilder append(java.lang.String)>(r2);

    $r7 = virtualinvoke $r6.<java.lang.StringBuilder: java.lang.String toString()>();

    return $r7;
}
```

3AC(jimple)



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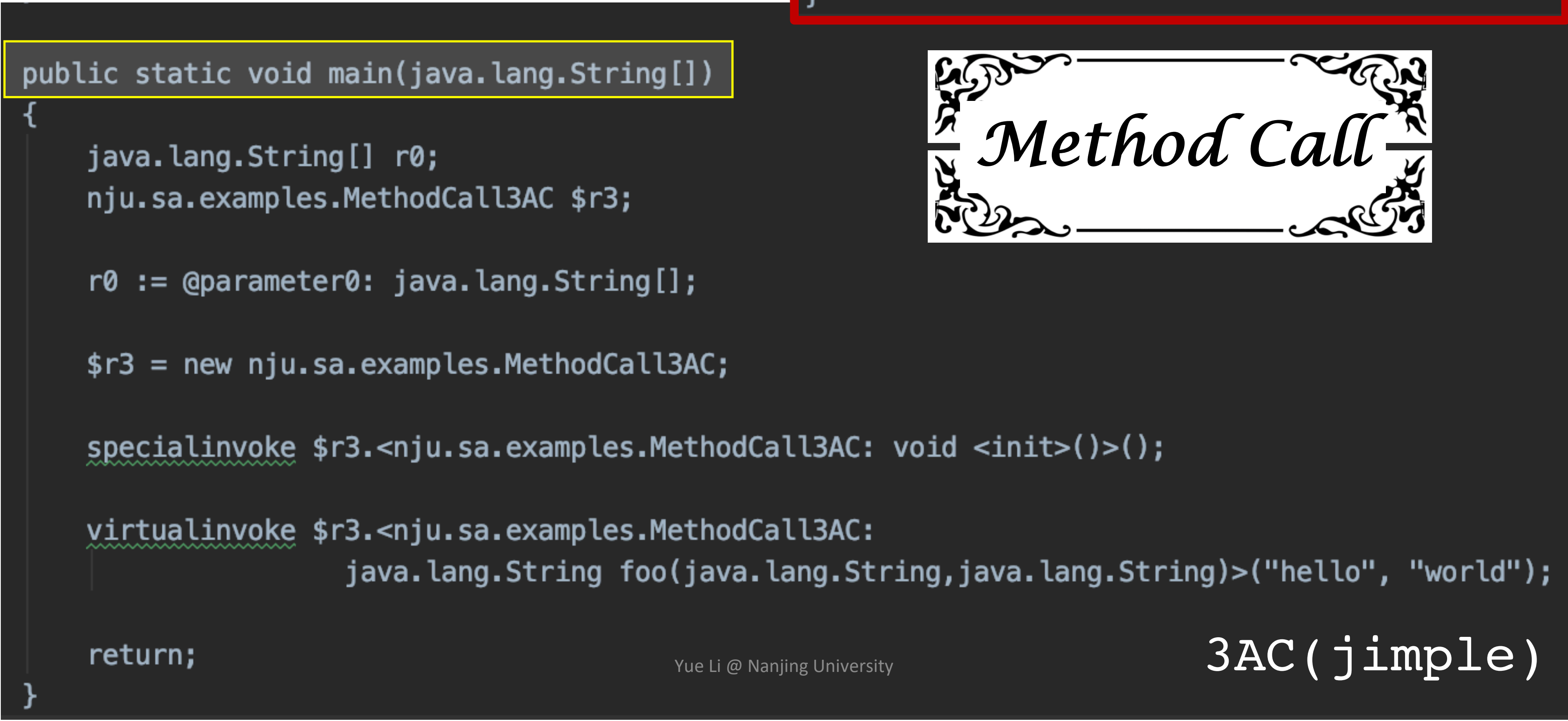
Java Src

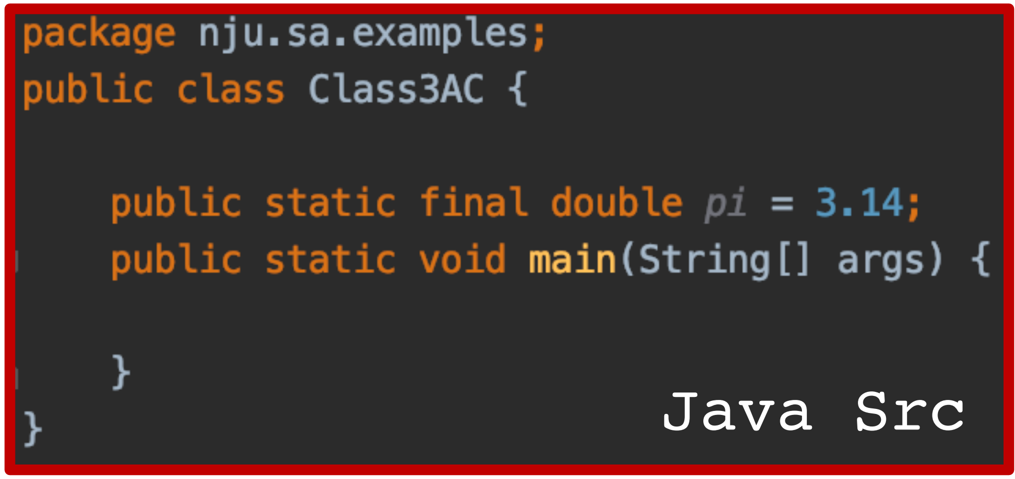
Method Call



```
public static void main(java.lang.String[])
{
    java.lang.String[] r0;
    nju.sa.examples.MethodCall3AC $r3;

    r0 := @parameter0: java.lang.String[];

    $r3 = new nju.sa.examples.MethodCall3AC;

    specialinvoke $r3.<nju.sa.examples.MethodCall3AC: void <init>()>();

    virtualinvoke $r3.<nju.sa.examples.MethodCall3AC:
                java.lang.String foo(java.lang.String,java.lang.String)>("hello", "world");

    return;
}
```

3AC(jimple)

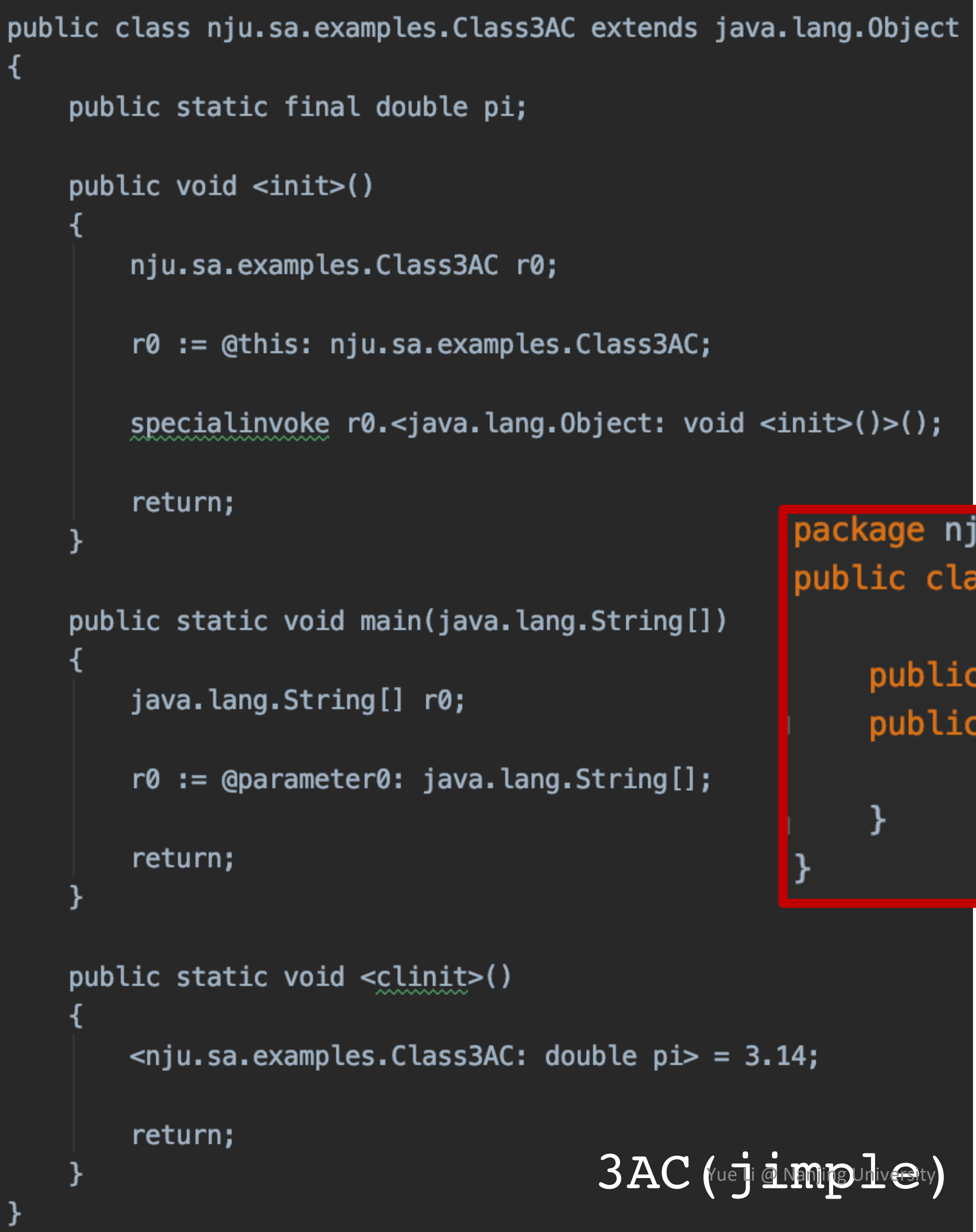
Class



```java
package nju.sa.examples;
public class Class3AC {

    public static final double pi = 3.14;
    public static void main(String[] args) {

    }
}
```

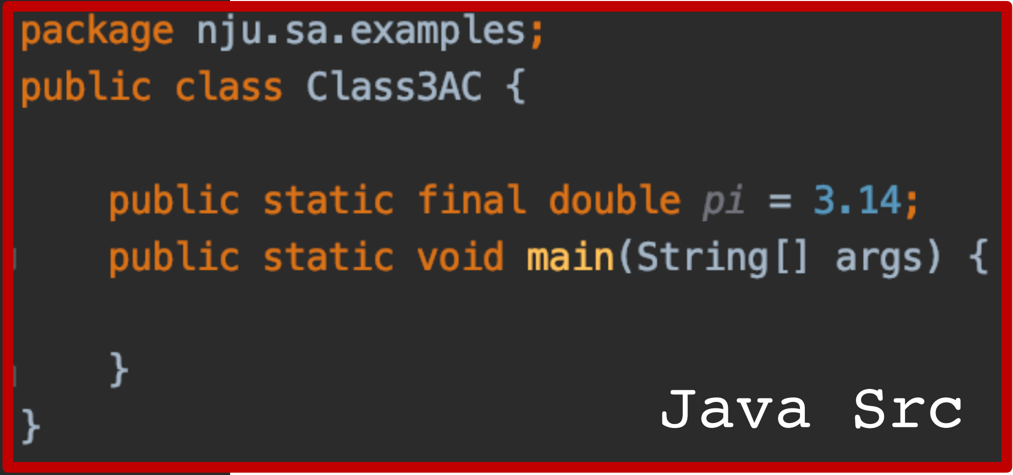
Java Src

Class



```
public class nju.sa.examples.Class3AC extends java.lang.Object
{
    public static final double pi;

    public void <init>()
    {
        nju.sa.examples.Class3AC r0;

        r0 := @this: nju.sa.examples.Class3AC;

        specialinvoke r0.<java.lang.Object: void <init>()>();

        return;
    }

    public static void main(java.lang.String[])
    {
        java.lang.String[] r0;

        r0 := @parameter0: java.lang.String[];

        return;
    }

    public static void <clinit>()
    {
        <nju.sa.examples.Class3AC: double pi> = 3.14;

        return;
    }
}
```

3AC (jimple)



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Java Src

Static Single Assignment (SSA)

Optional material

- All assignments in SSA are to variables with distinct names
  - Give each definition a fresh name
  - Propagate fresh name to subsequent uses
  - Every variable has exactly one definition

```
p = a + b
q = p - c
p = q * d
p = e - p
q = p + q
```

3AC

$$\begin{aligned} p_1 &= a + b \\ q_1 &= p_1 - c \\ p_2 &= q_1 * d \\ p_3 &= e - p_2 \\ q_2 &= p_3 + q_1 \end{aligned}$$

SSA

Static Single Assignment (SSA)

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```

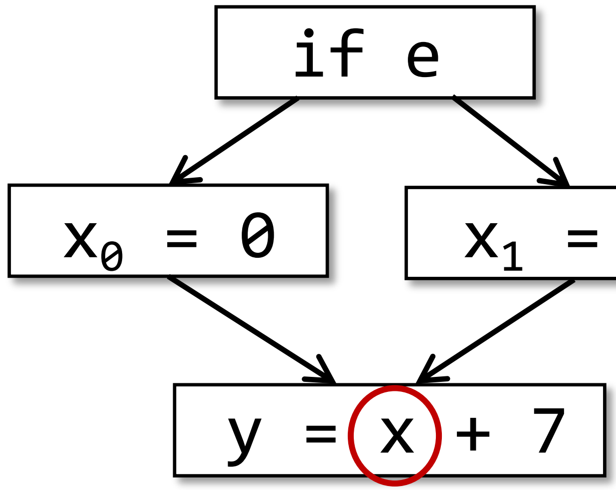
3AC

$p_1 = a + b$
$q_1 = p_1 - c$
$p_2 = q_1 * d$
$p_3 = e - p_2$
$q_2 = p_3 + q_1$

SSA

Static Single Assignment (SSA)

- What if a variable use is at control flow merges?



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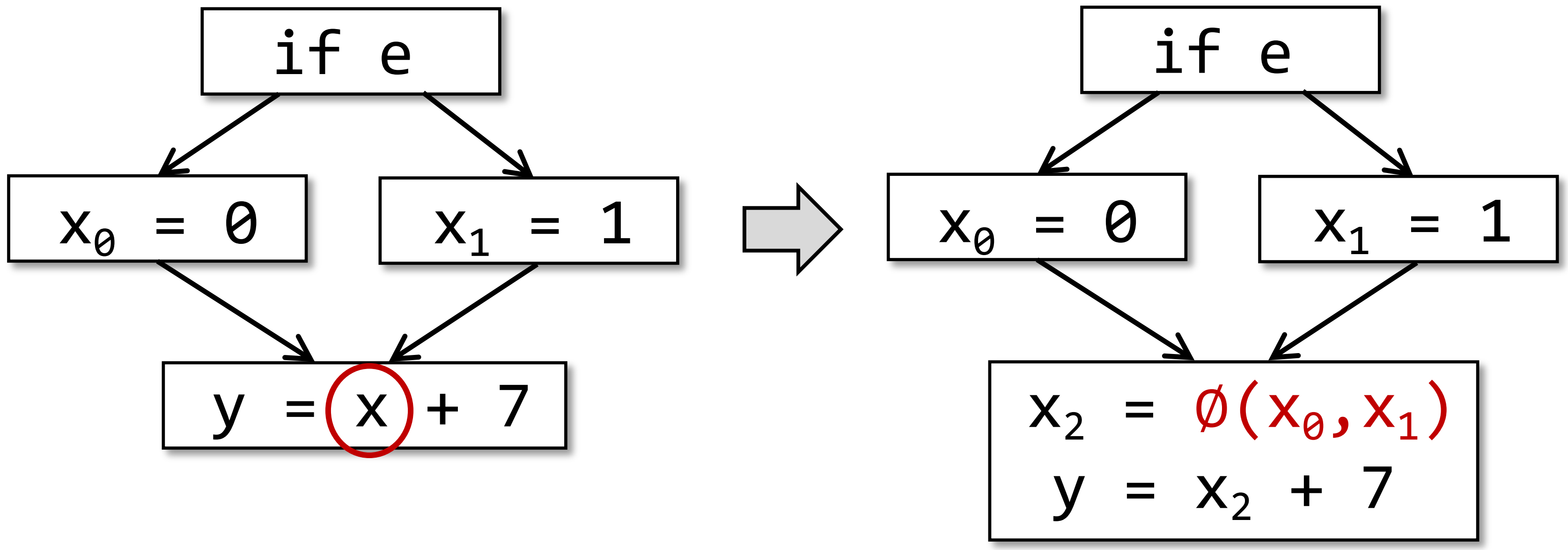

- A special merge operator, ∅ (called phi-function), is introduced to select the values at merge nodes
- ∅(x_0,x_1) has the value x_0 if the control flow passes through the true part of the conditional and the value x_1 otherwise

Why SSA?

Why not SSA?

Why SSA?

- Flow information is indirectly incorporated into the unique variable names

May help deliver some simpler analyses, e.g., flow-insensitive analysis gains partial precision of flow-sensitive analysis via SSA

- Define-and-Use pairs are explicit

Enable more effective data facts storage and propagation in some on-demand tasks

Some optimization tasks perform better on SSA (e.g., conditional constant propagation, global value numbering)

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Why not SSA?

- SSA may introduce too many variables and phi-functions
- May introduce inefficiency problem when translating to machine code (due to copy operations)

Control Flow Analysis

- Usually refer to building Control Flow Graph (CFG)

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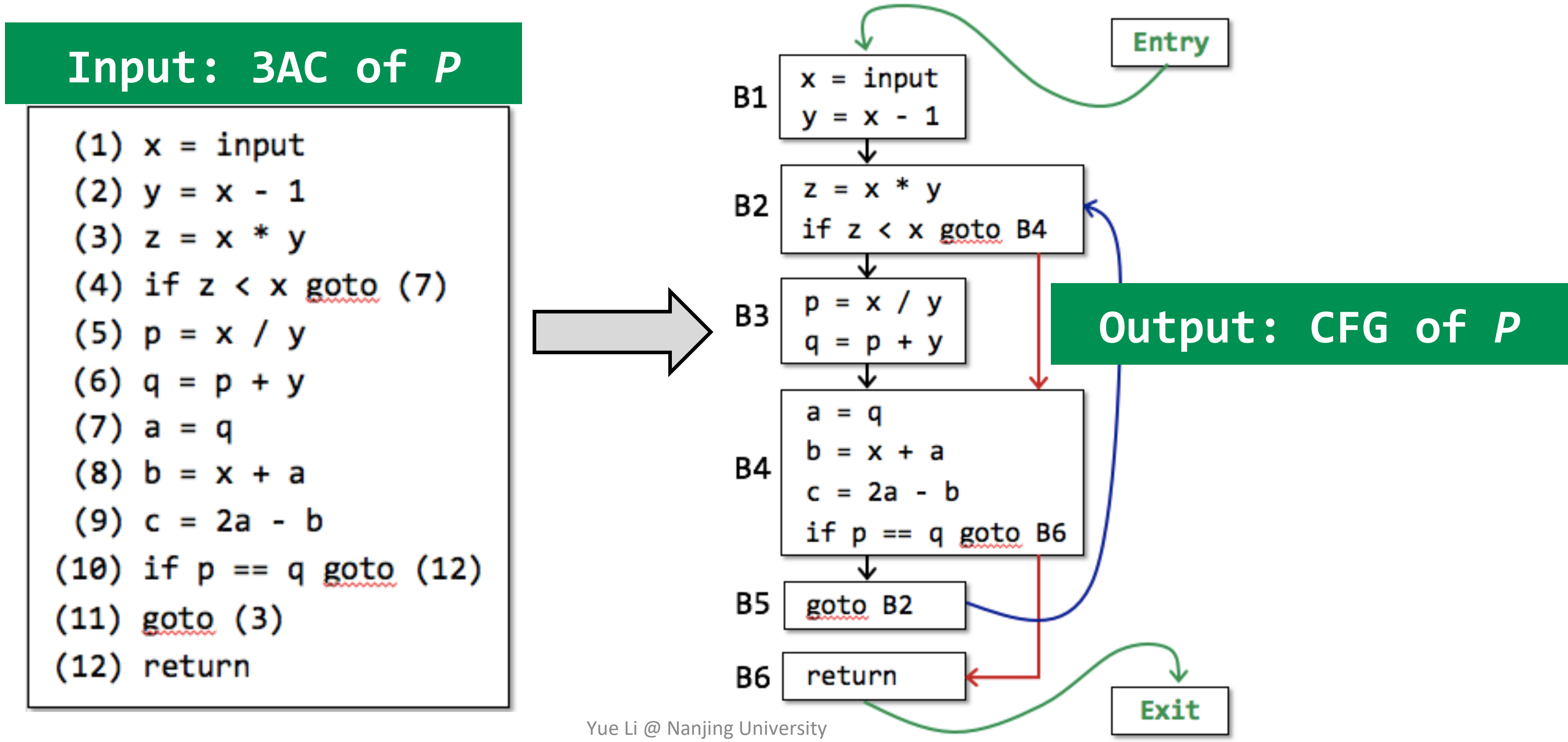

Input: 3AC of *P*

```
 (1) x = input
 (2) y = x - 1
 (3) z = x * y
 (4) if z < x goto (7)
 (5) p = x / y
 (6) q = p + y
 (7) a = q
 (8) b = x + a
 (9) c = 2a - b
(10) if p == q goto (12)
(11) goto (3)
(12) return
```

Output: CFG of *P*

```
Entry
B1  x = input
    y = x - 1
B2  z = x * y
    if z < x goto B4
B3  p = x / y
    q = p + y
B4  a = q
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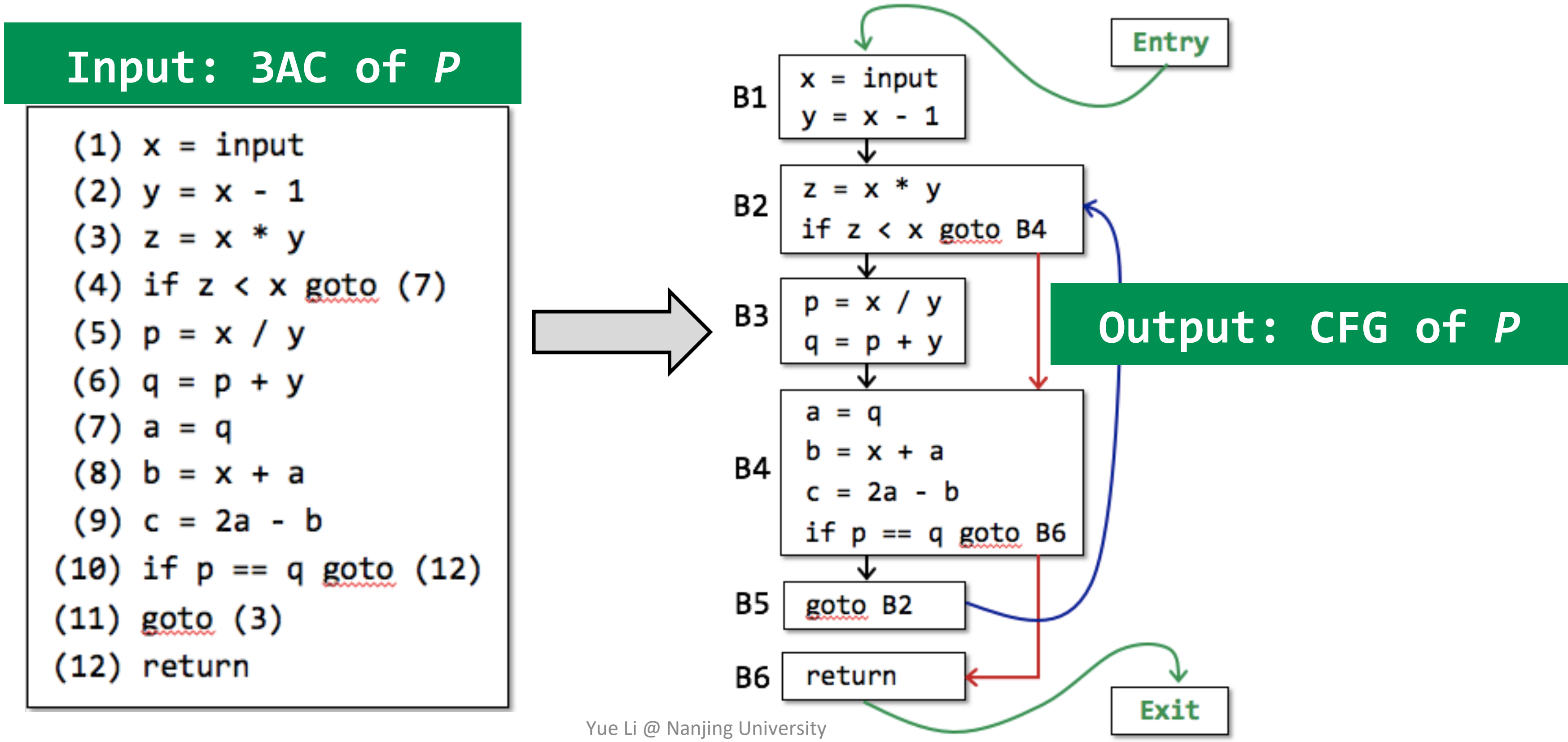
    c = 2a - b
    if p == q goto B6
B5  goto B2
B6  return
Exit
```

Control Flow Analysis

- Usually refer to building Control Flow Graph (CFG)
- CFG serves as the basic structure for static analysis



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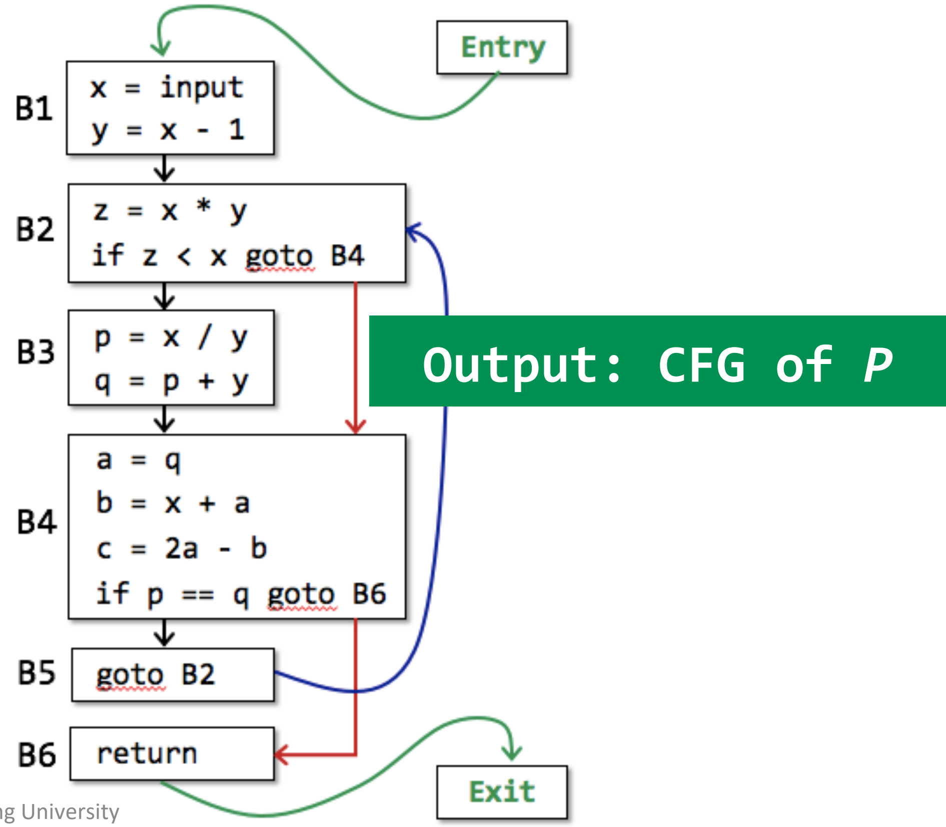

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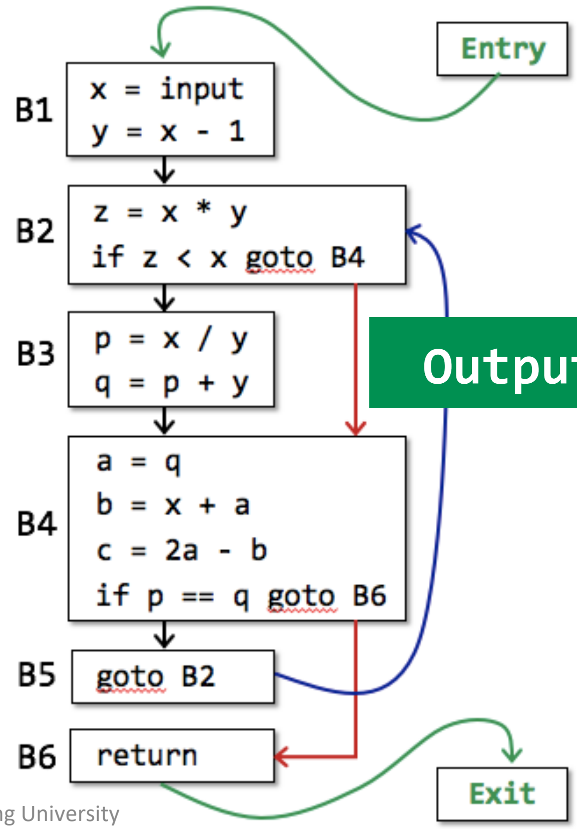

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    if z < x goto B4
B3  p = x / y
    q = p + y
B4  a = q
    b = x + a
    c = 2a - b
    if p == q goto B6
B5  goto B2
B6  return
```

Output: CFG of *P*

Basic Blocks (BB)

- Basic blocks (BB) are maximal sequences of consecutive three-address instructions with the properties that

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 a = q
 b = x + a
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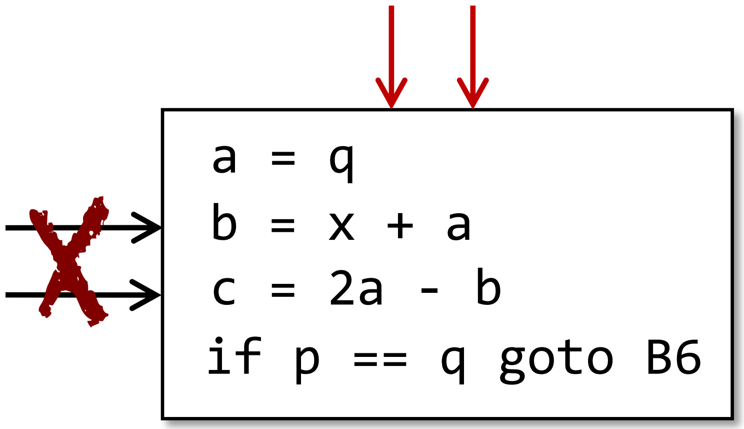
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Basic Blocks (BB)

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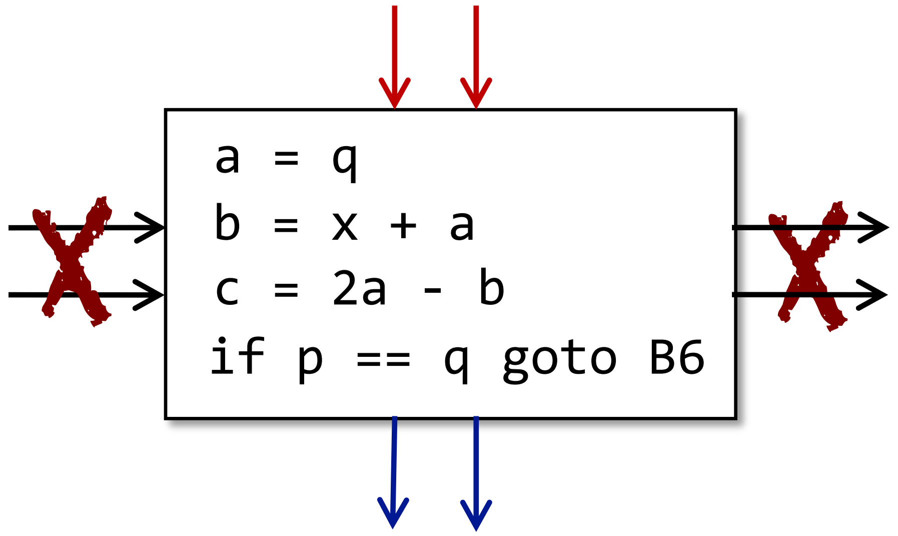

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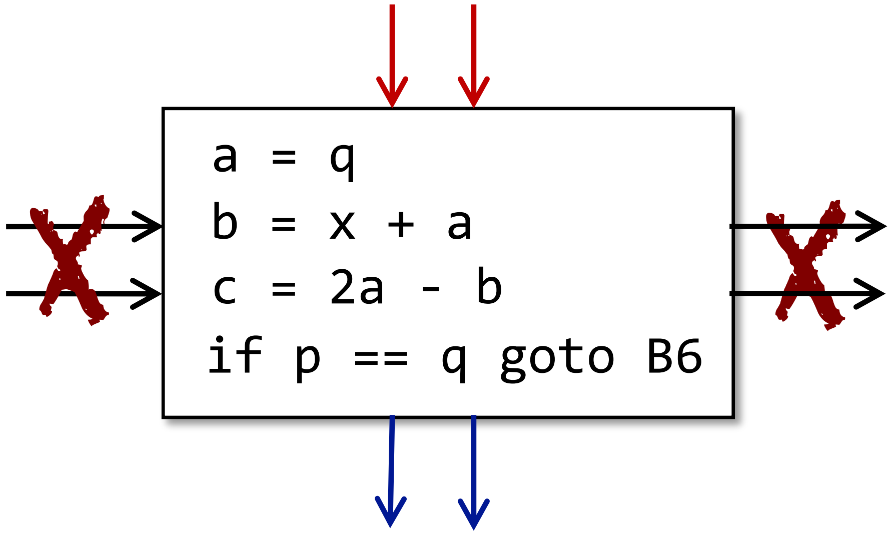
Now try to design the algorithm to build BBs by yourself!



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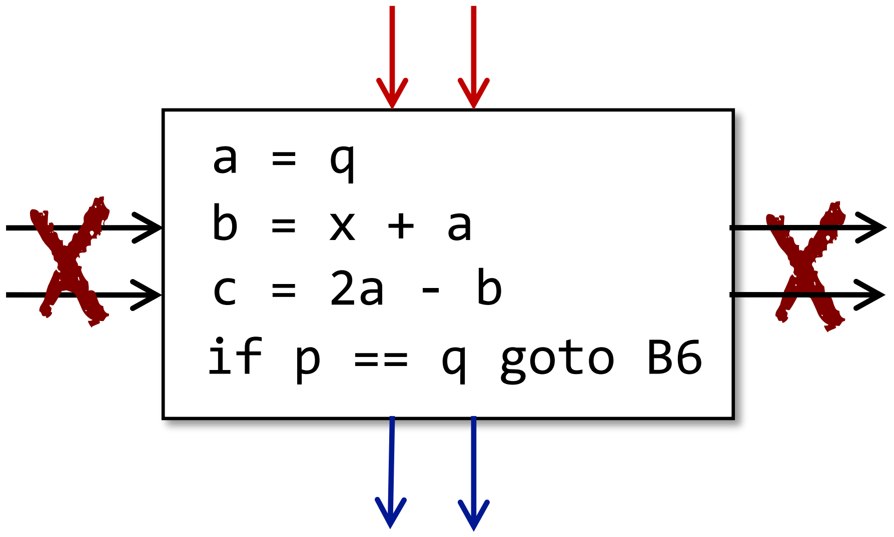

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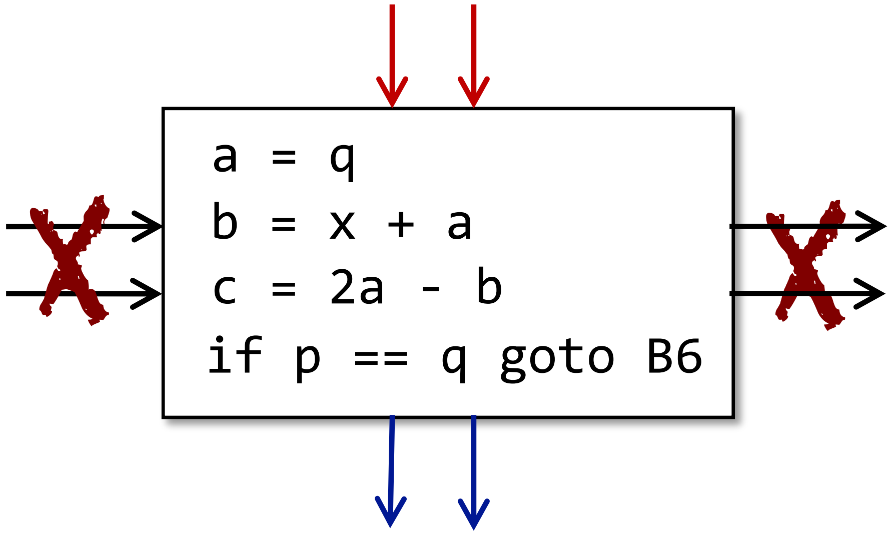

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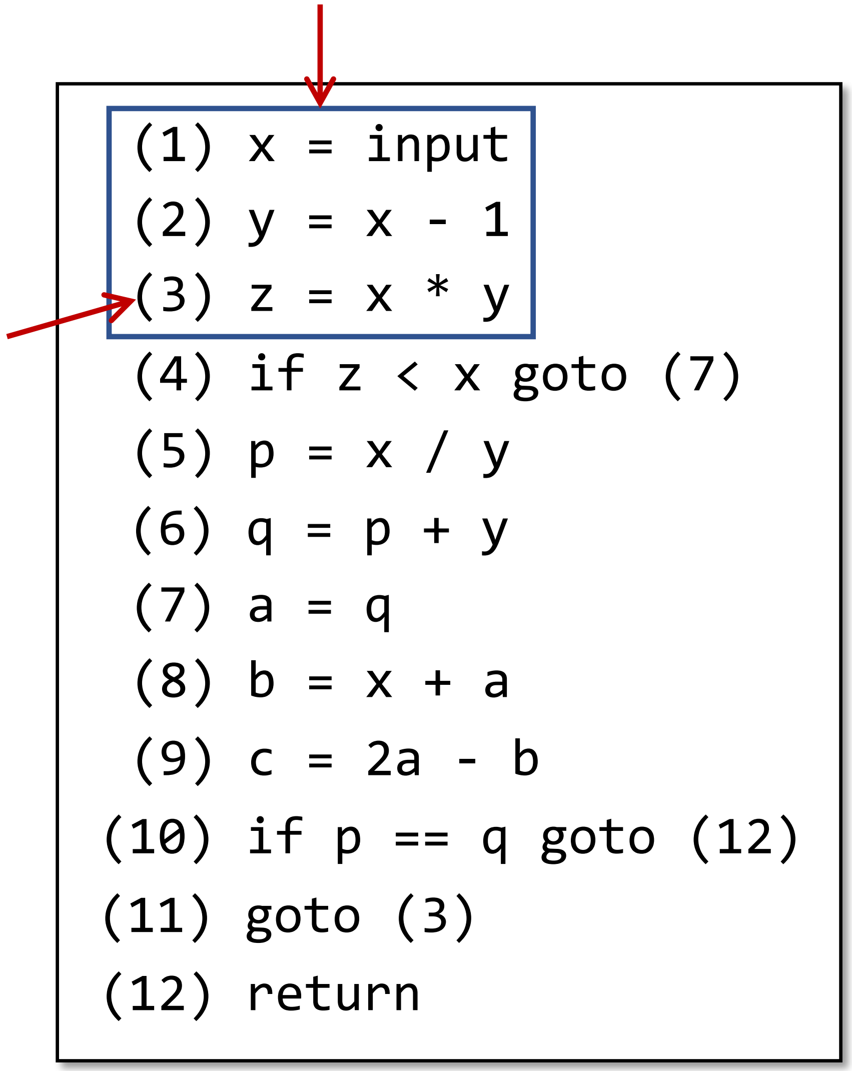

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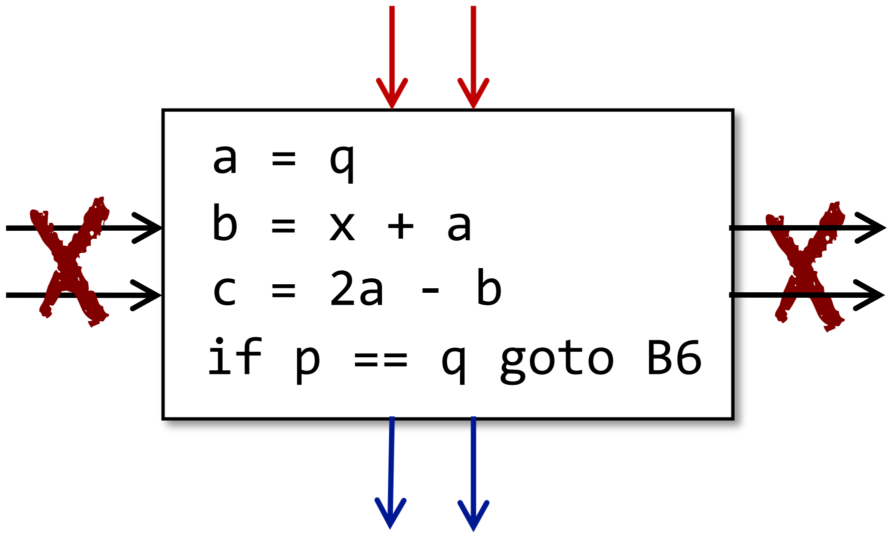

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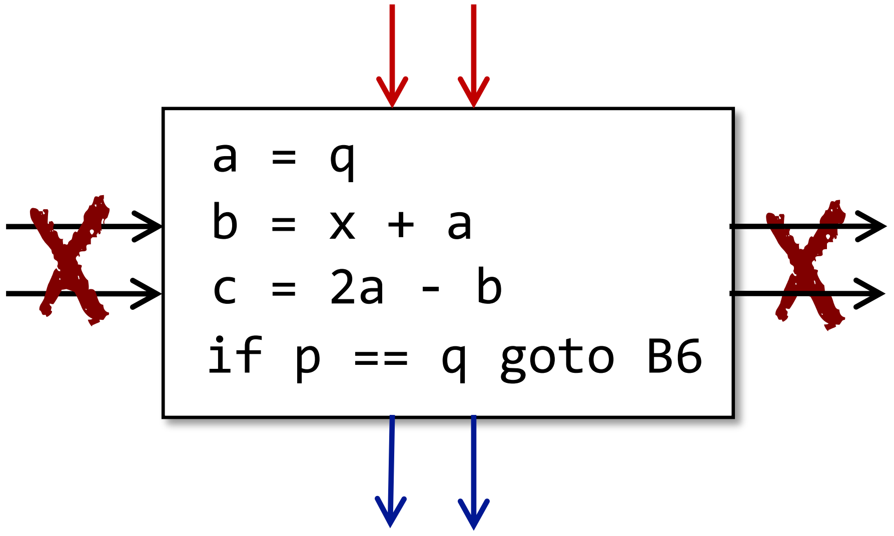

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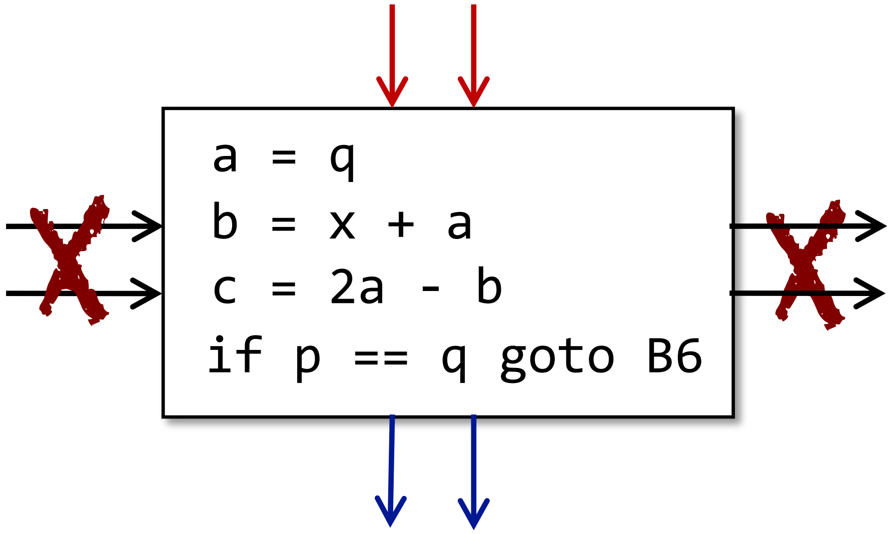

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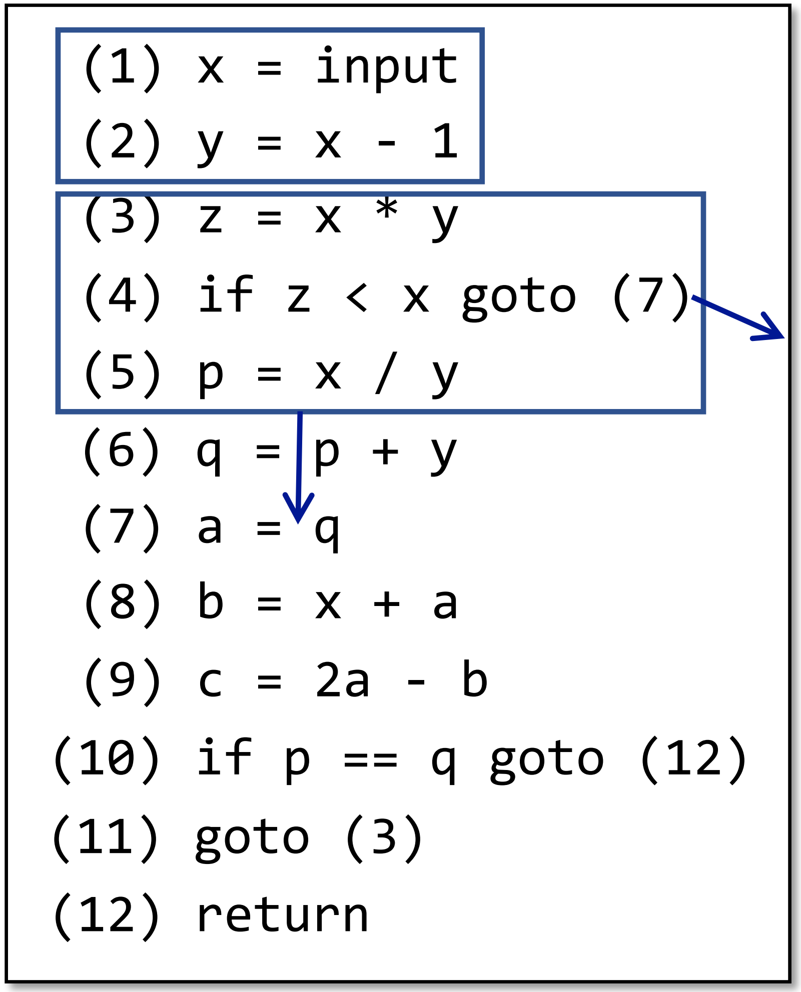

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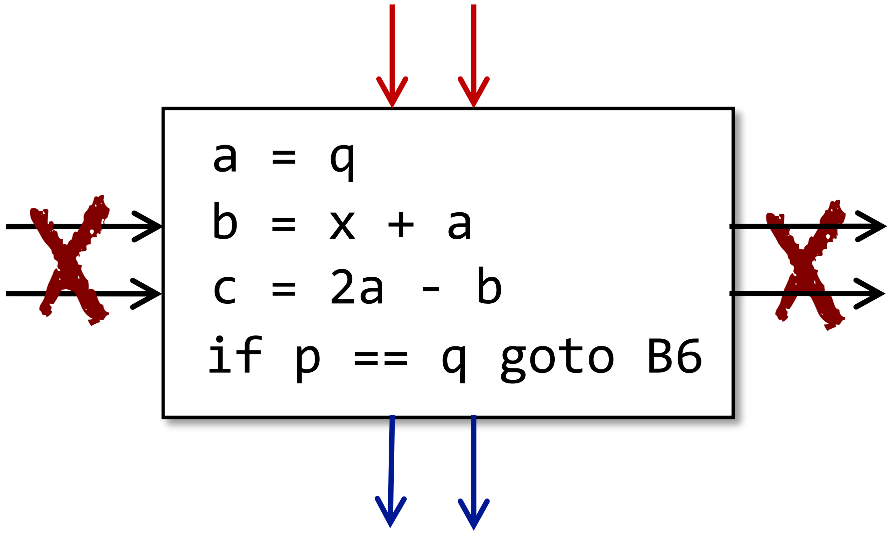

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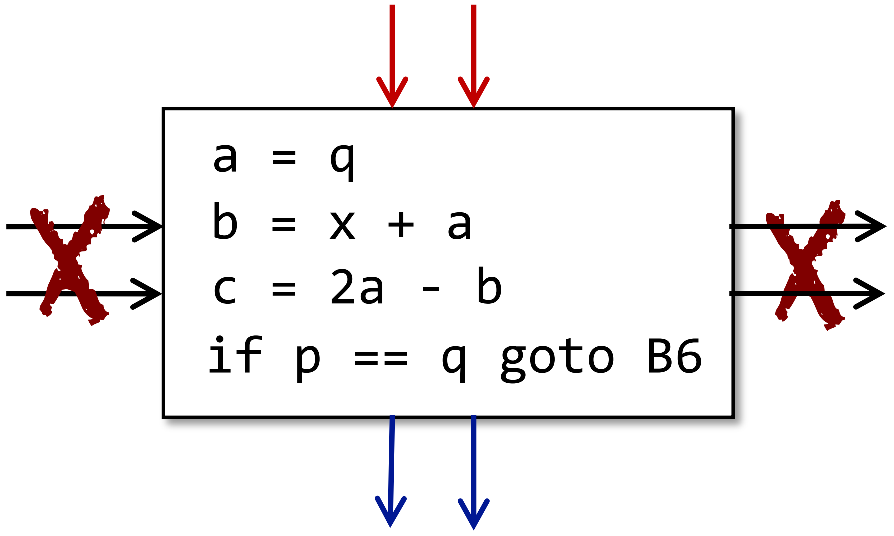
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How to build Basic Blocks?

INPUT: A sequence of three-address instructions of *P*

OUTPUT: A list of basic blocks of *P*

METHOD: (1) Determine the leaders in *P*

- The first instruction in *P* is a leader
- Any target instruction of a conditional or unconditional jump is a leader
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(2) Build BBs for P

- A BB consists of a leader and all its subsequent instructions until the next leader

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How to build CFG on top of BBs?

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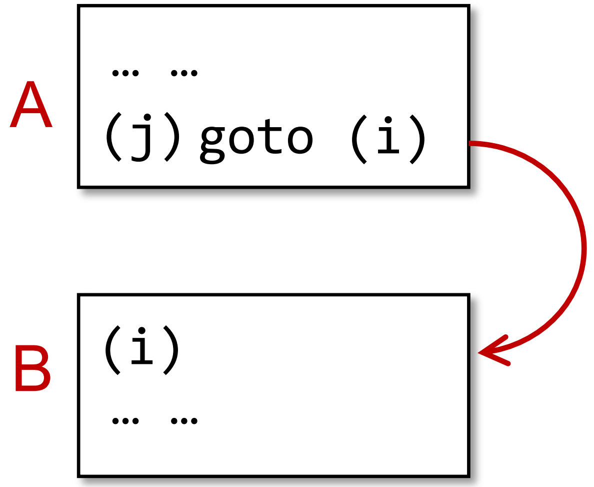

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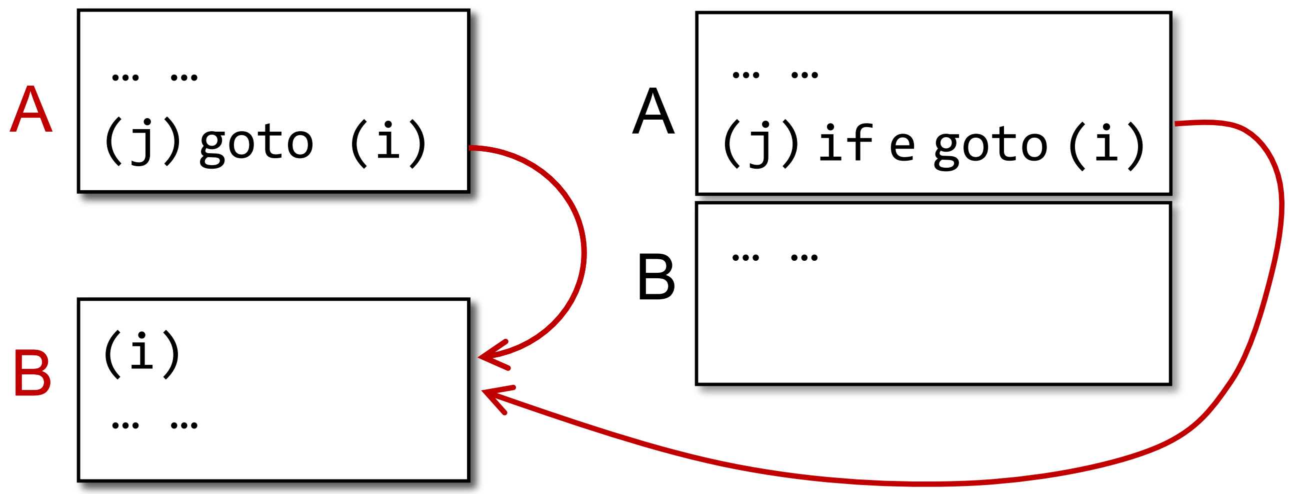

Control Flow Graph (CFG)

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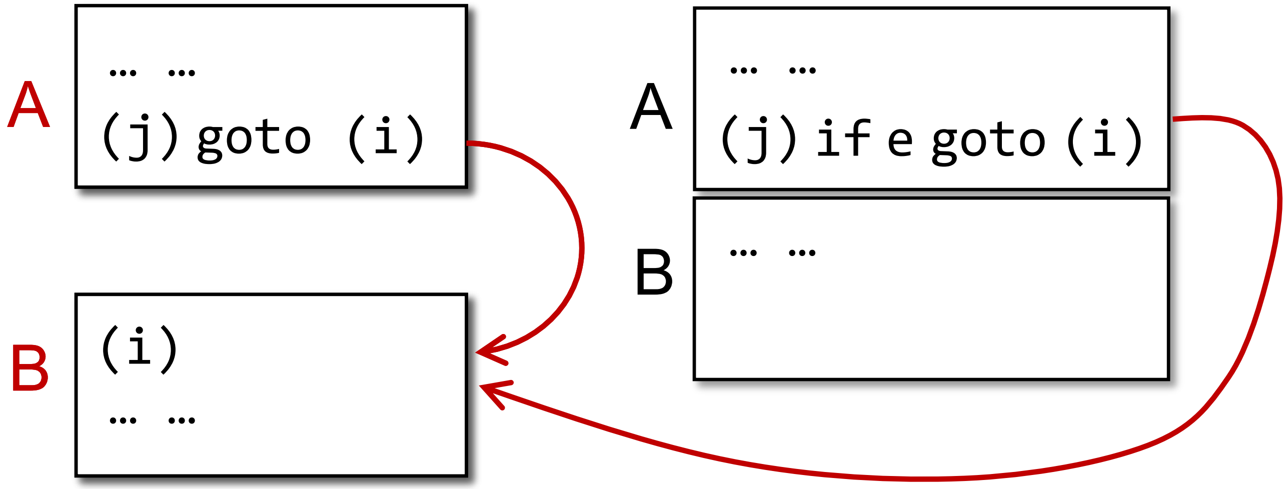

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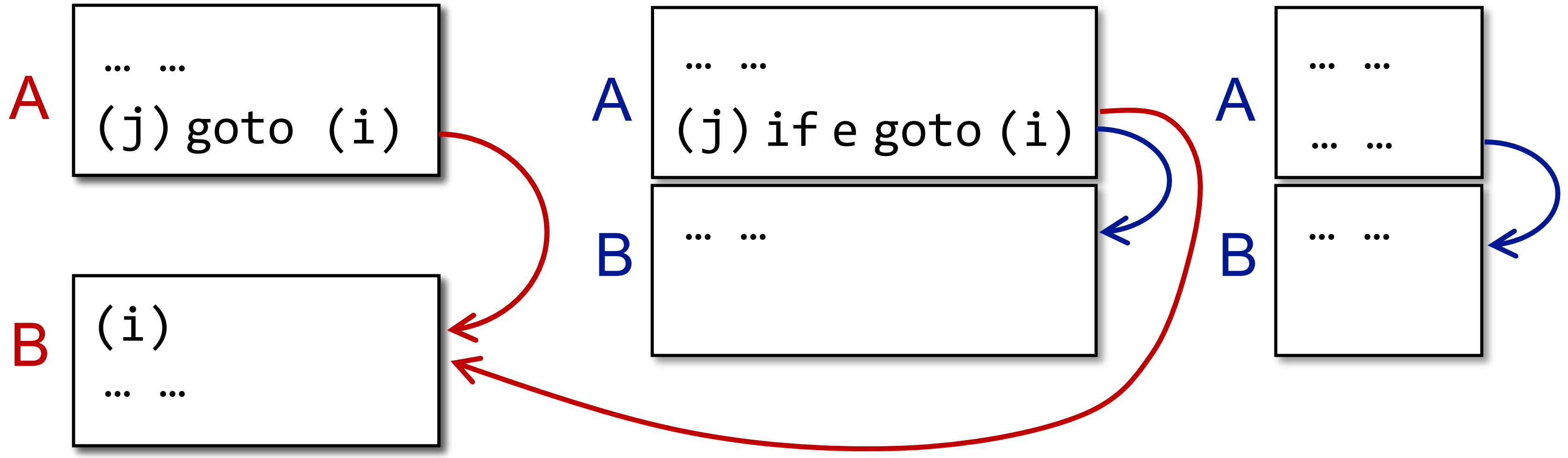

Control Flow Graph (CFG)

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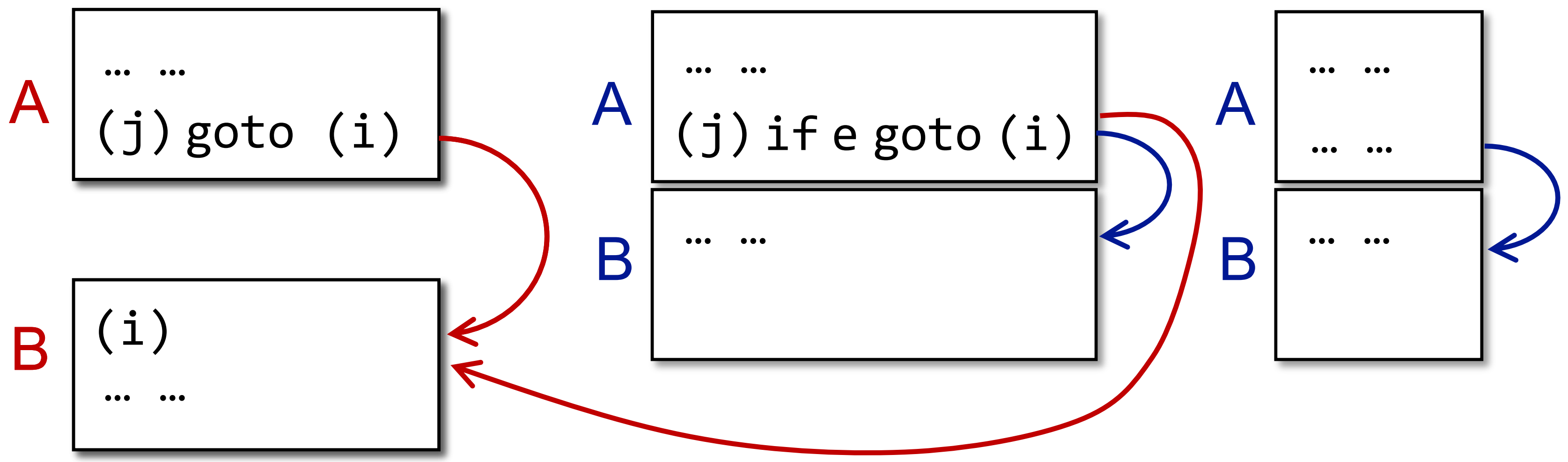

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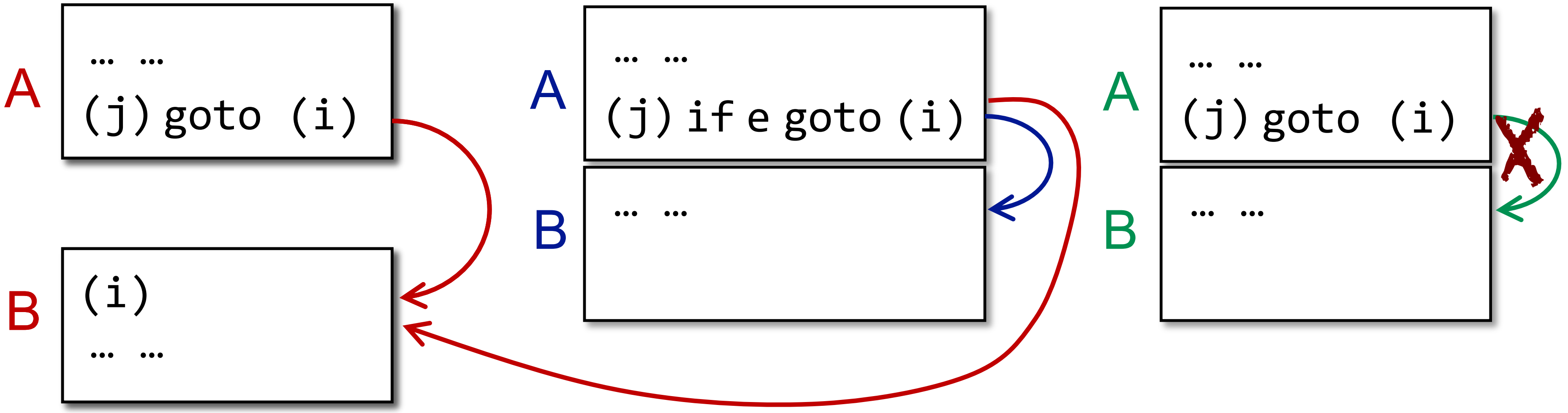
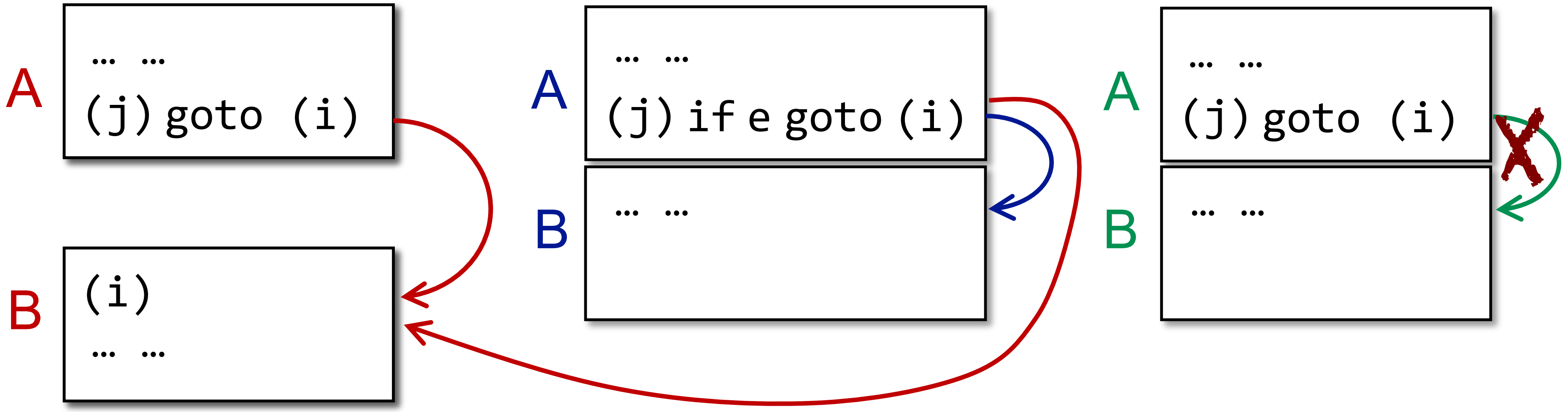


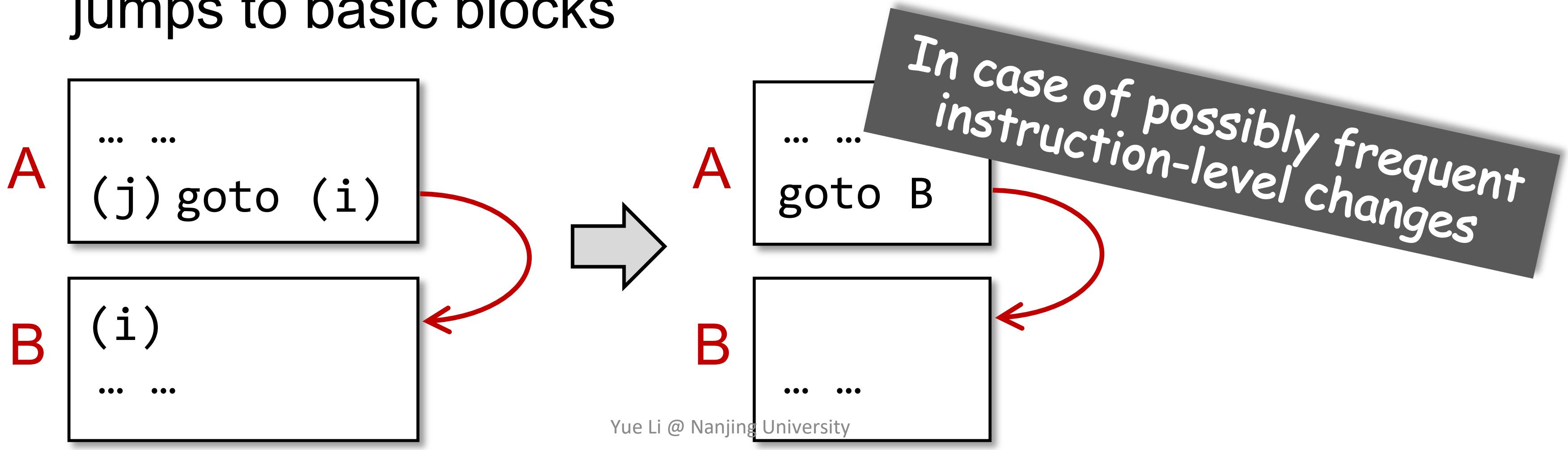
Control Flow Graph (CFG)

- The nodes of CFG are basic blocks
- There is an edge from block A to block B if and only if
  - There is a conditional or unconditional jump from the end of A to the beginning of B
  - B immediately follows A in the original order of instructions and A does not end in an unconditional jump



Control Flow Graph (CFG)

- The nodes of CFG are basic blocks
- There is an edge from block A to block B if and only if
  - There is a conditional or unconditional jump from the end of A to the beginning of B
  - B immediately follows A in the original order of instructions and A does not end in an unconditional jump
- It is normal to replace the jumps to instruction labels by jumps to basic blocks



```
B1   (1) x = input
     (2) y = x - 1

B2   (3) z = x * y
     (4) if z < x goto (7)

B3   (5) p = x / y
     (6) q = p + y

B4    (7) a = q
      (8) b = x + a
      (9) c = 2a - b
     (10) if p == q goto (12)

B5   (11) goto (3)

B6   (12) return
```

⇨

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Add edges in CFG

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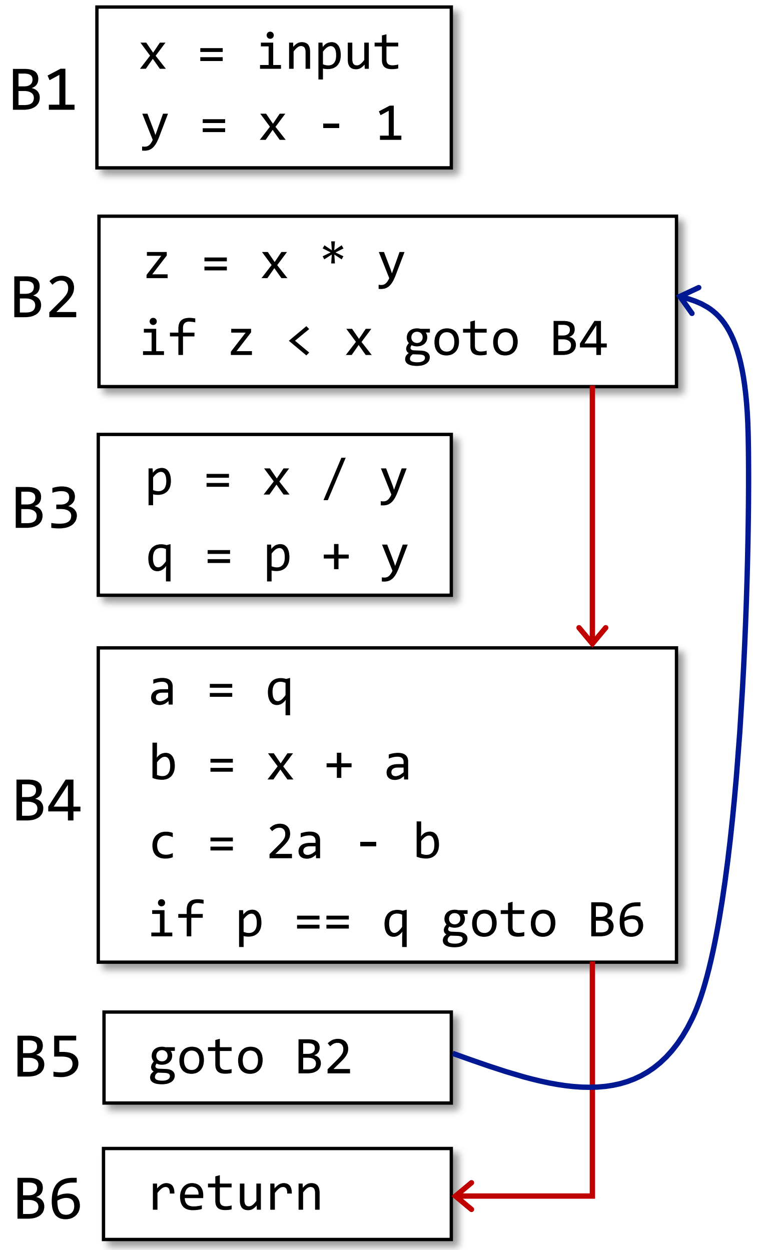

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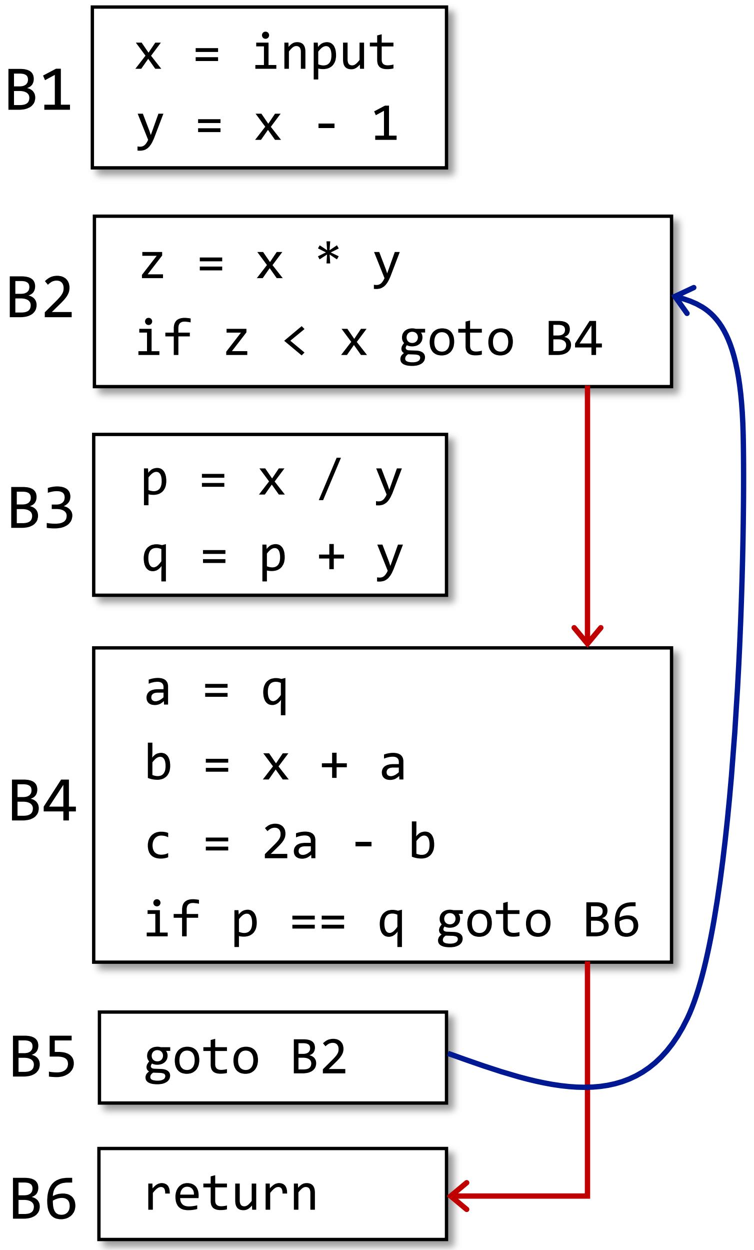
Add edges in CFG



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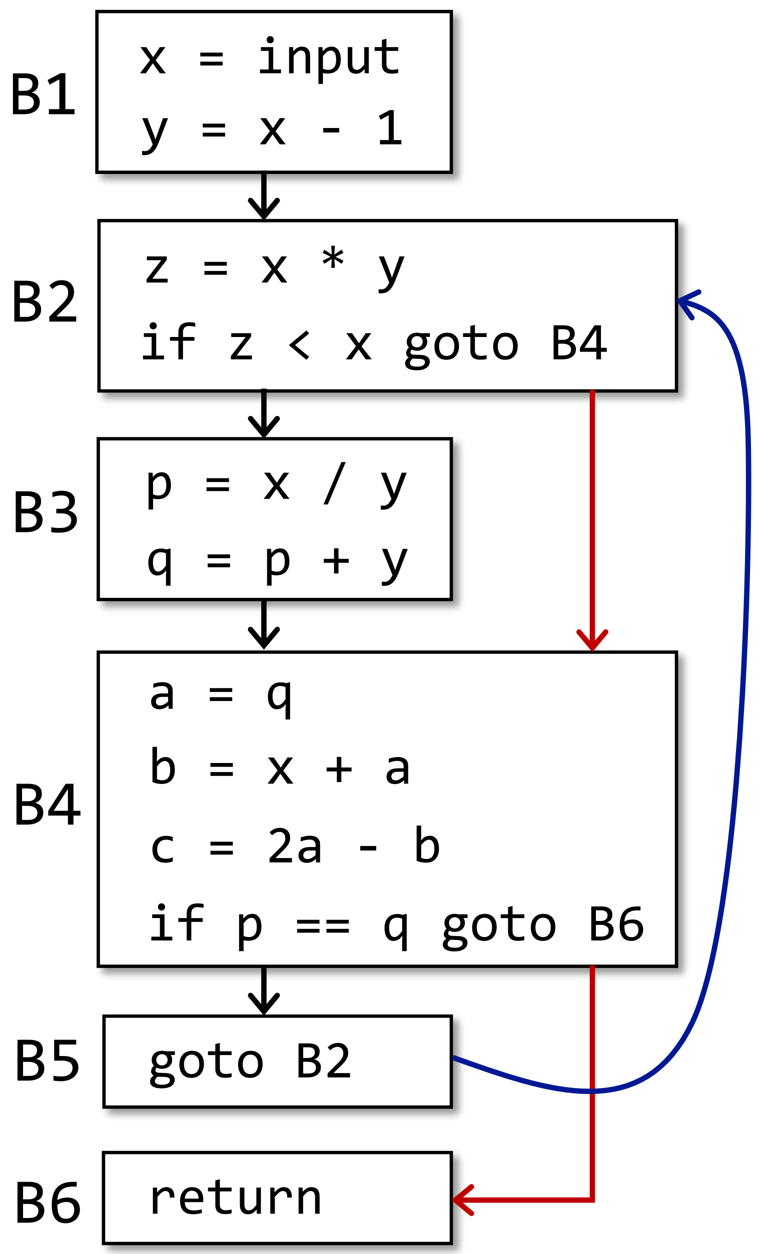
B immediately follows **A** in the original order of instructions and **A** does not end in an unconditional jump



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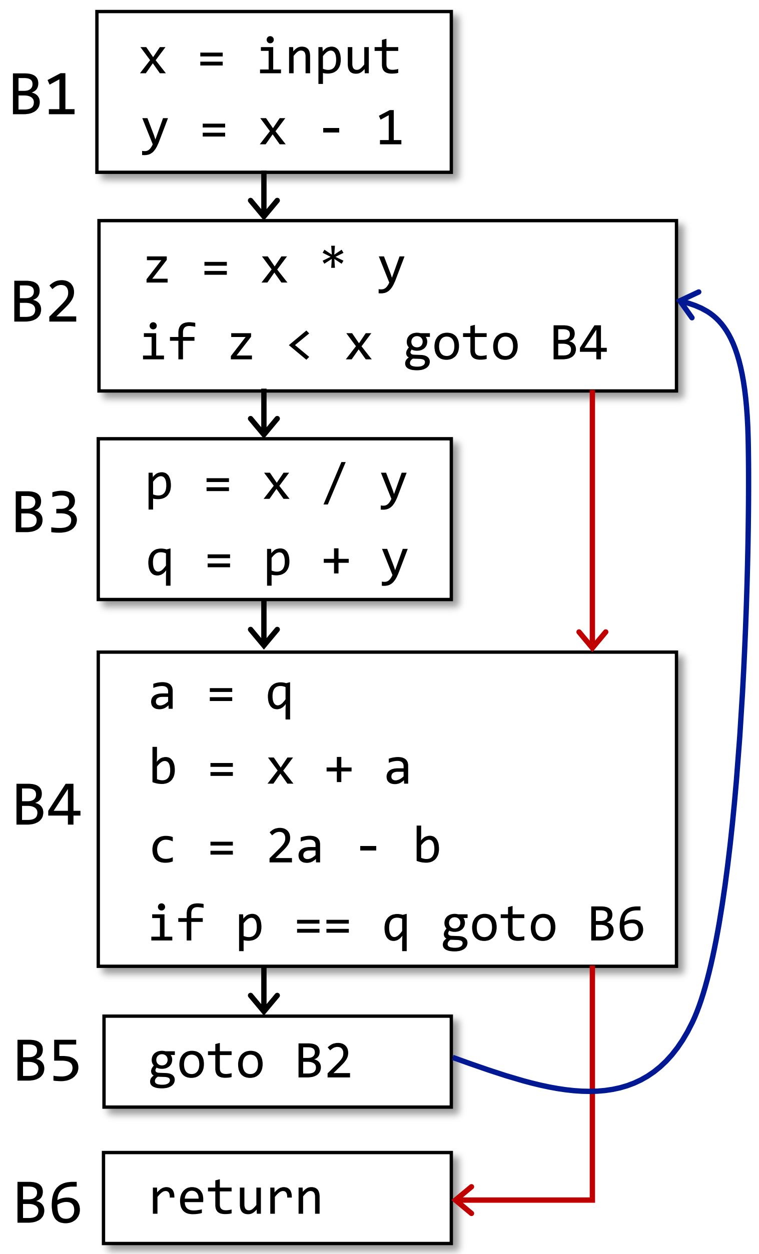

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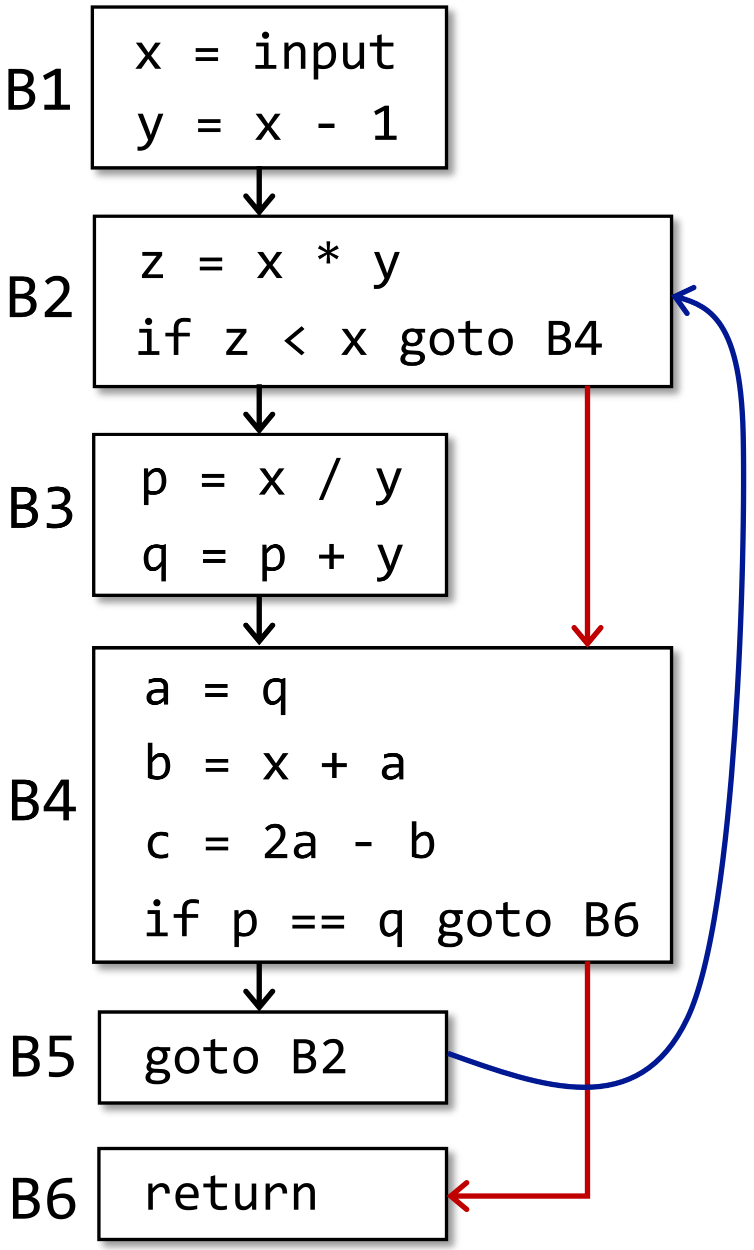
We say that **A** is a **predecessor** of **B**, and **B** is a **successor** of **A**

Add edges in CFG



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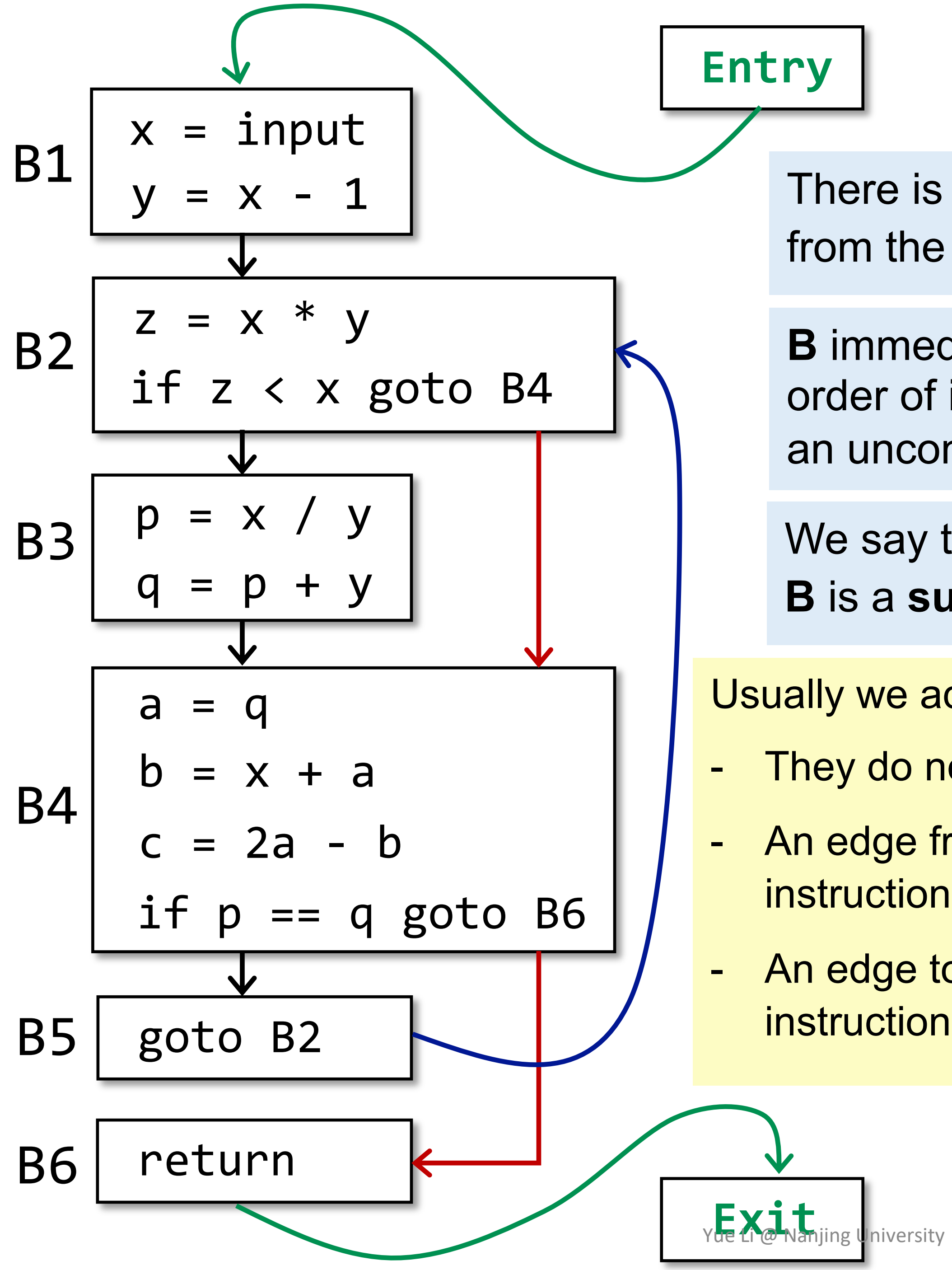
Usually we add two nodes, **Entry** and **Exit**.

- They do not correspond to executable IR
- An edge from Entry to the BB containing the first instruction of IR
- An edge to Exit from any BB containing an instruction that could be the last instruction of IR

Add edges in CFG



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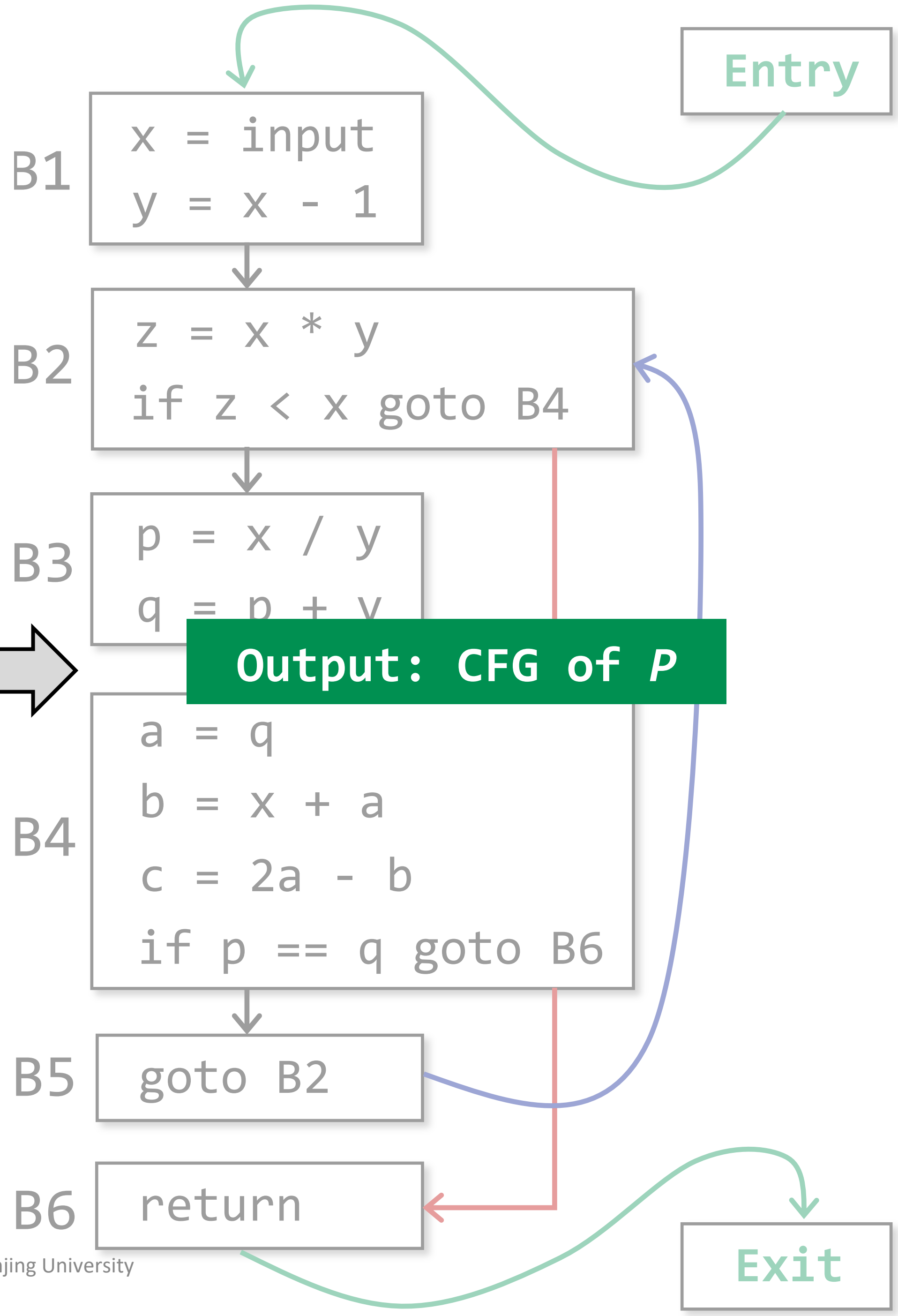
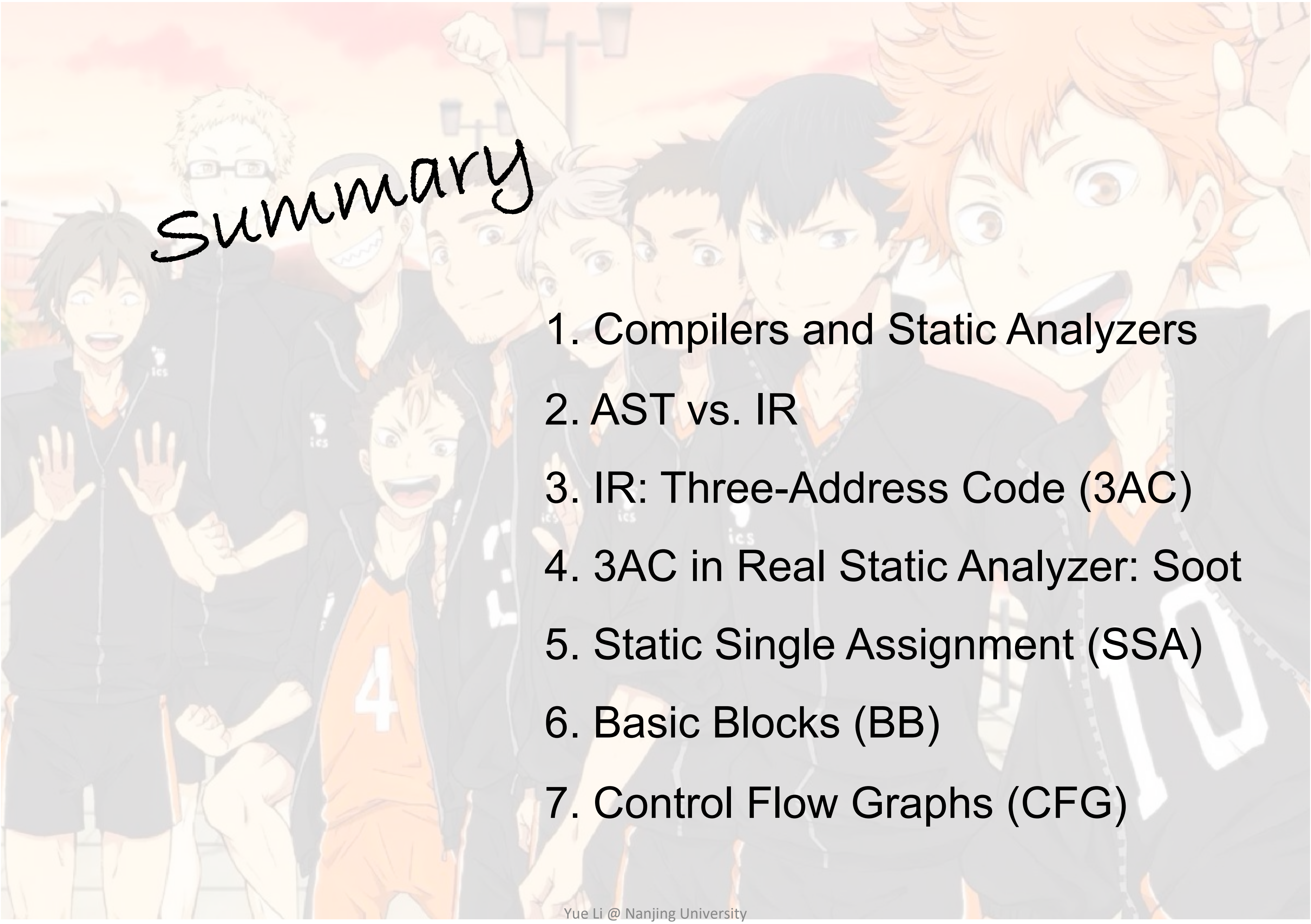
Input: 3AC of *P*

Output: CFG of *P*





Summary

1. Compilers and Static Analyzers
2. AST vs. IR
3. IR: Three-Address Code (3AC)
4. 3AC in Real Static Analyzer: Soot
5. Static Single Assignment (SSA)
6. Basic Blocks (BB)
7. Control Flow Graphs (CFG)

The X You Need To Understand in This Lecture

- The relation between compilers and static analyzers
- Understand 3AC and its common forms
- How to build basic blocks on top of IR
- How to construct control flow graphs on top of BBs?