Static Program Analysis

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2020 Spring

Static Program Analysis

Intermediate Representation

Nanjing University

Yue Li

2020

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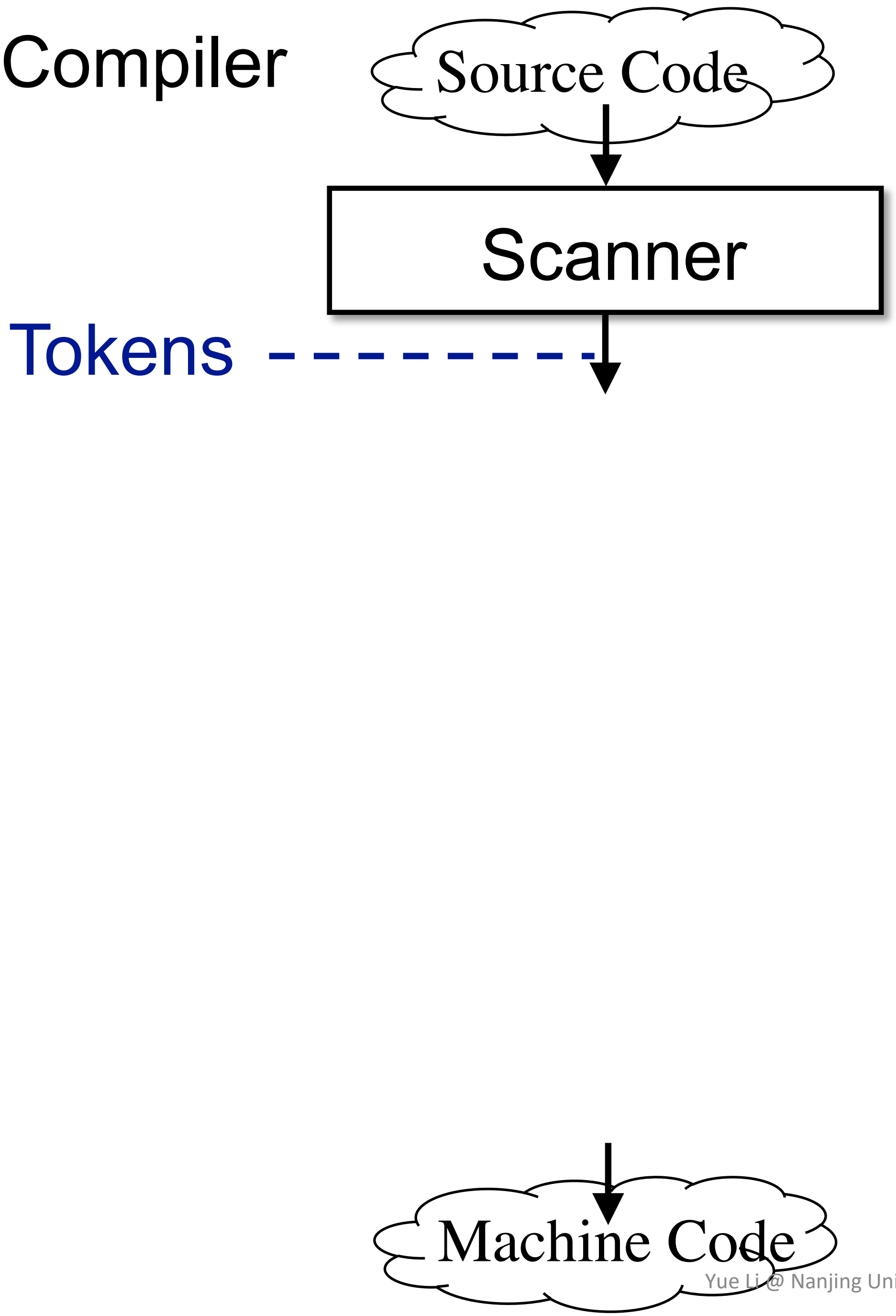
Compiler

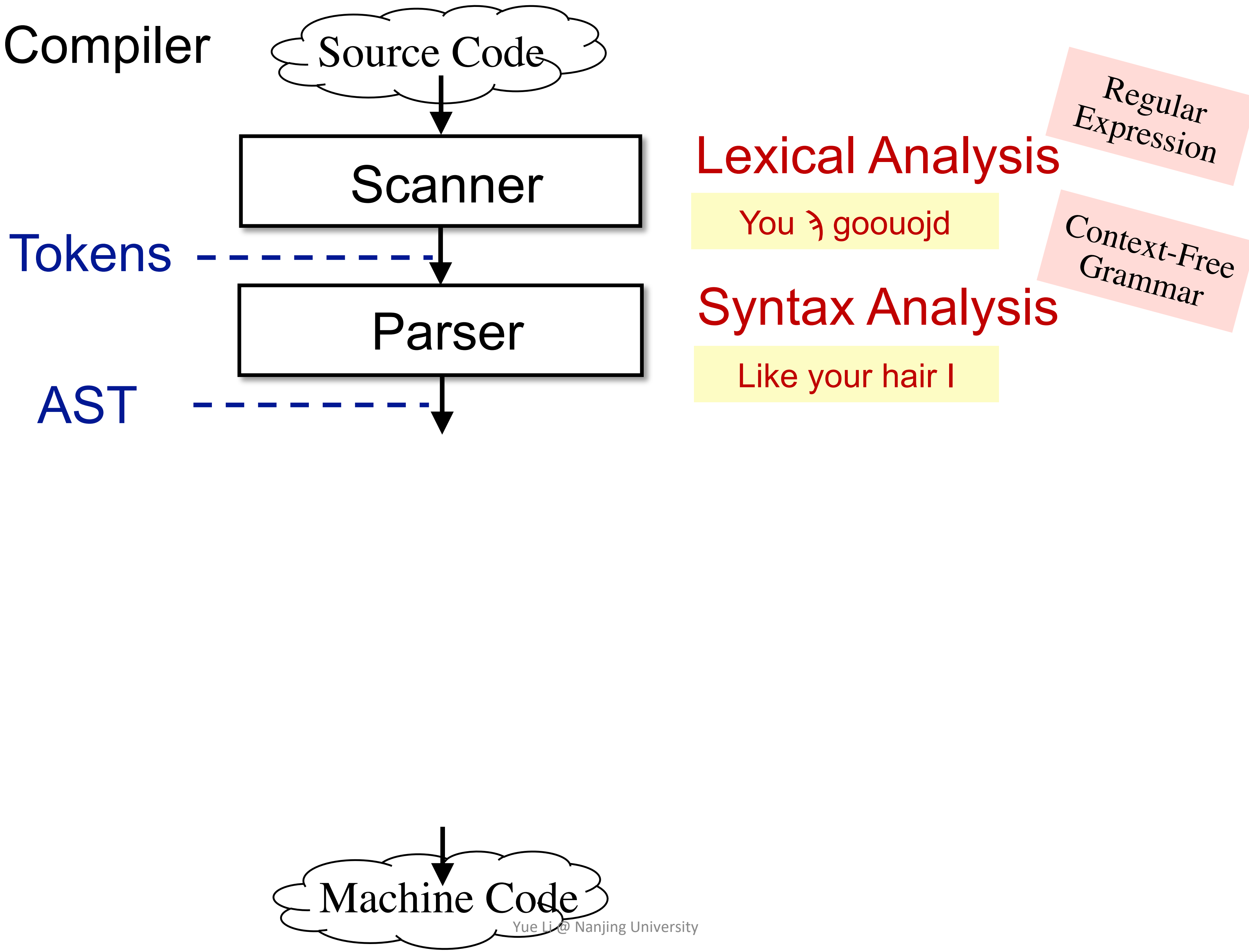
Compiler



Lexical Analysis

You [illegible] goouojd

Regular Expression


Compiler
Source Code
Scanner
Tokens
Parser
AST
Machine Code
Lexical Analysis
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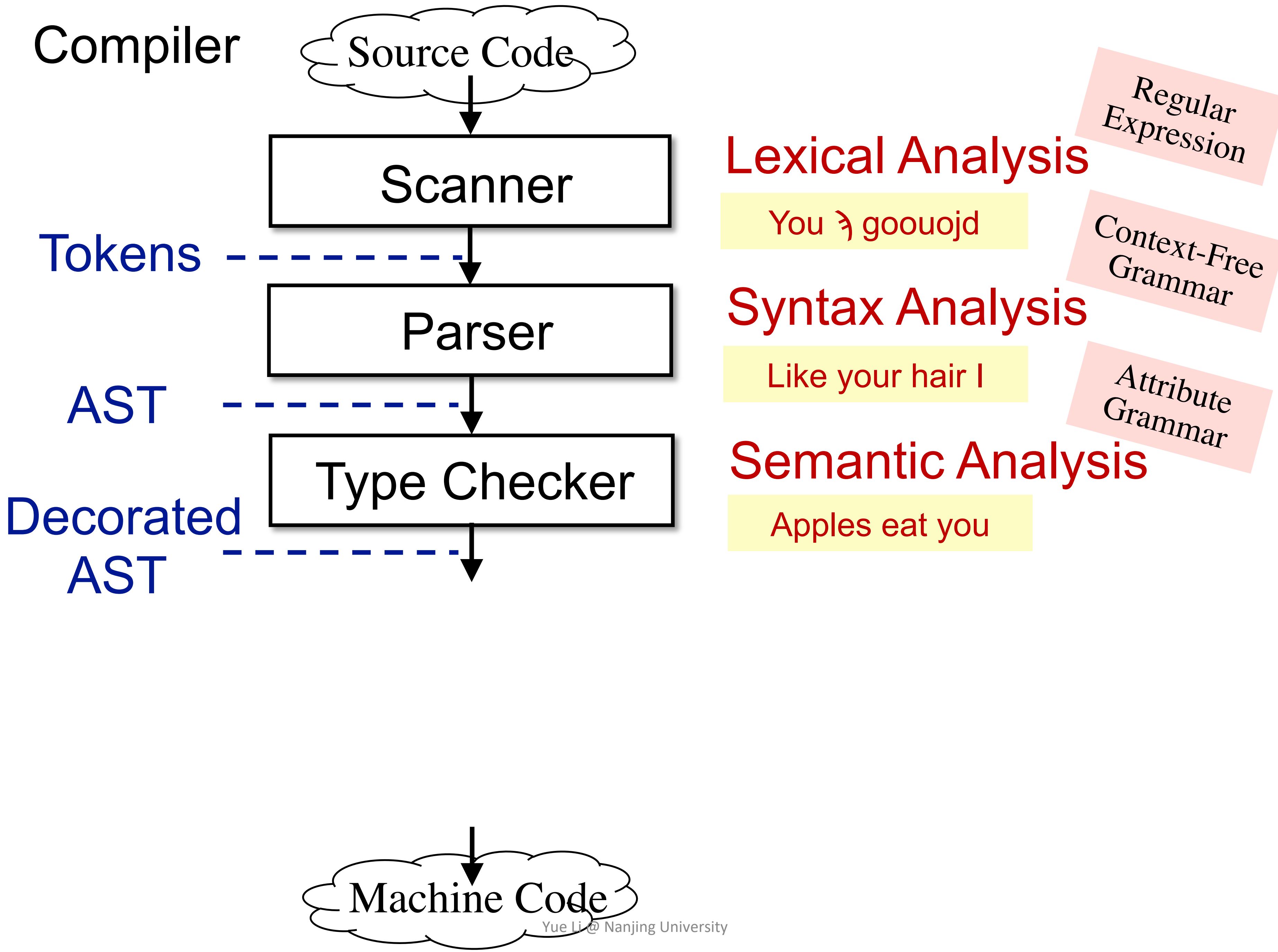
Syntax Analysis
Like your hair I
Regular Expression
Context-Free Grammar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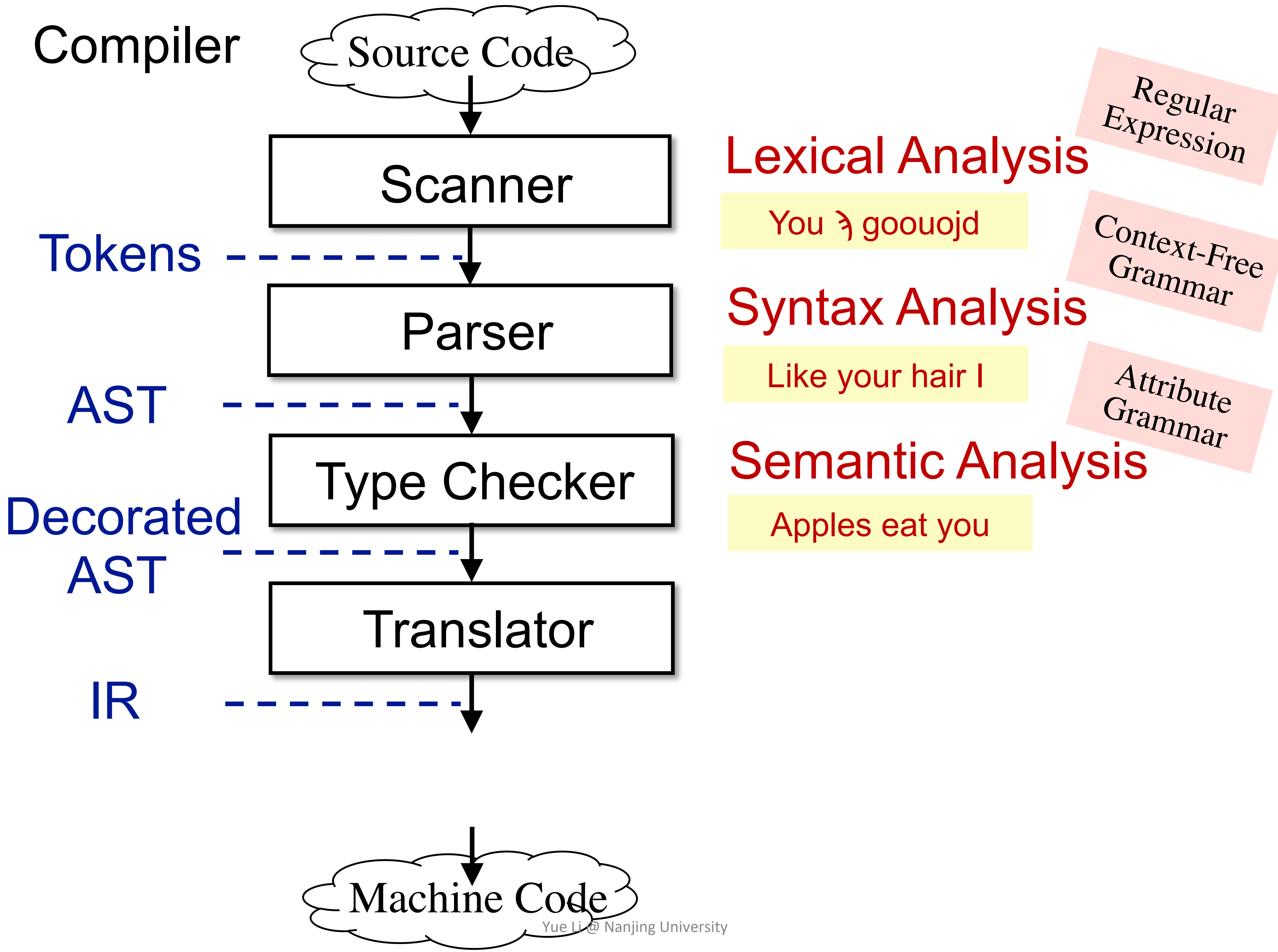

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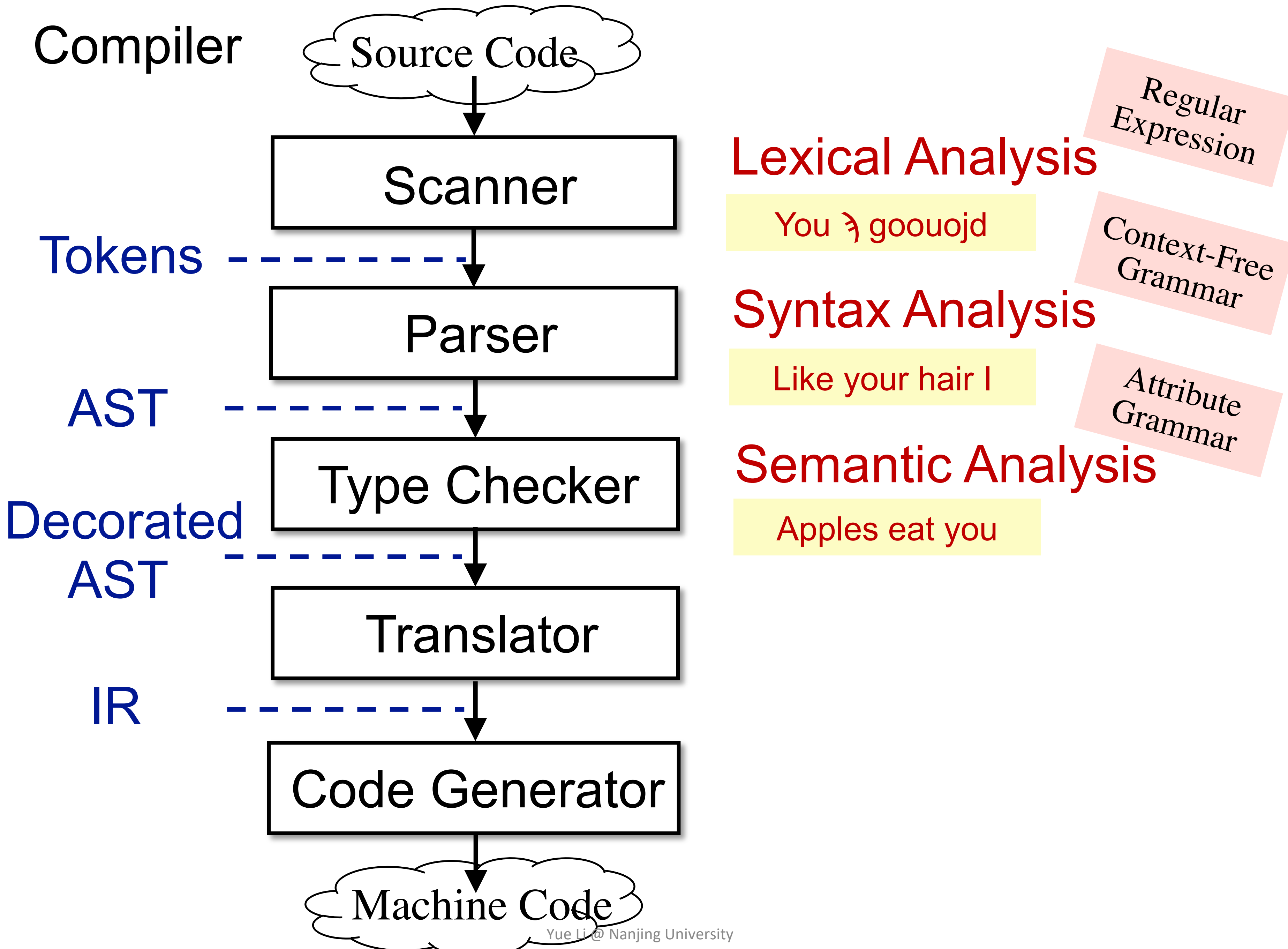
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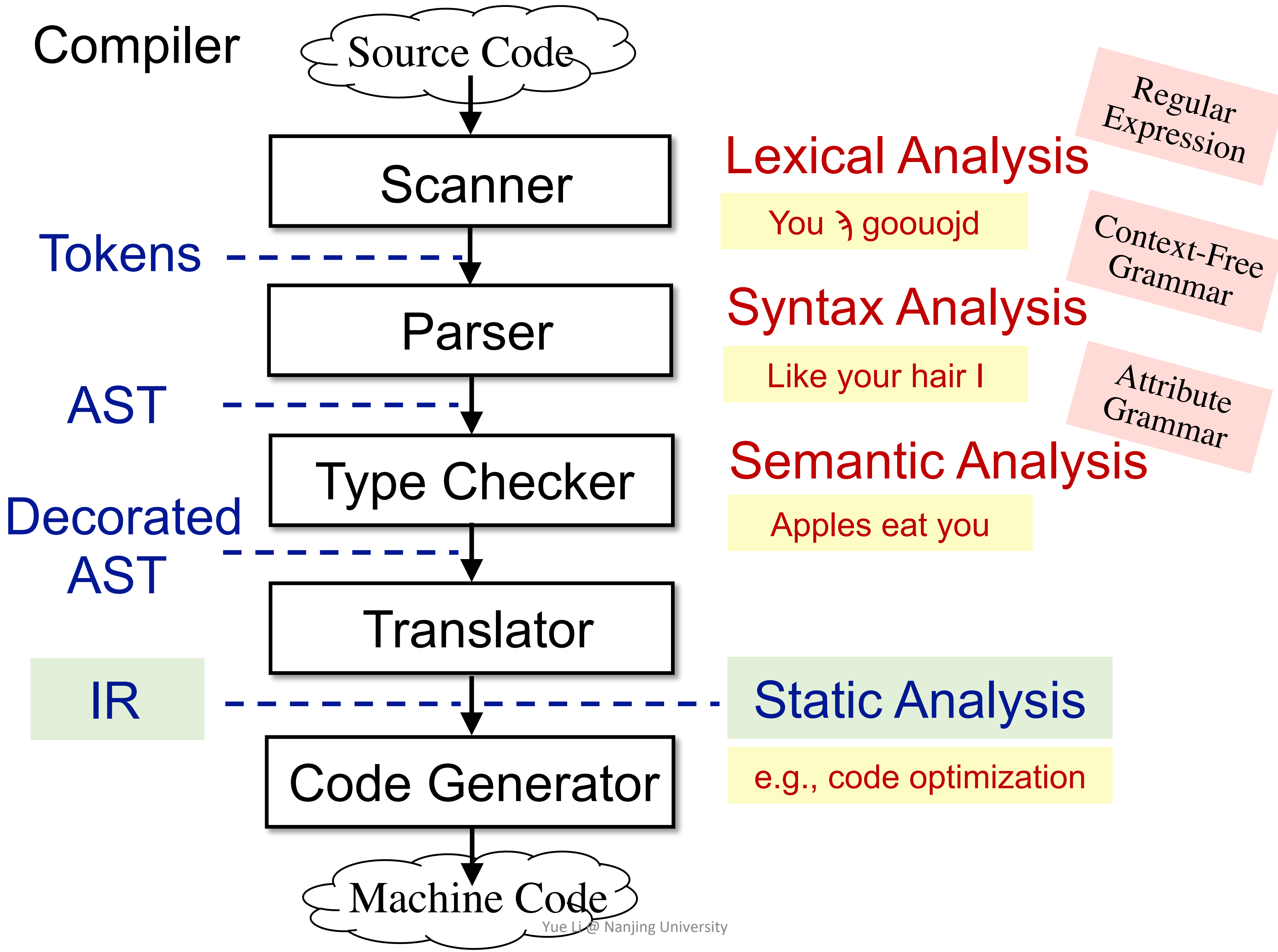
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e.g., code optimization
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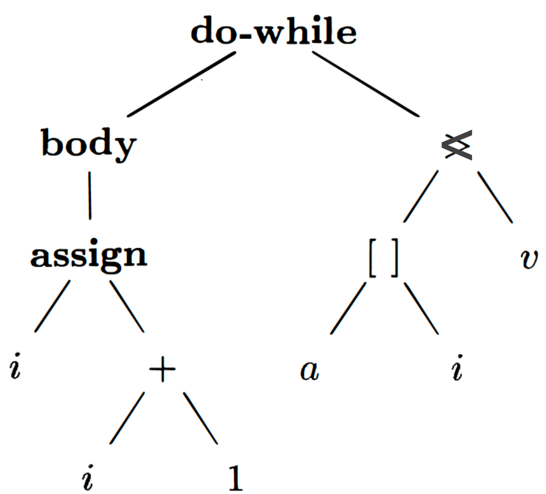
AST vs. IR

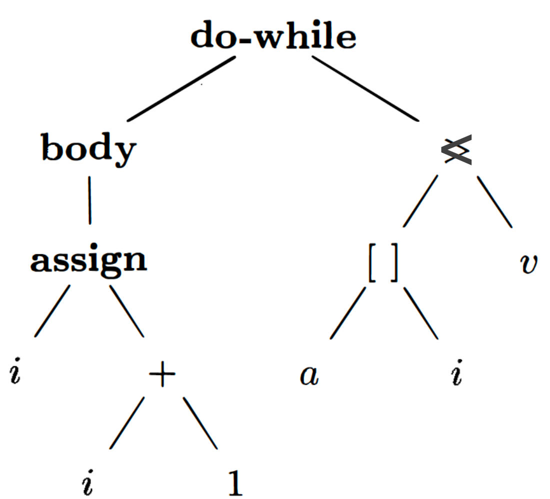
AST




```
"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

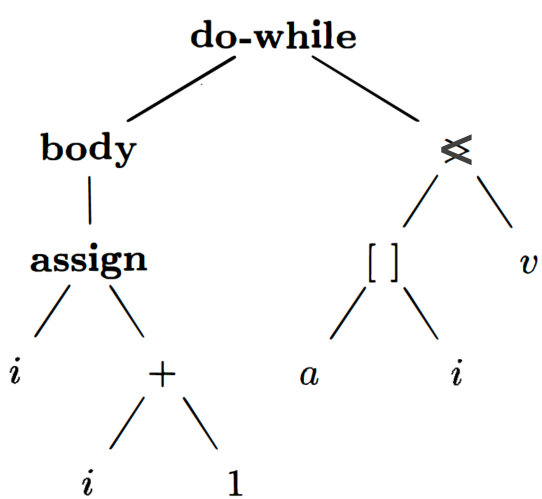
- high-level and closed to grammar structure
- usually language dependent
- suitable for fast type checking
- lack of control flow information

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

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

AST



IR

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1: i = i + 1
2: t1 = a [ i ]
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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.

$$t2 = a + b + 3 \Rightarrow \begin{array}{l} t1 = a + b \\ t2 = t1 + 3 \end{array}$$

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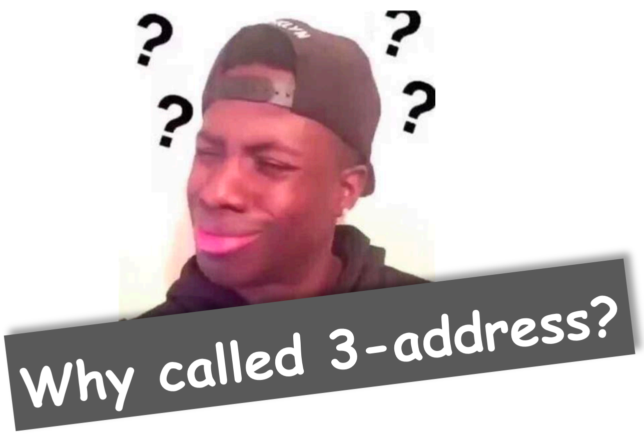

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t2 = a + b + 3 ⇨ t1 = a + b
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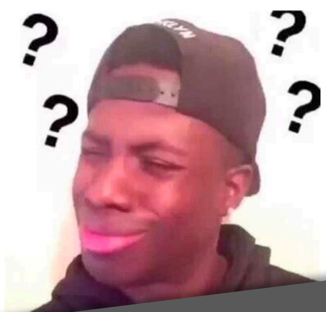
Each 3AC contains at most 3 addresses



Why called 3-address?

Intermediate Representation (IR)

- 3-Address Code (3AC)

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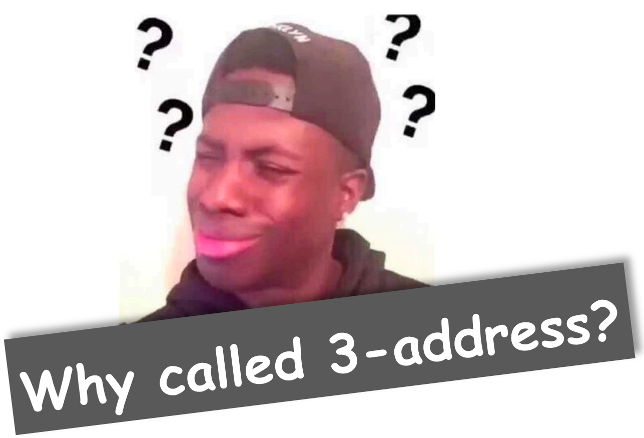

Address can be one of the following:

- Name: a, b
- Constant: 3
- Compiler-generated temporary: t1, t2

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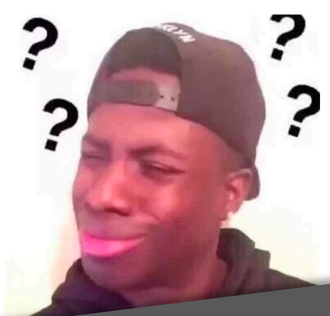

Why called 3-address?

Address can be one of the following:

- Name: a, b
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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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goto L: unconditional 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

```java
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

```java
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

```
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");
    }
}
```

Java Src

Method Call

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

    String foo(String para1, String para2) {
        return para1 + " " + para2;
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        String result = mc.foo("hello", "world");
    }
}
```

Java Src

Method Call

```
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)

Method Call

Java Src

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

    String foo(String para1, String para2) {
        return para1 + " " + para2;
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    public static void main(String[] args) {
        MethodCall3AC mc = new MethodCall3AC();
        String result = mc.foo("hello", "world");
    }
}
```

3AC(jimple)

```
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;
}
```

Class

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

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

    }
}
```

Java Src

```
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)

Class

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package nju.sa.examples;
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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

3AC	SSA
$p = a + b$	$p_1 = a + b$
$q = p - c$	$q_1 = p_1 - c$
$p = q * d$	$p_2 = q_1 * d$
$p = e - p$	$p_3 = e - p_2$
$q = p + q$	$q_2 = p_3 + q_1$

Static Single Assignment (SSA)

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


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

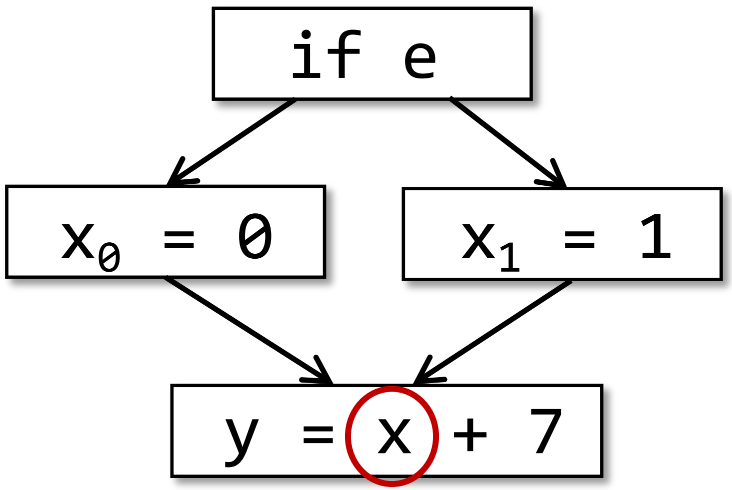
3AC

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

SSA

Static Single Assignment (SSA)

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



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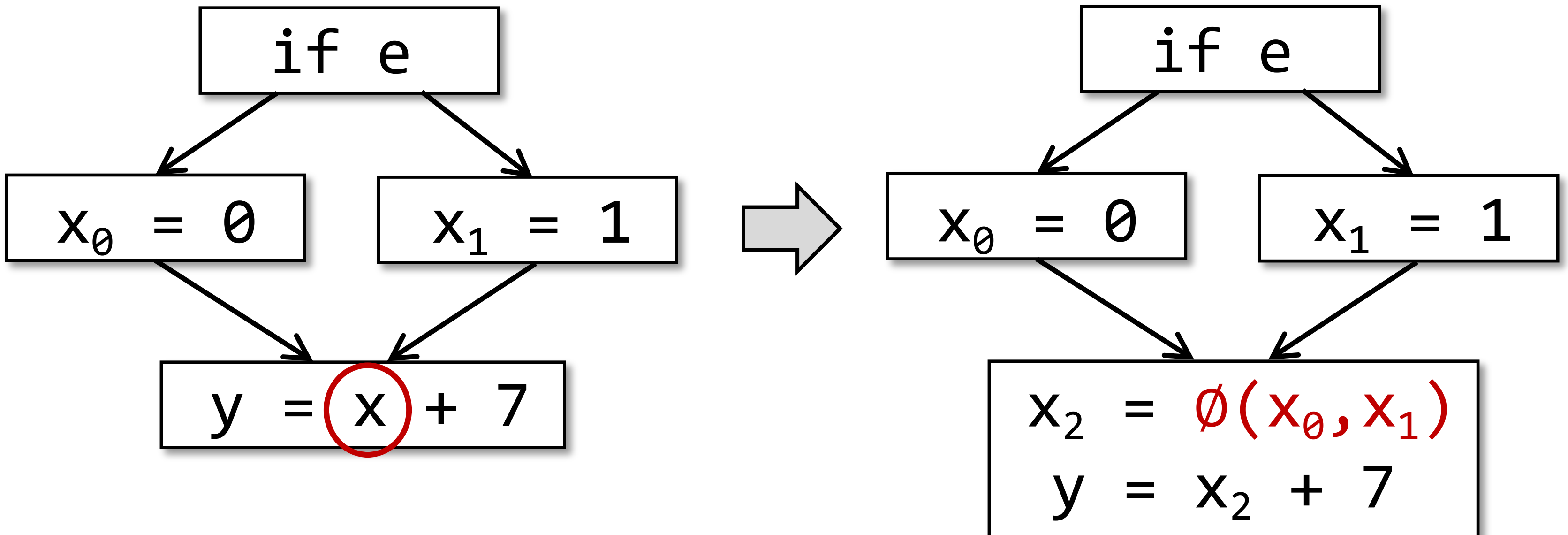

  - A special merge operator, Ø (called phi-function), is introduced to select the values at merge nodes
  - $Ø(x_0,x_1)$ has the value x_0 if the control flow passes through the true part of the conditional and the value x_1 otherwise

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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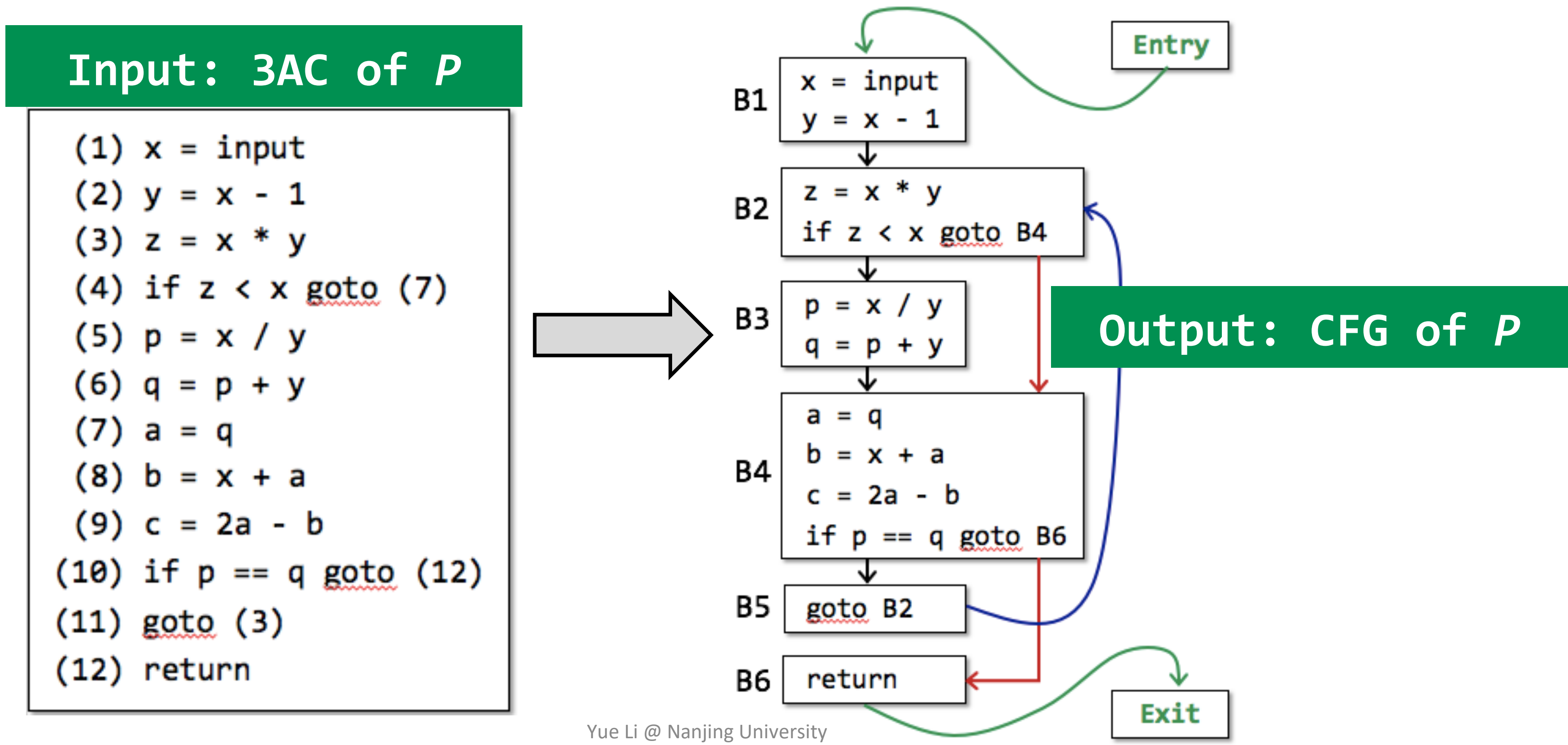
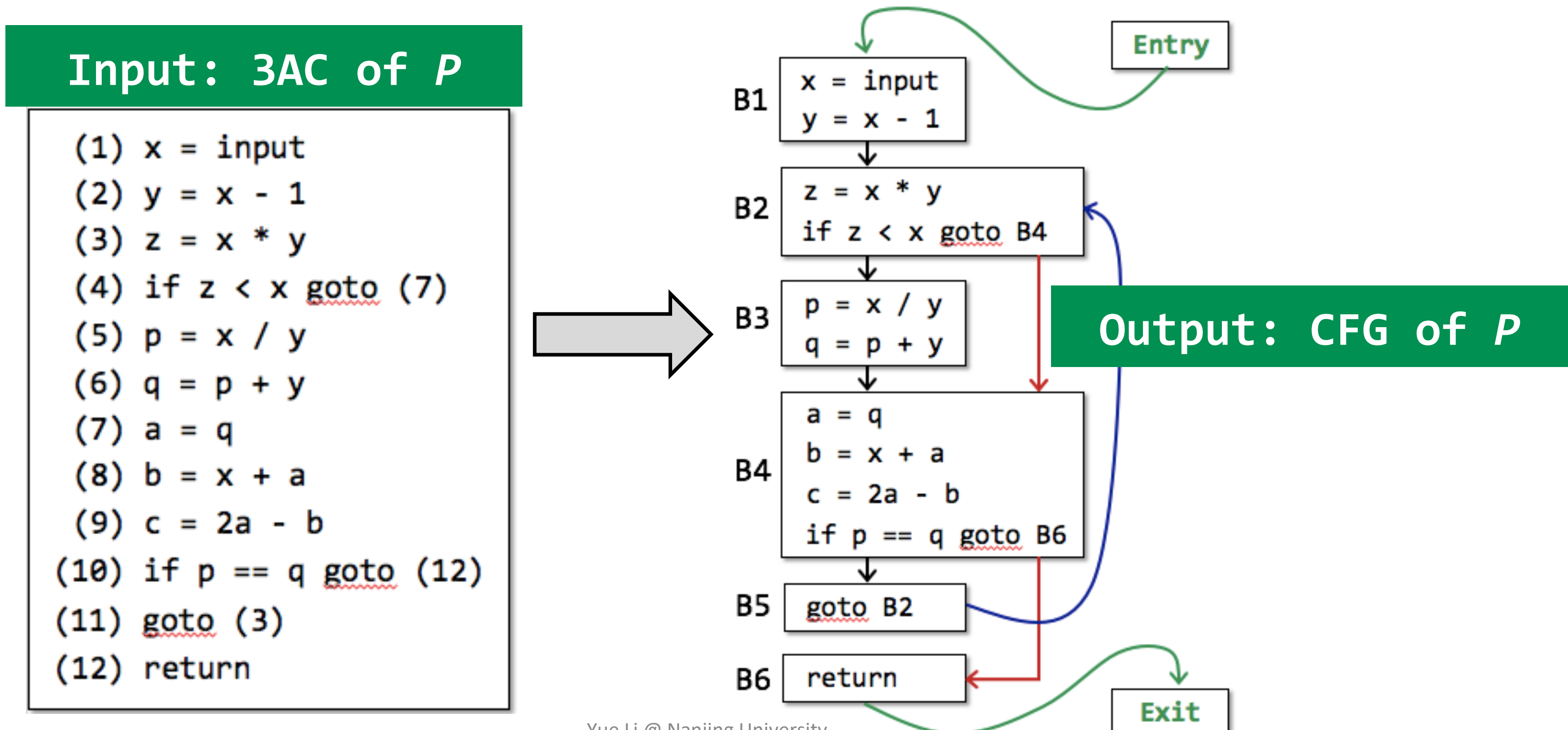


Control Flow Analysis

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



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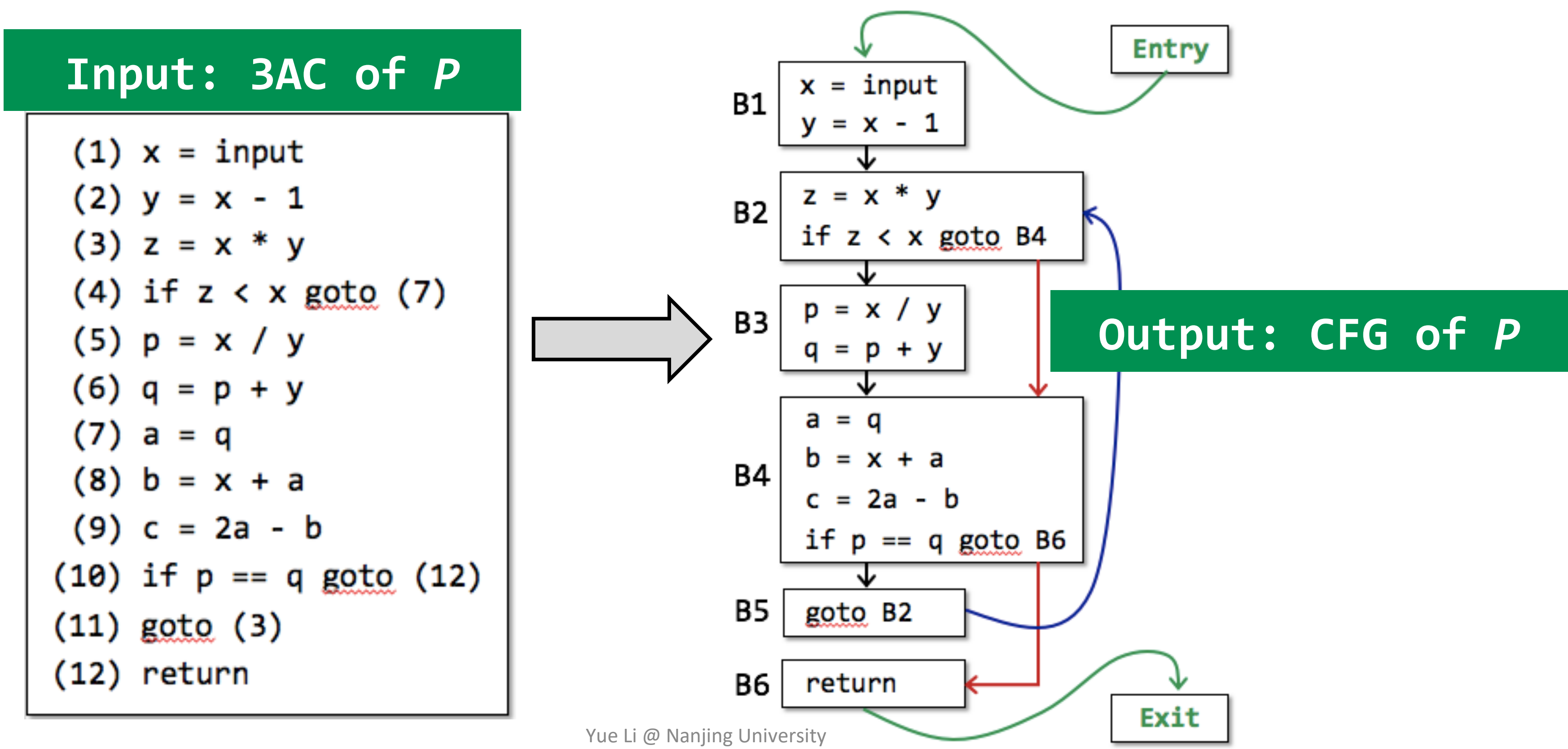
- The node in CFG can be an individual 3-address instruction, or (usually) a Basic Block (BB)



Control Flow Analysis

- Usually refer to building Control Flow Graph (CFG)
- CFG serves as the basic structure for static analysis
- The node in CFG can be an individual 3-address instruction, or (usually) a Basic Block (BB)

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)
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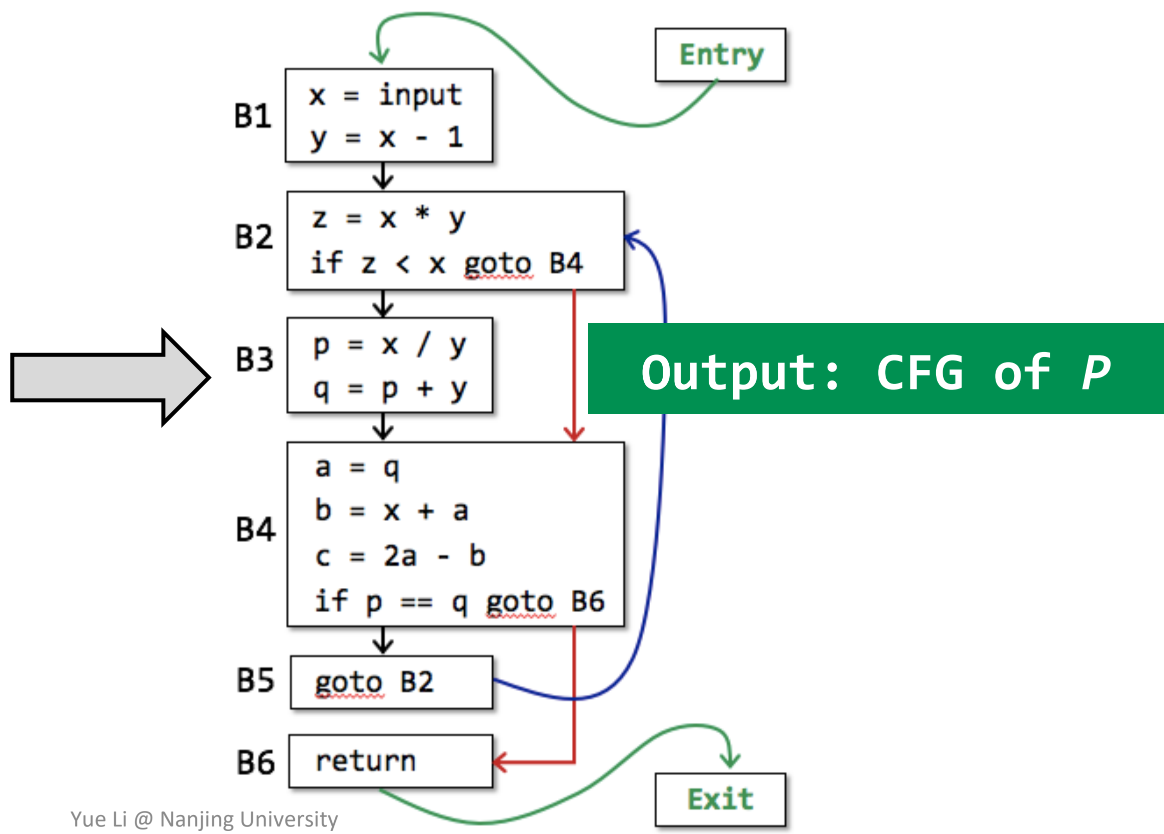

Basic Blocks (BB)

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

```
a = q
b = x + a
c = 2a - b
if p == q goto B6
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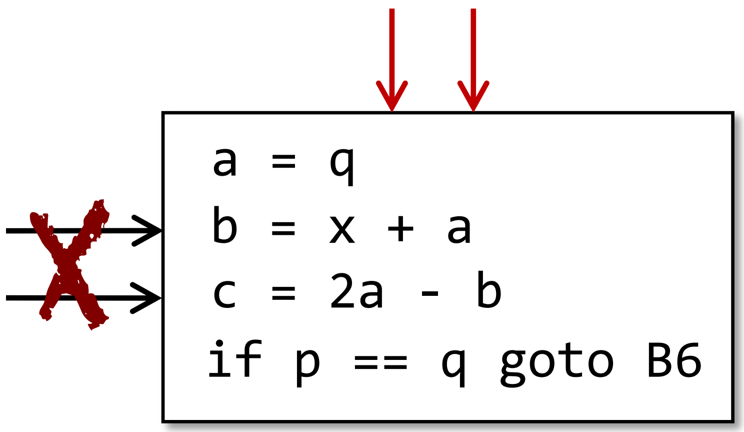

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- Basic blocks (BB) are maximal sequences of consecutive three-address instructions with the properties that
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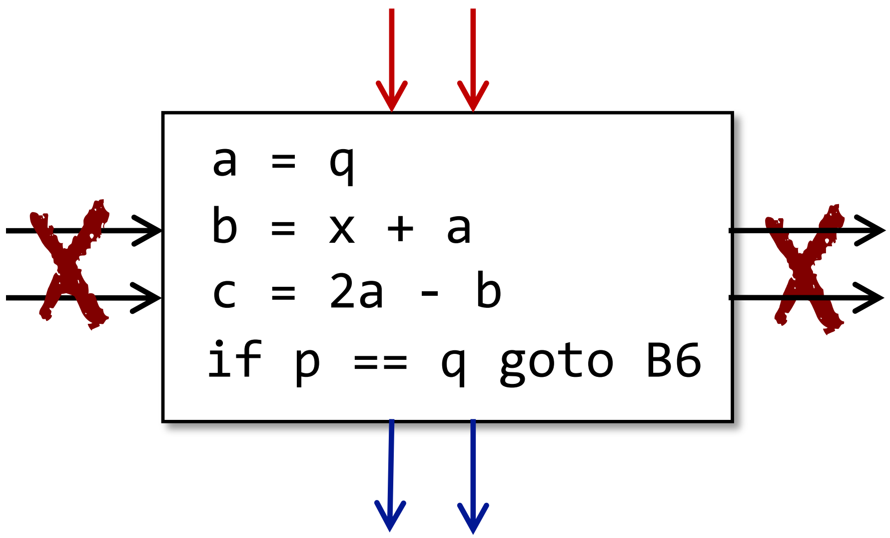

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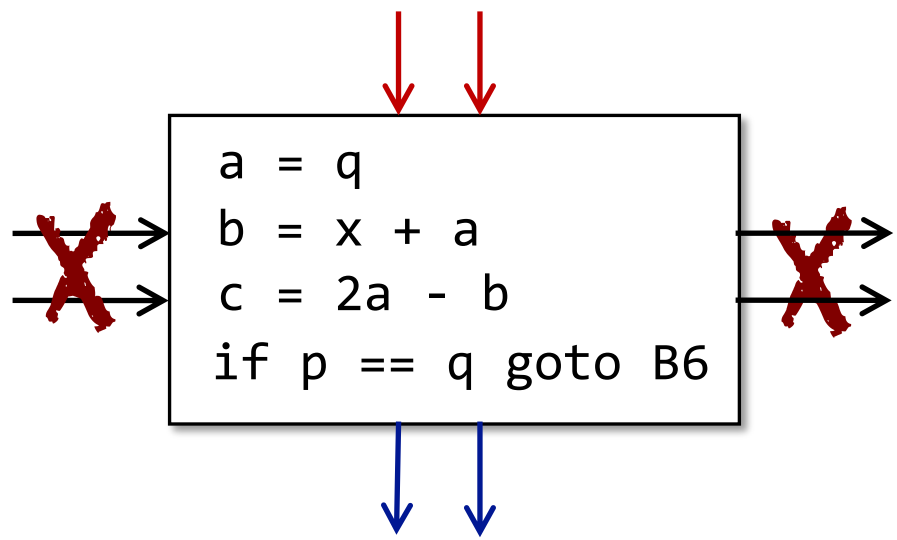
Now try to design the algorithm to build BBs by yourself!



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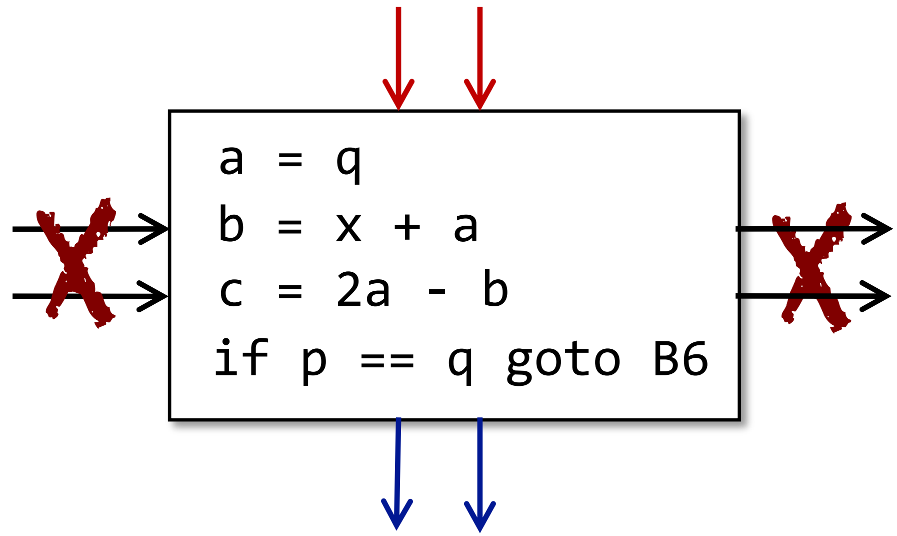

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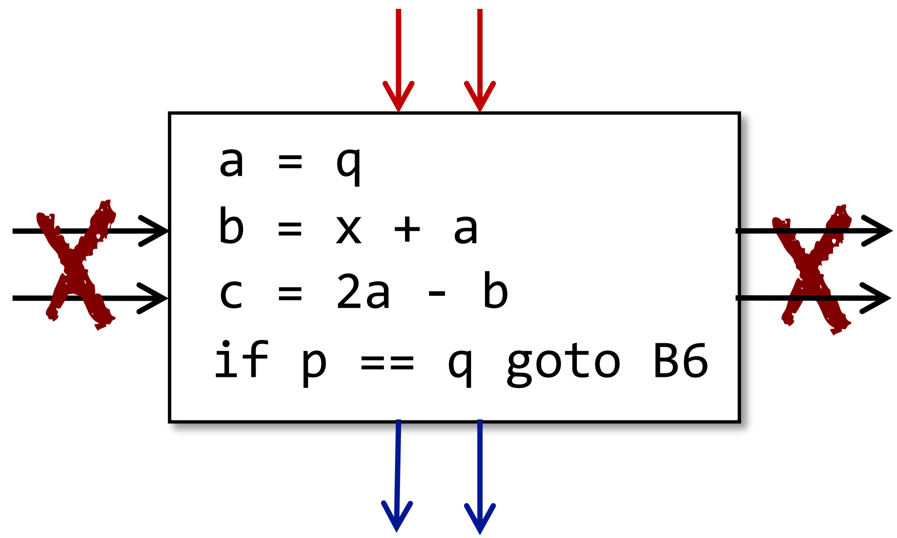

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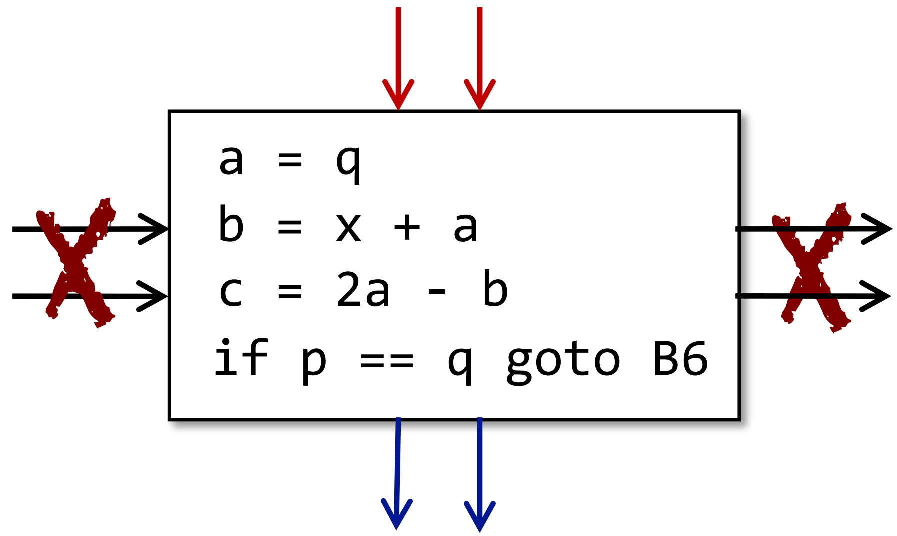

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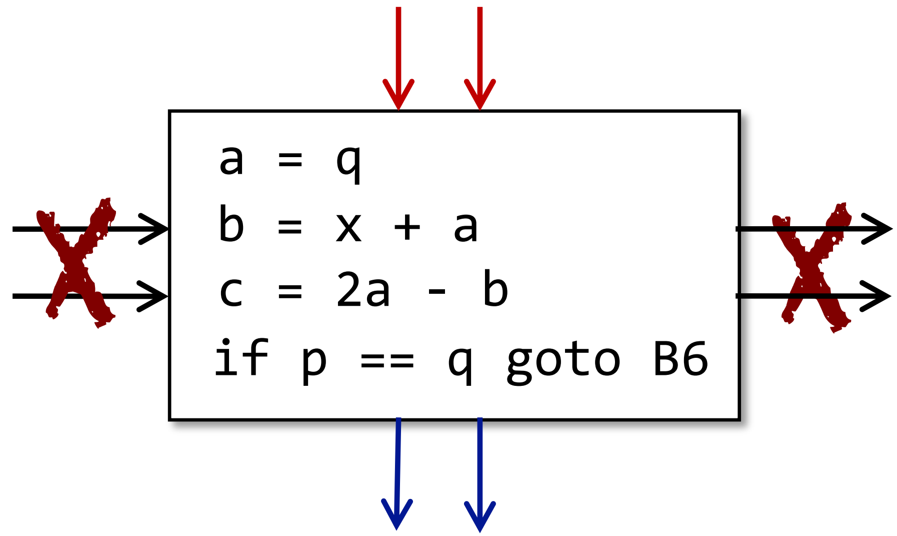

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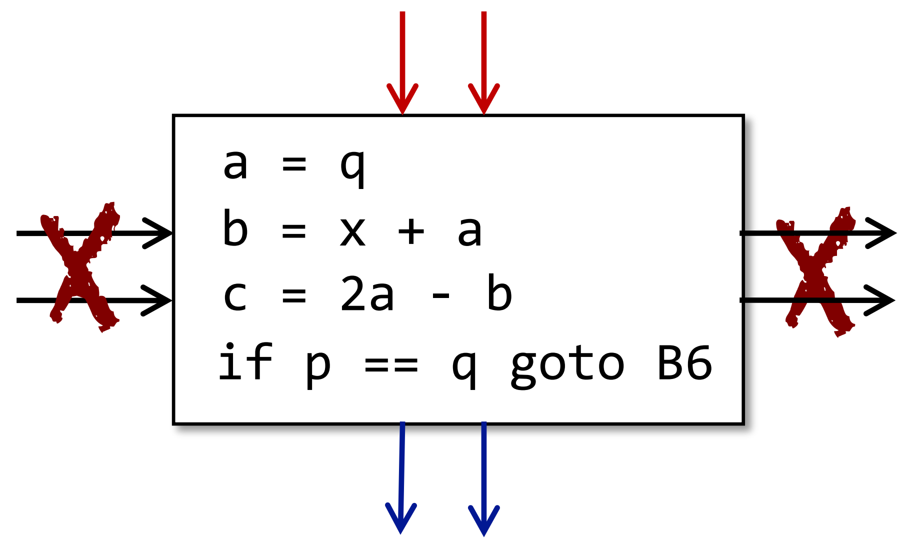

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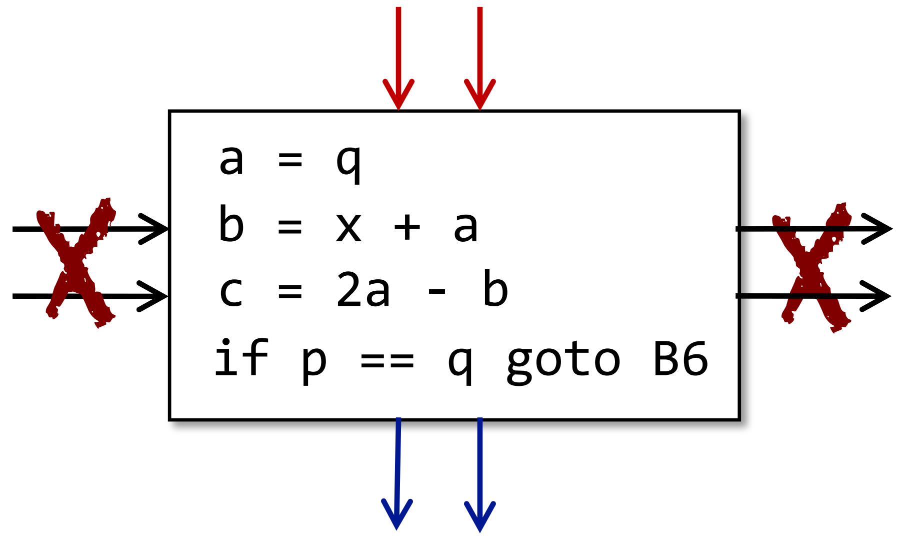

How to build Basic Blocks?

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
- Any instruction that immediately follows a conditional or unconditional jump is a leader

(2) Build BBs for P

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

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Input: 3AC of *P*

Output: BBs of *P*

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- B3 {(5)}
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How to build CFG on top of BBs?

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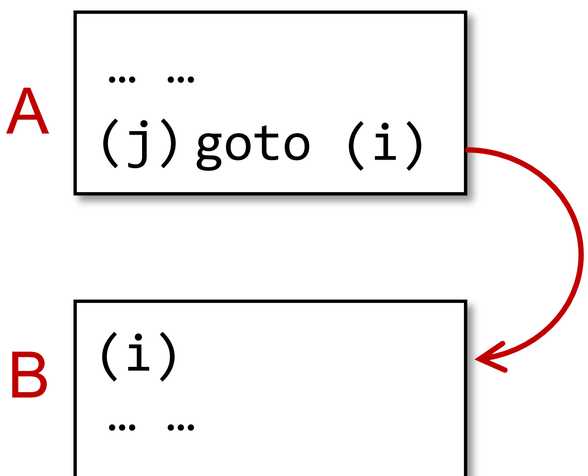

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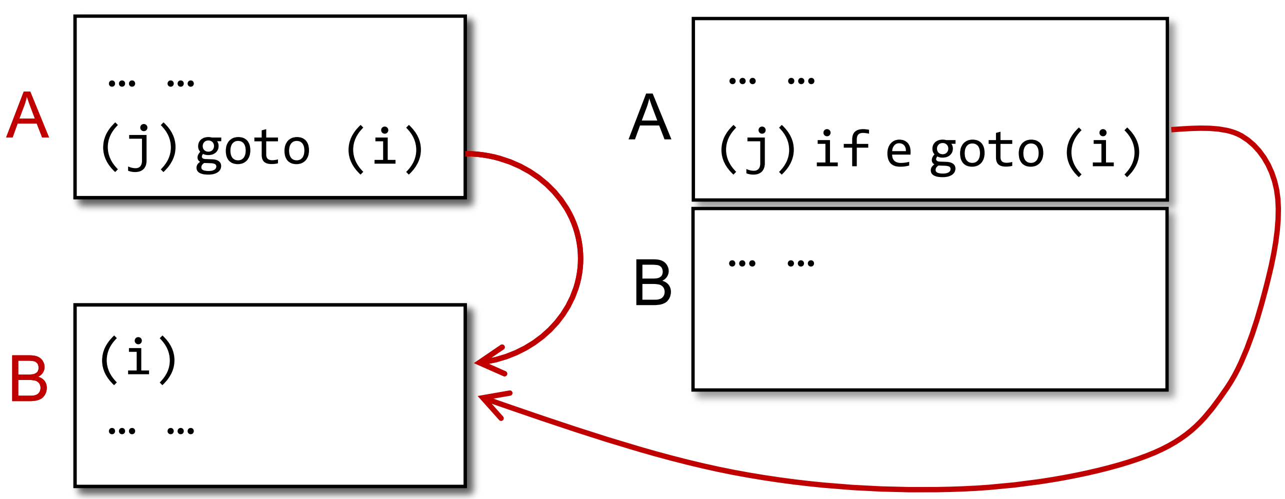

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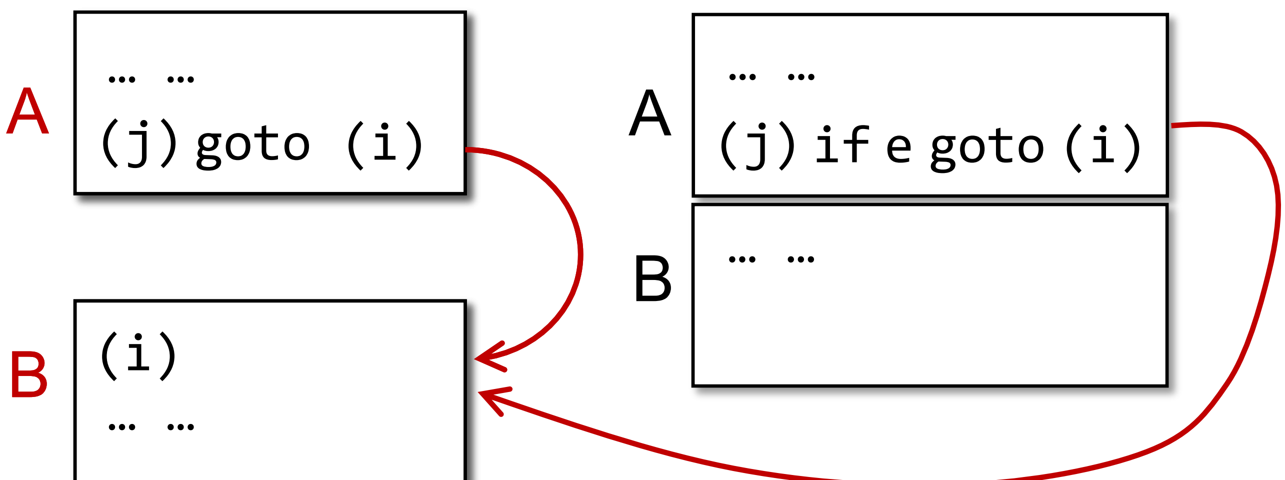

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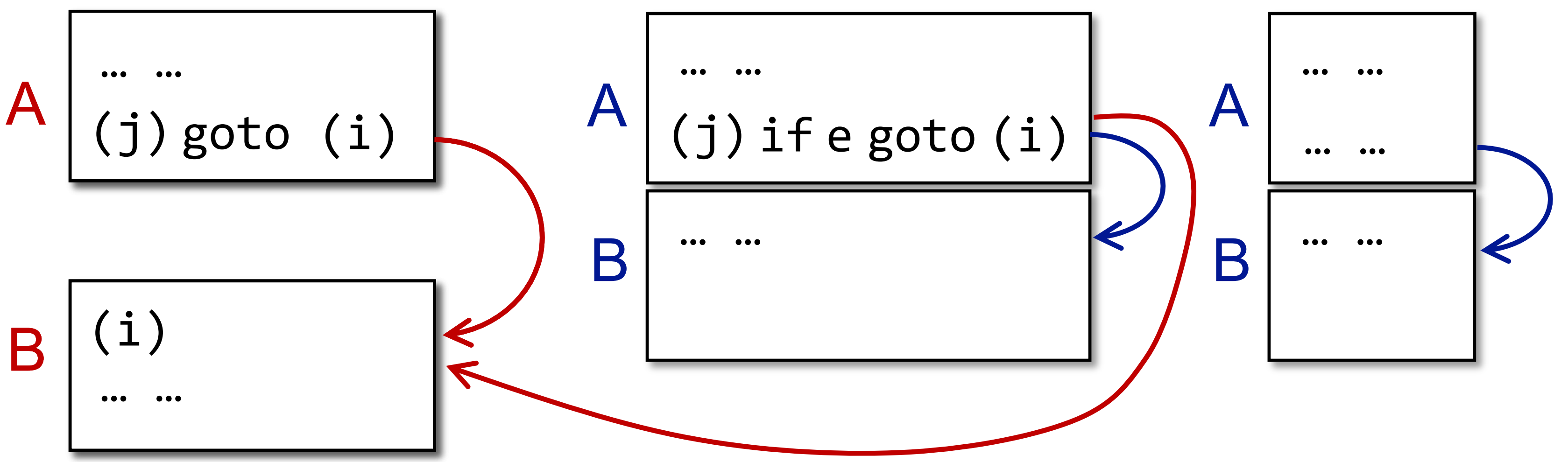

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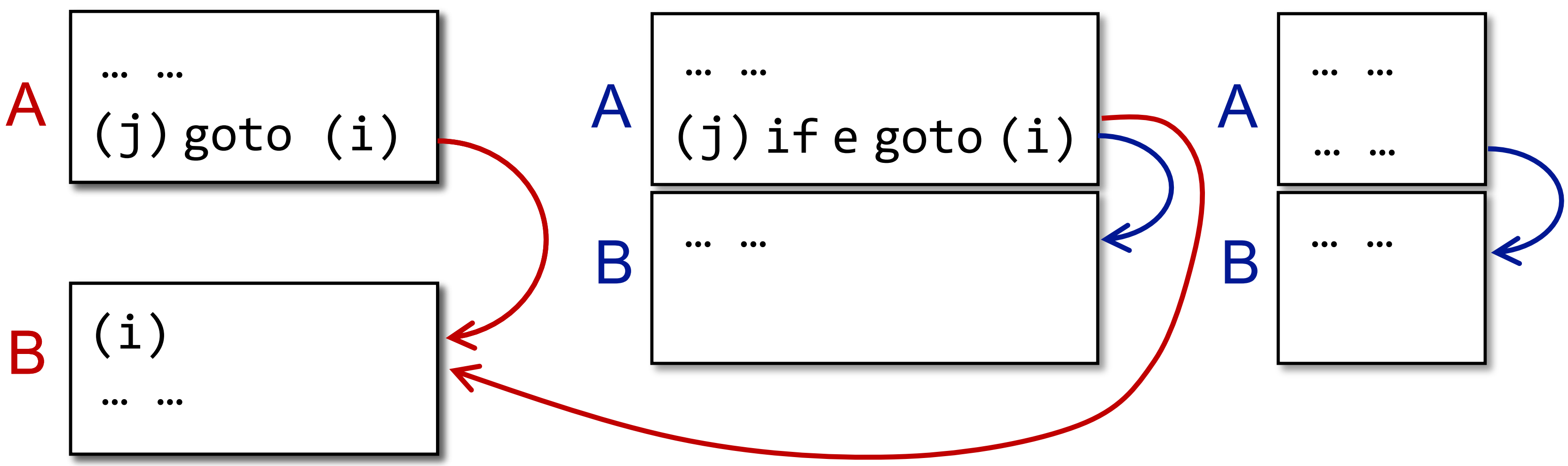

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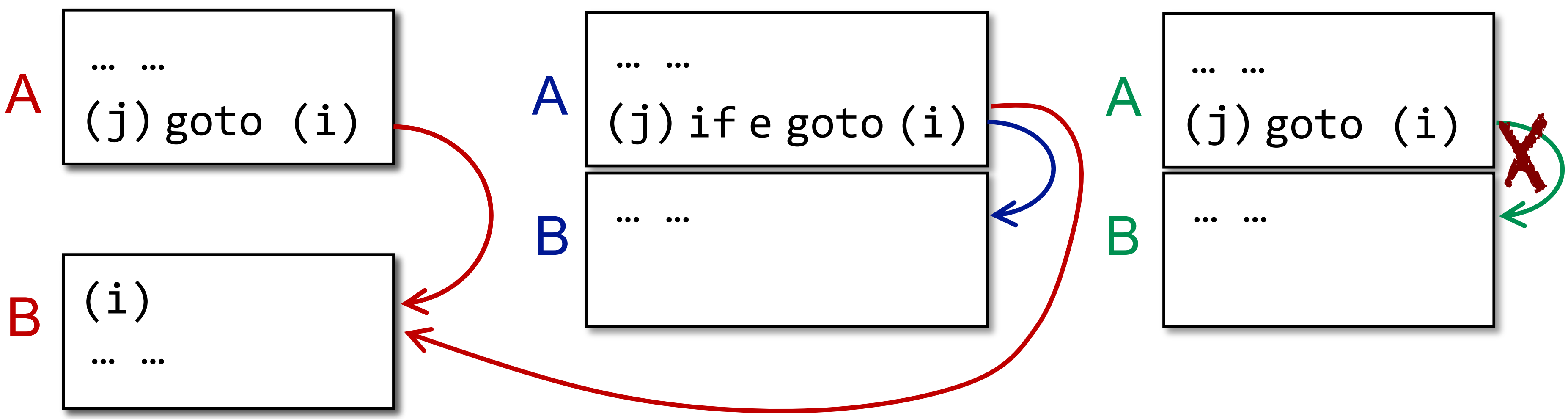
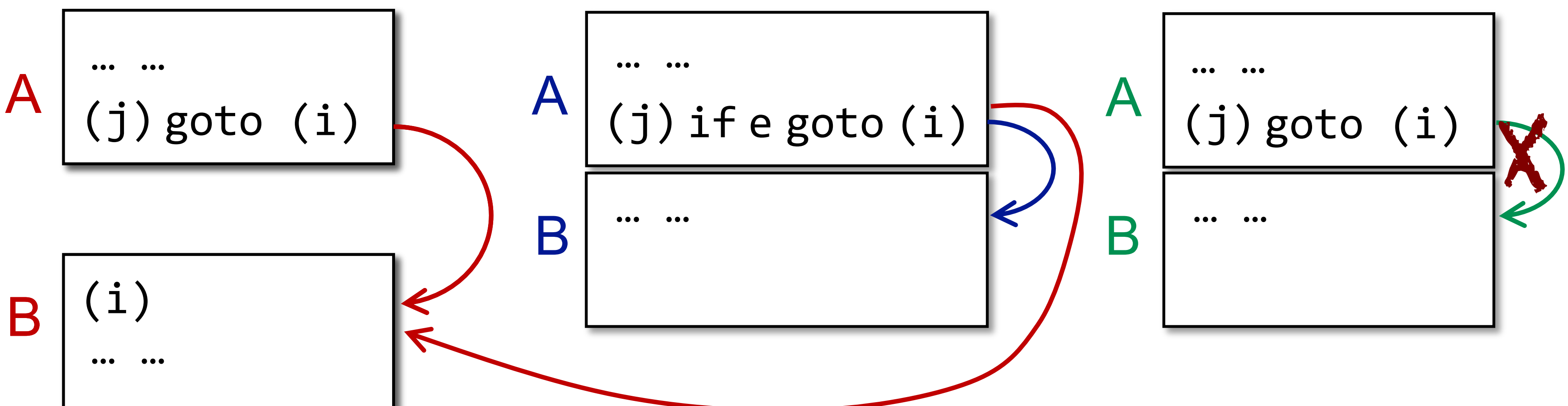


Control Flow Graph (CFG)

- 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



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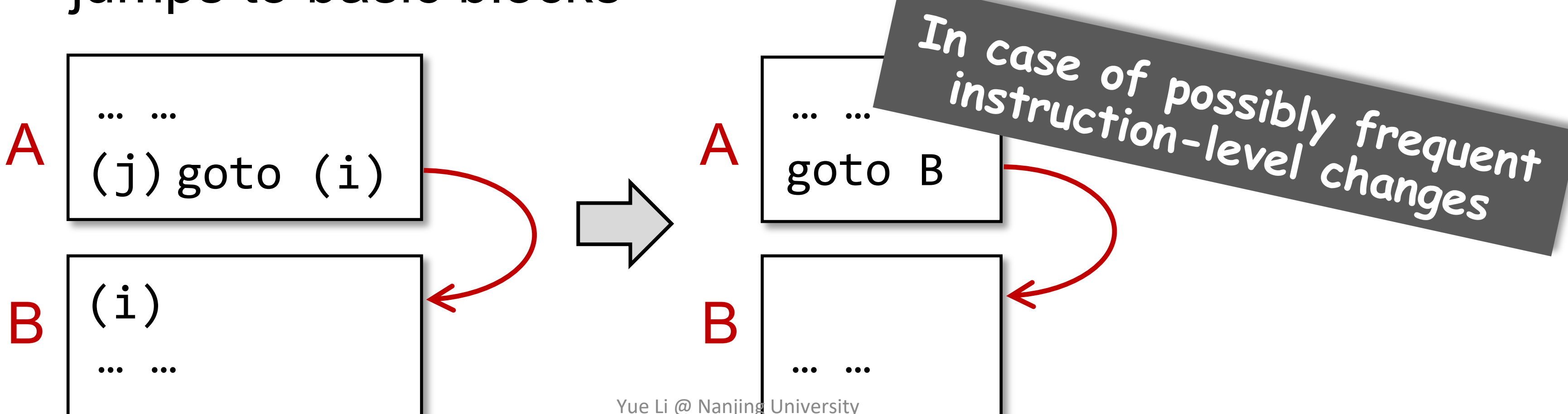
- It is normal to replace the jumps to instruction labels by jumps to basic blocks



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B4   (7) a = q
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```

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B1  x = input
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    if z < x goto B4

B3  p = x / y
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B4  a = q
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B5  goto B2

B6  return
```

Add edges in CFG

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x = input
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Add edges in CFG

There is a conditional or unconditional jump from the end of **A** to the beginning of **B**

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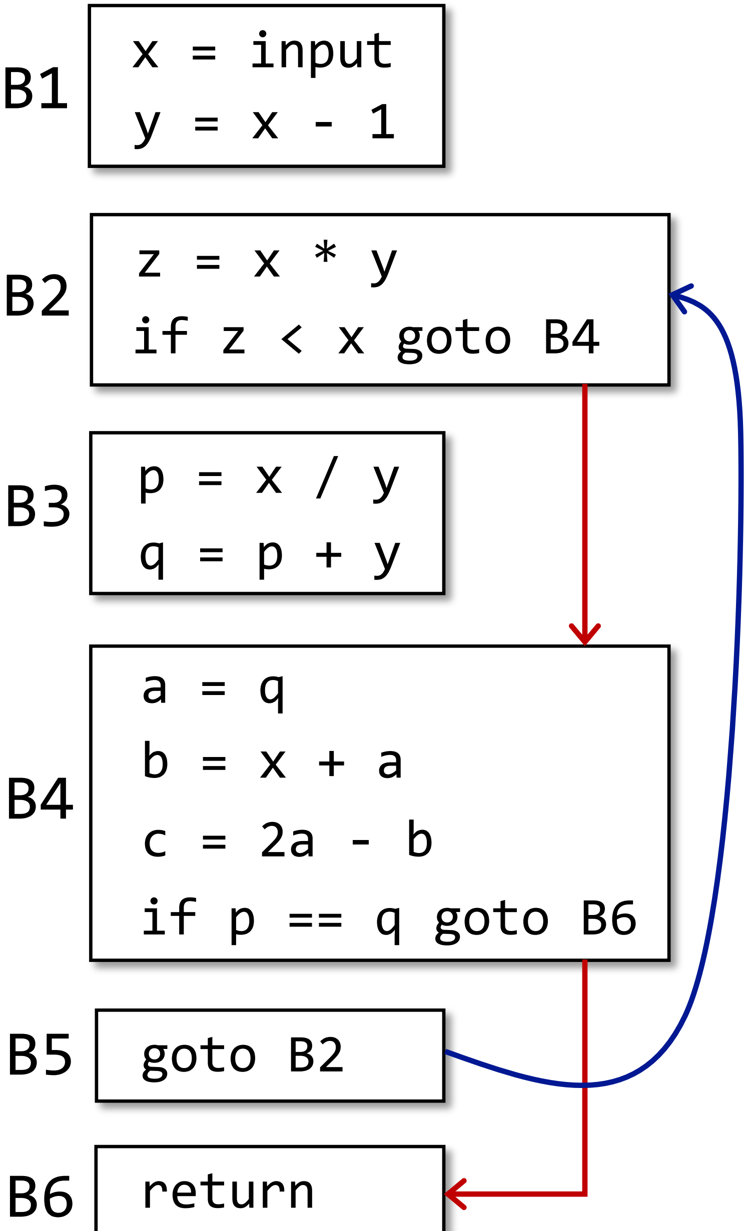
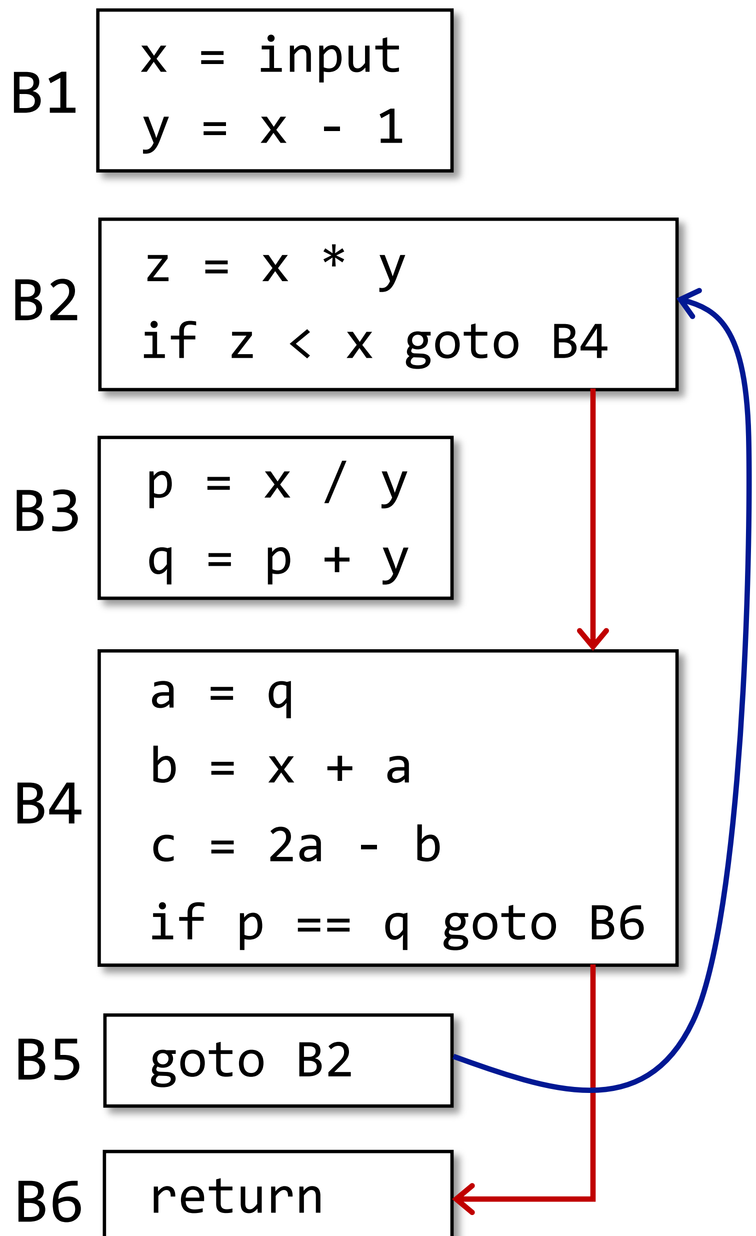
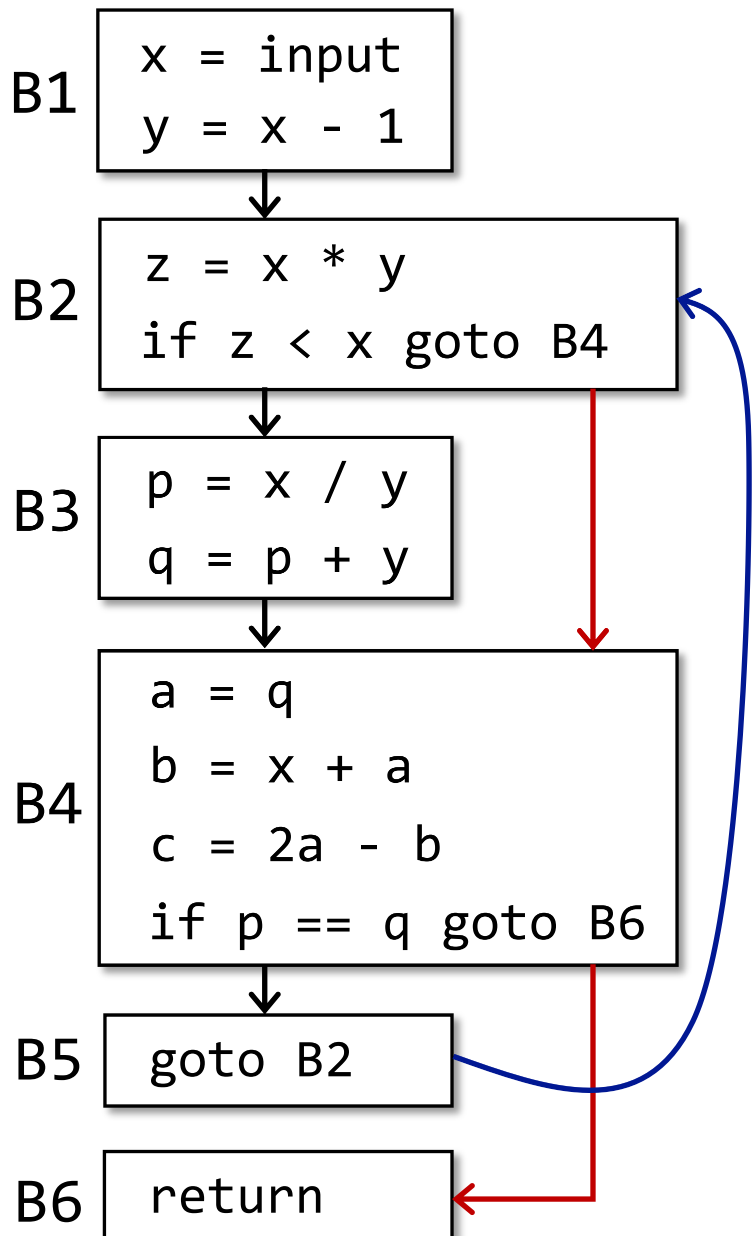


Add edges in CFG

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





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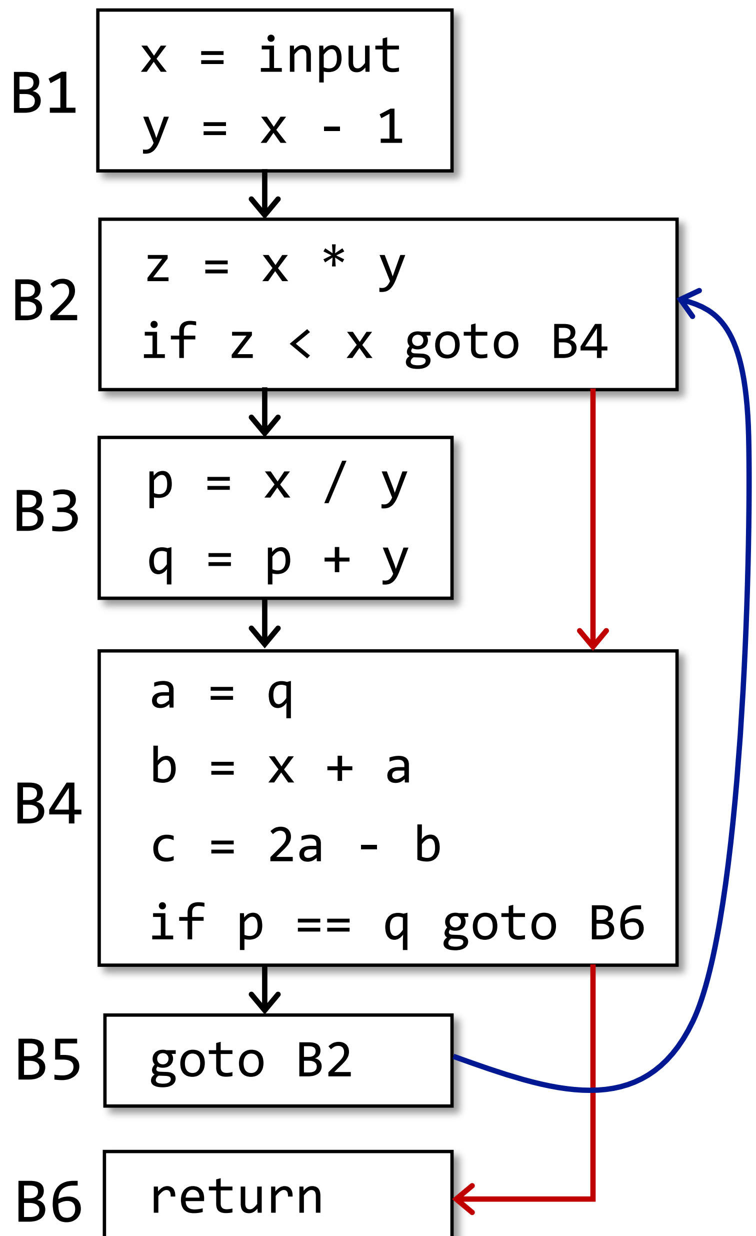

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We say that **A** is a **predecessor** of **B**, and **B** is a **successor** of **A**

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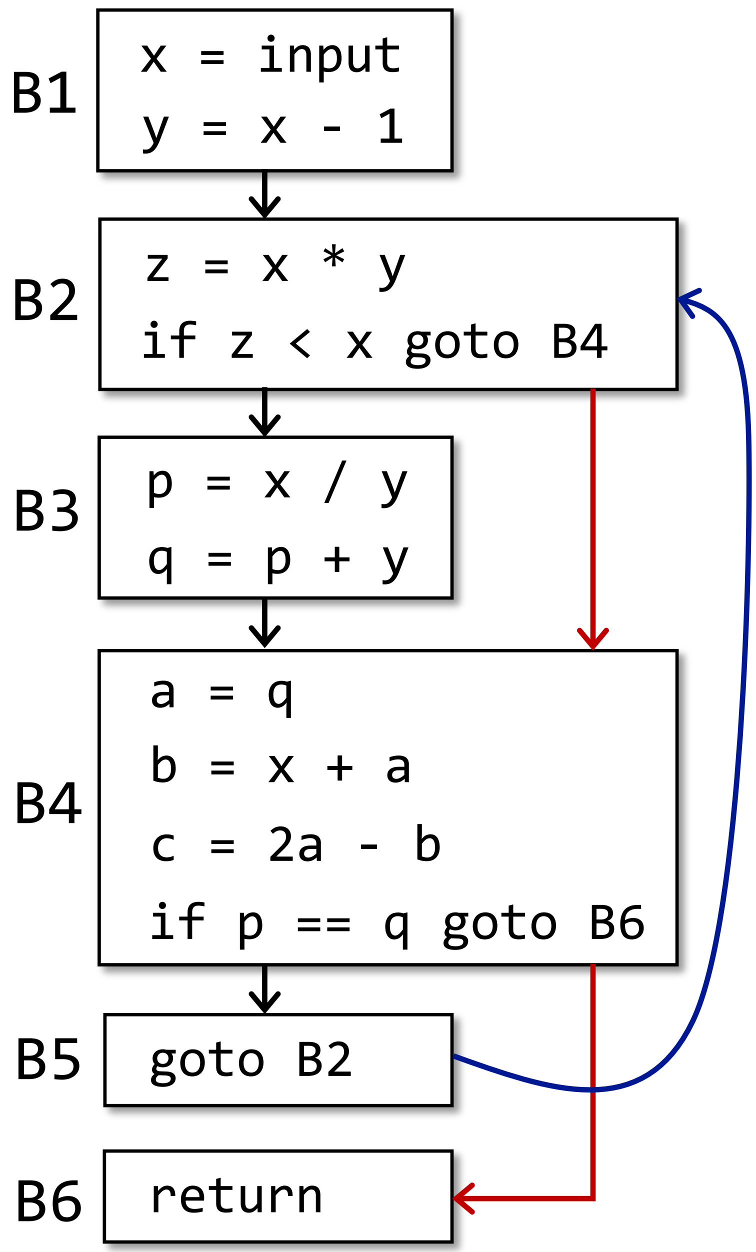

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Usually we add two nodes, **Entry** and **Exit**.

- They do not correspond to executable IR
- A edge from Entry to the BB containing the first instruction of IR
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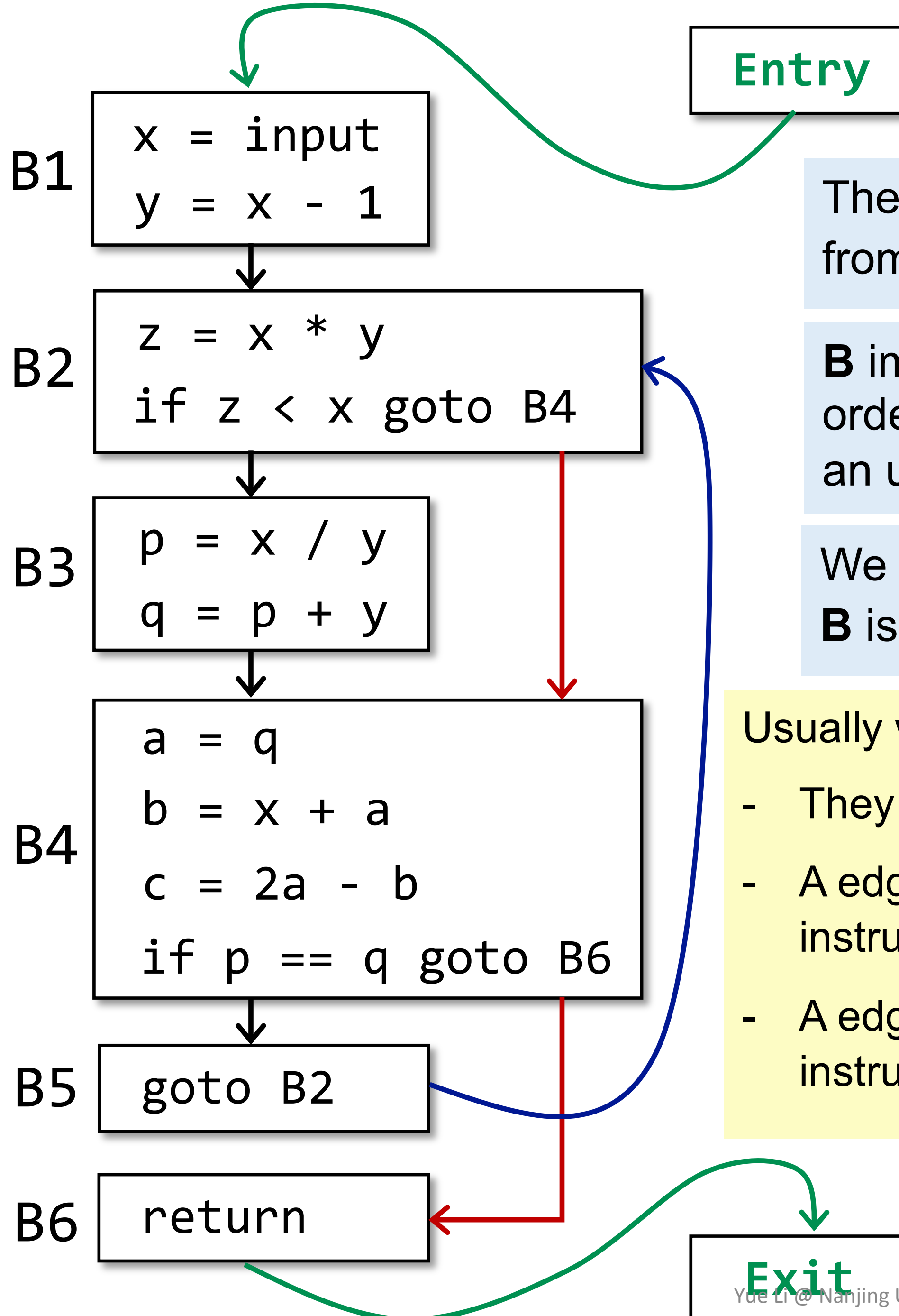

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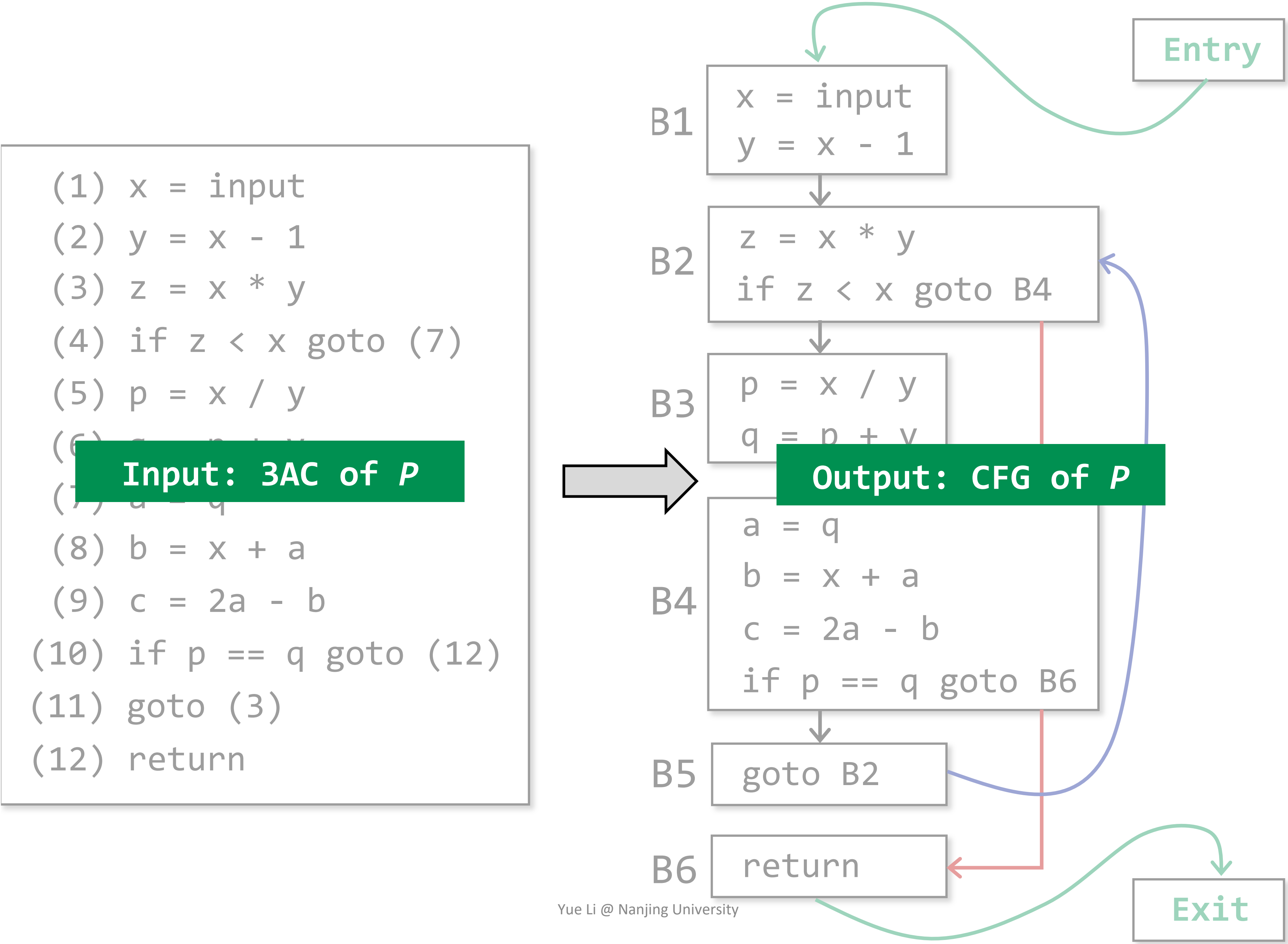
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(5) p = x / y
Input: 3AC of P
(8) b = x + a
(9) c = 2a - b
(10) if p == q goto (12)
(11) goto (3)
(12) return
Entry
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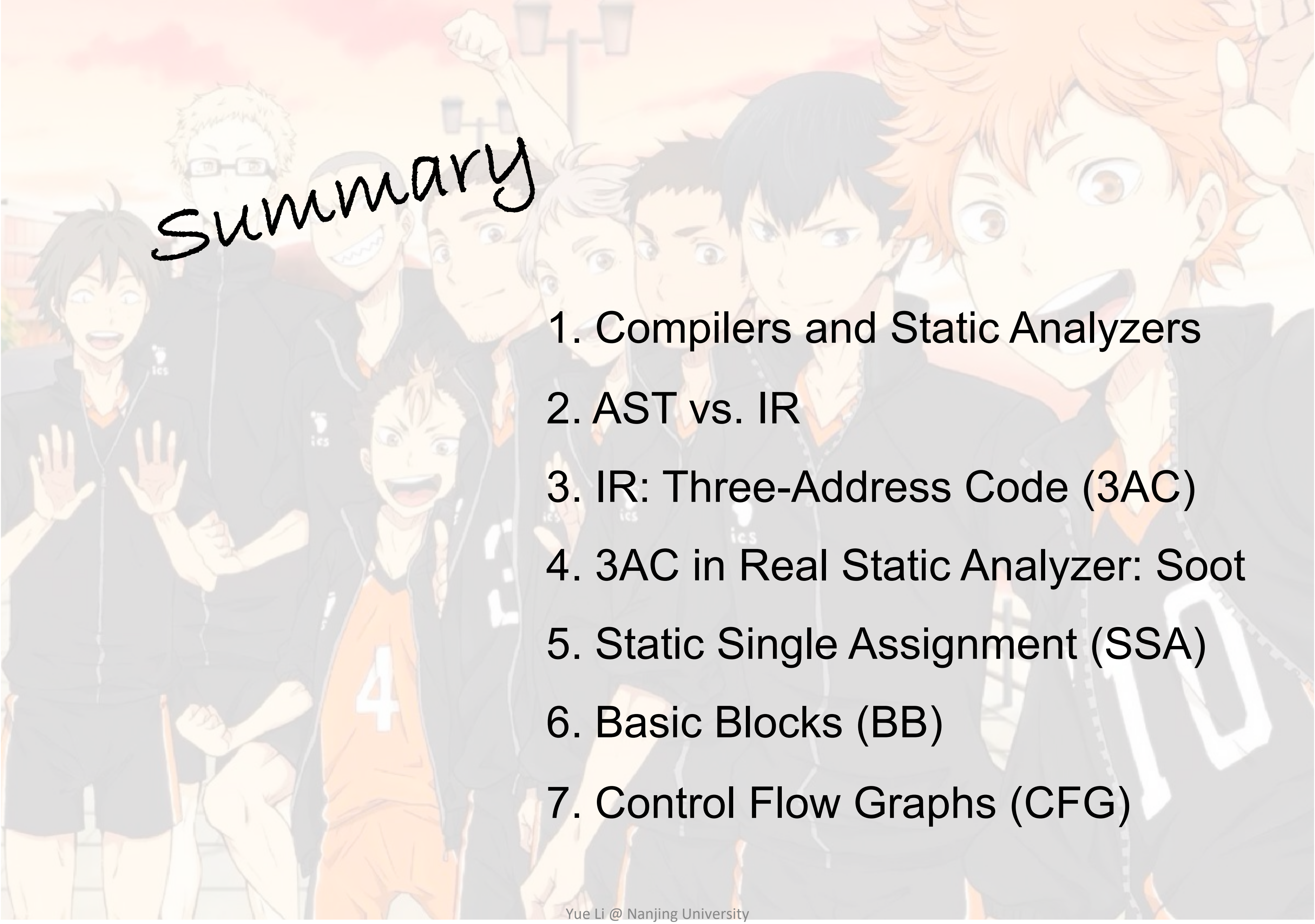
x = input
y = x - 1
B2
z = x * y
if z < x goto B4
B3
p = x / y
q = p + y
Output: CFG of P
B4
a = q
b = x + a
c = 2a - b
if p == q goto B6
B5
goto B2
B6
return
Exit



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 (in IR jimple)
- How to build basic blocks on top of IR
- How to construct control flow graphs on top of BBs?

软件分析

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