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

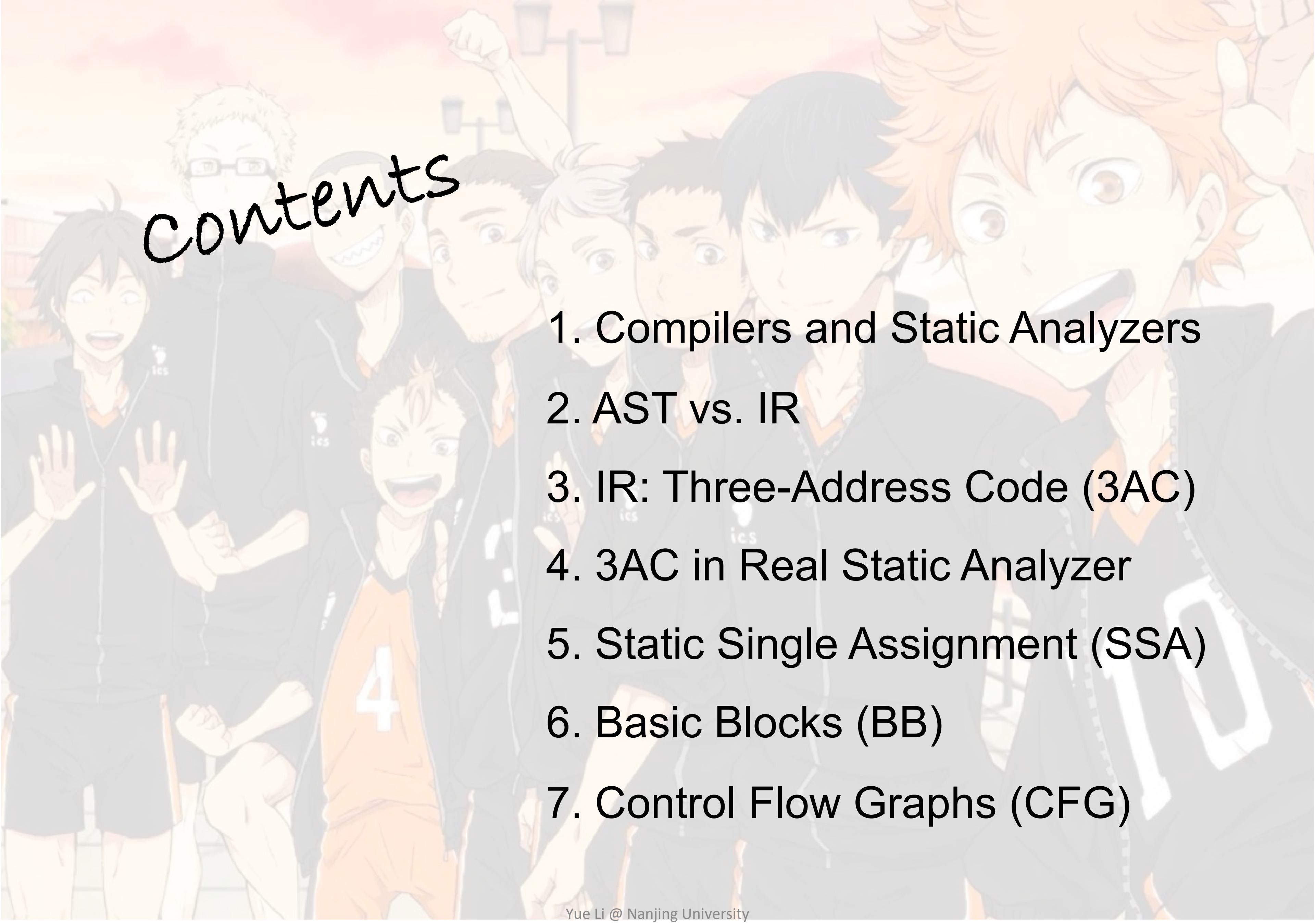
Static Program Analysis

Intermediate Representation

Nanjing University

Yue Li

Fall 2021



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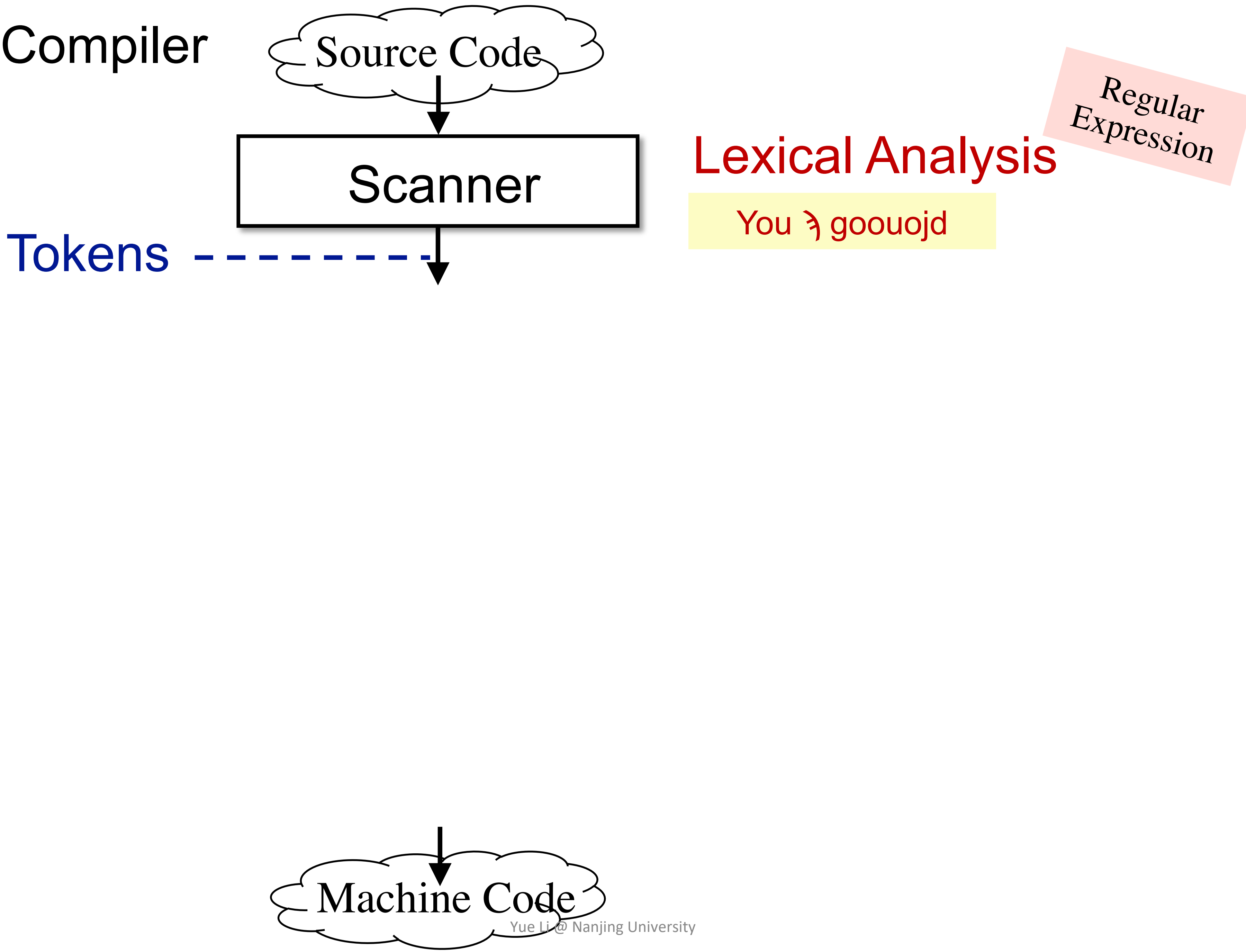
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Machine Code

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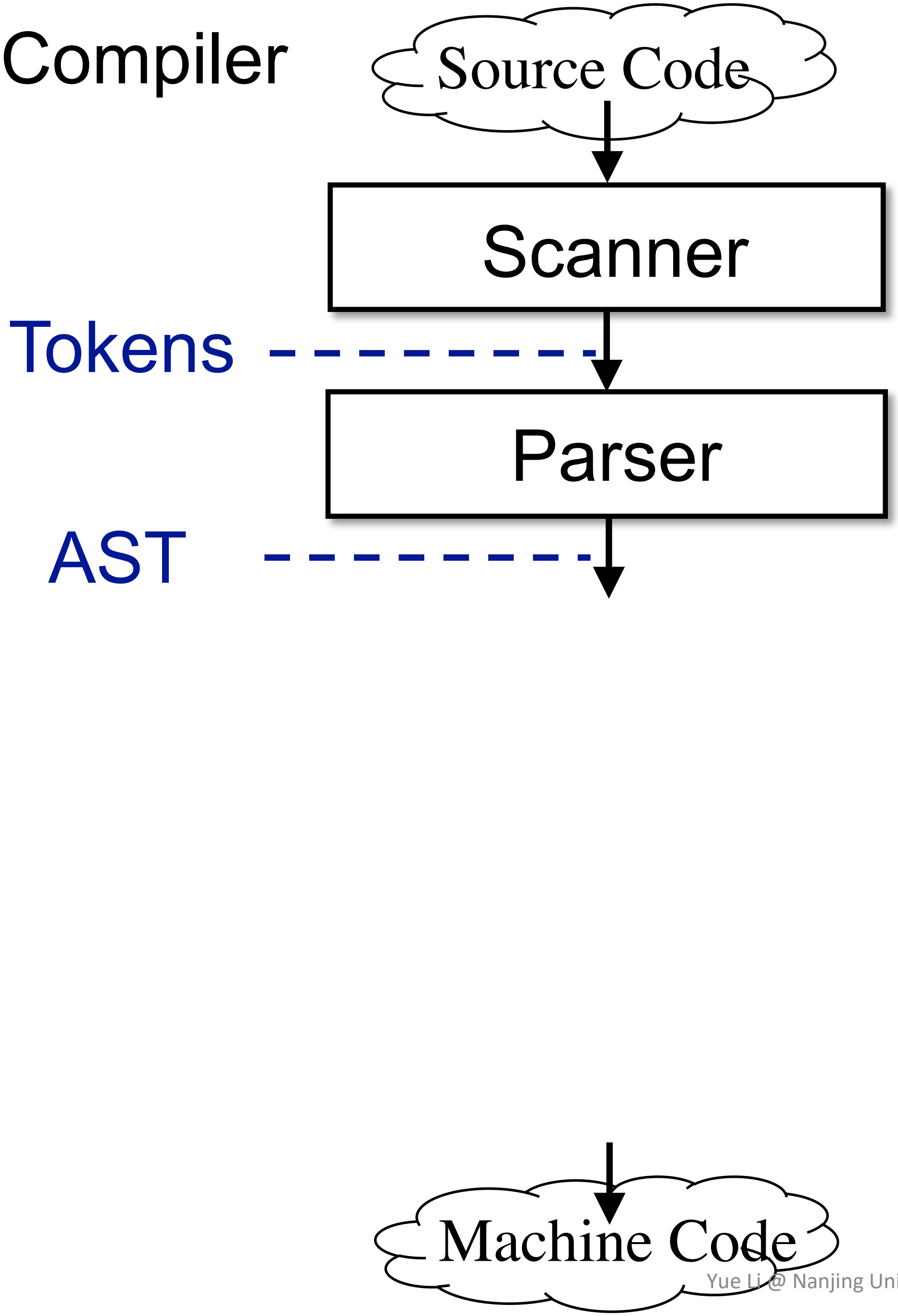


Lexical Analysis

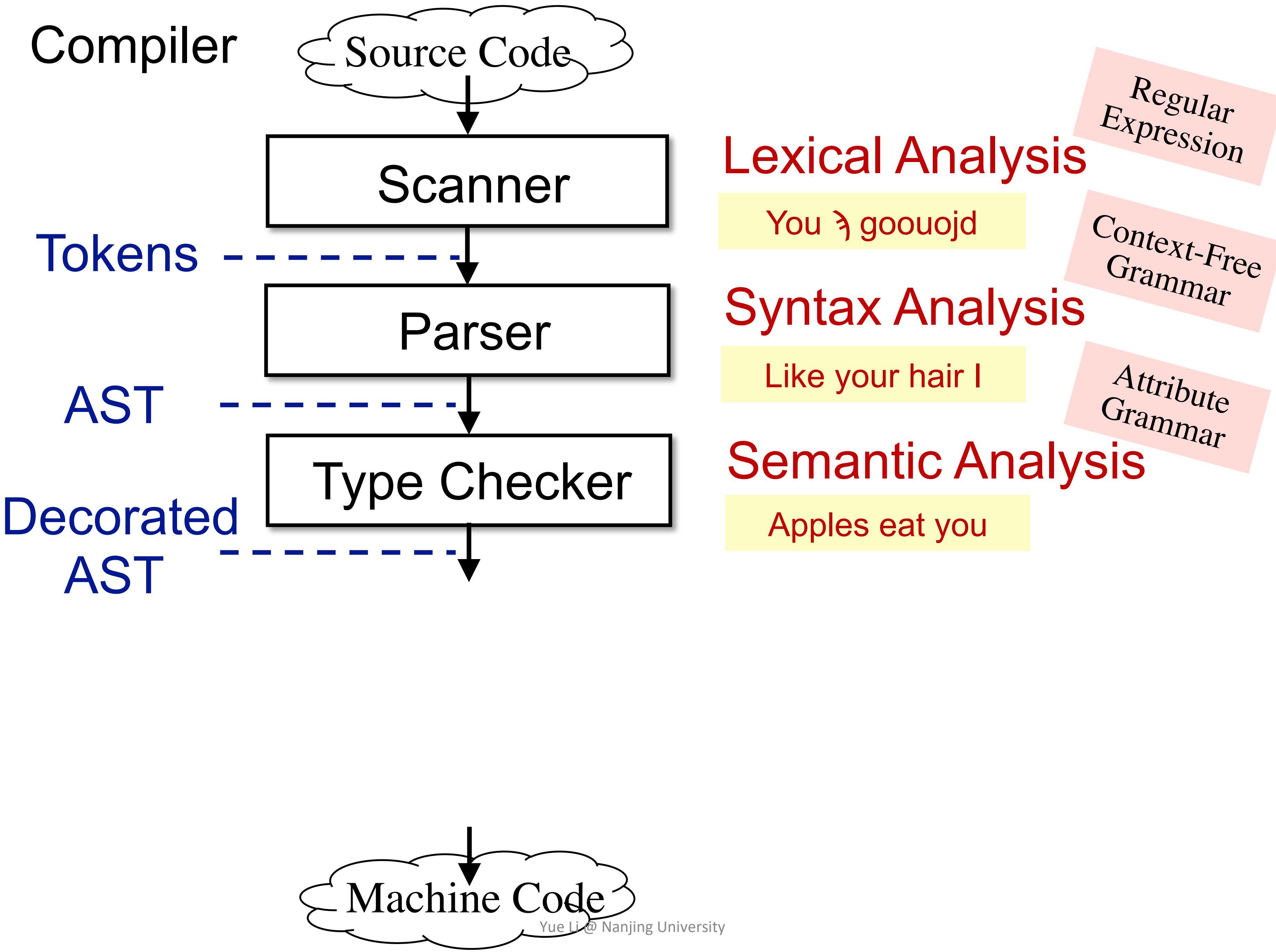
You goouojd

Syntax Analysis

Like your hair I

Regular Expression

Context-Free Grammar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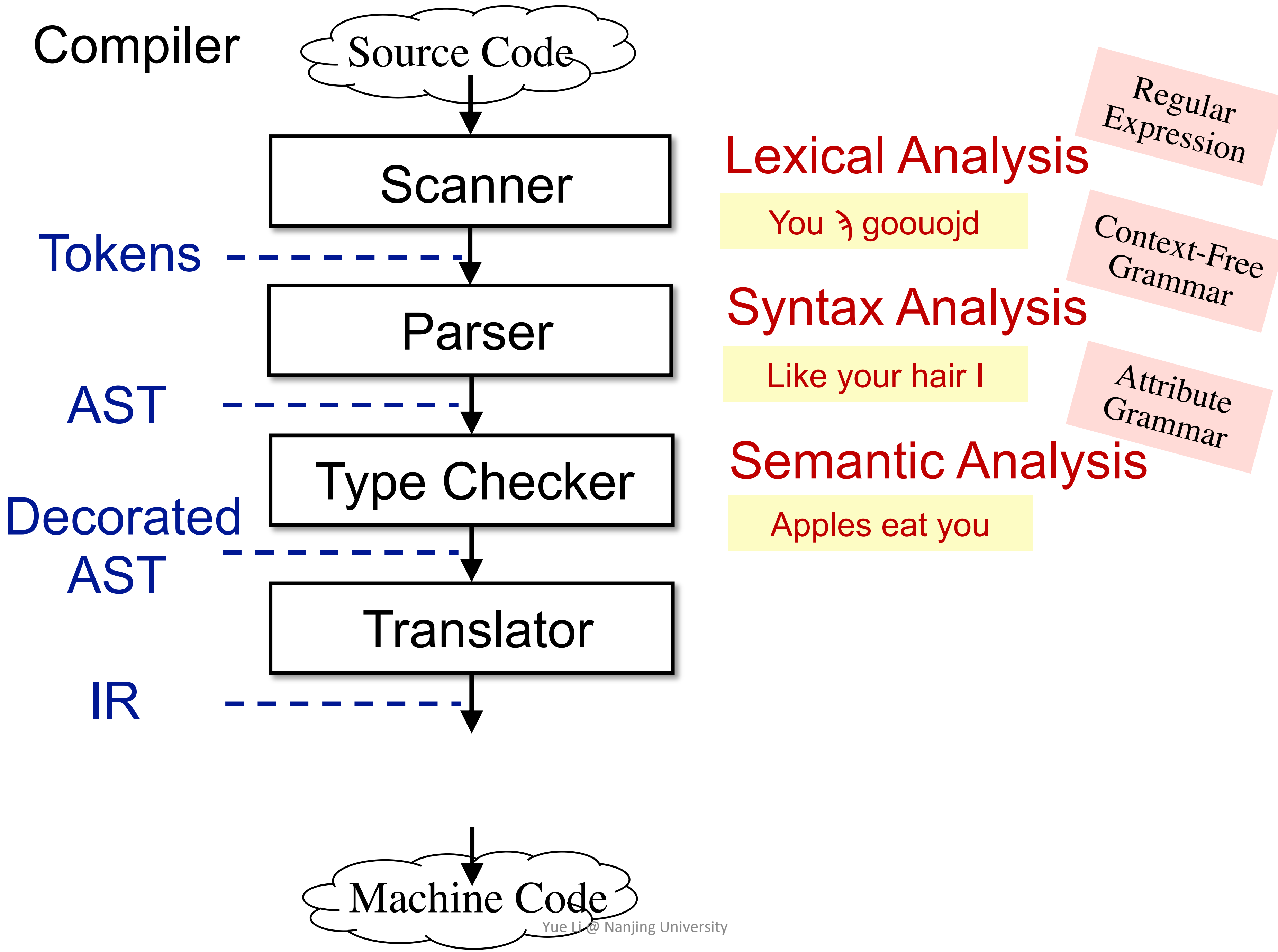
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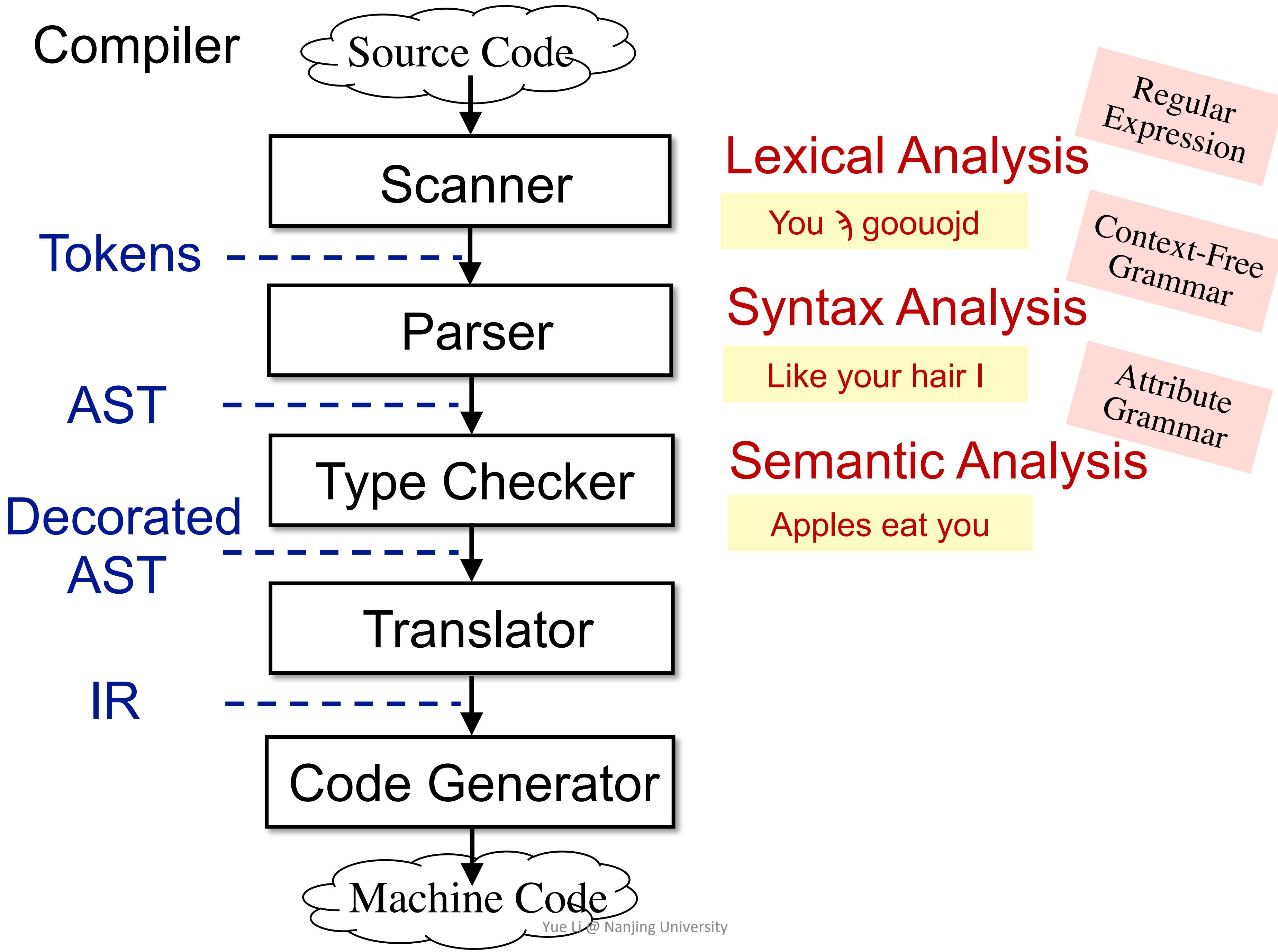
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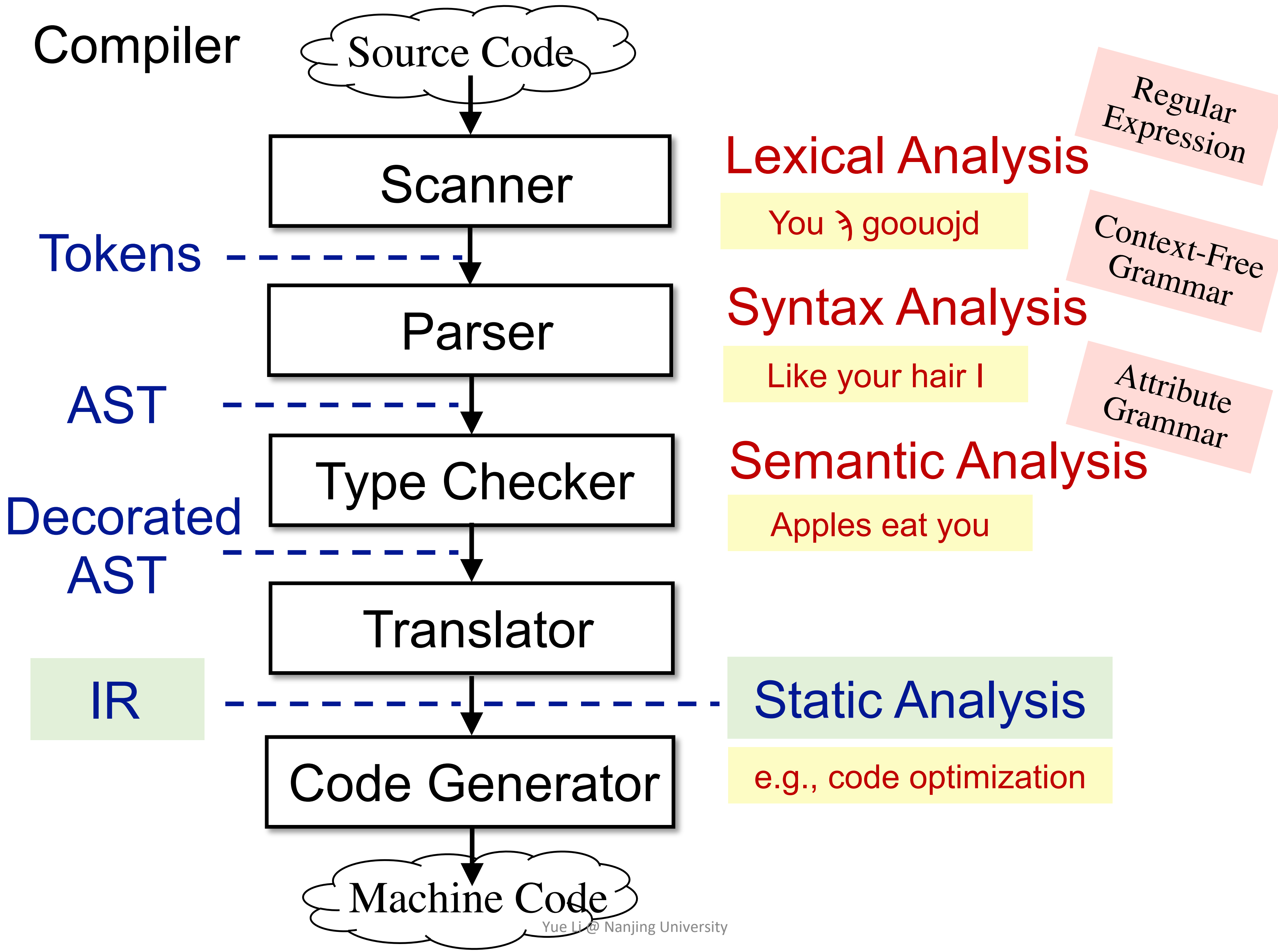
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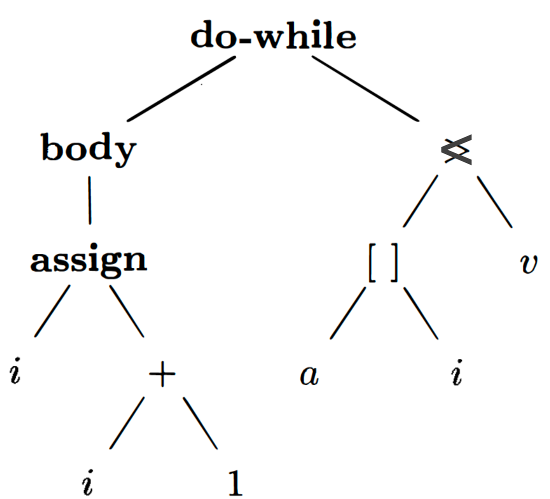
Static Analysis
e.g., code optimization

AST vs. IR

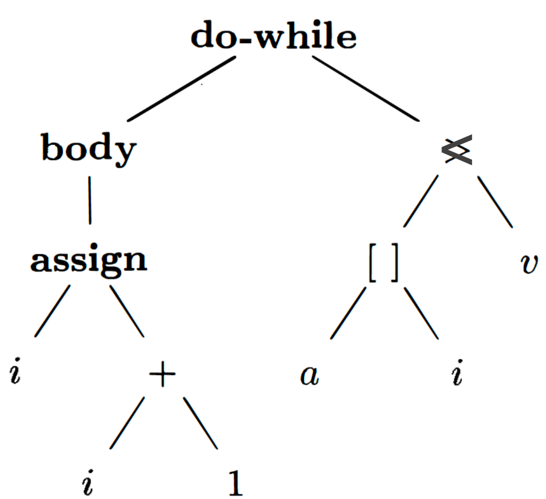
AST




```
"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

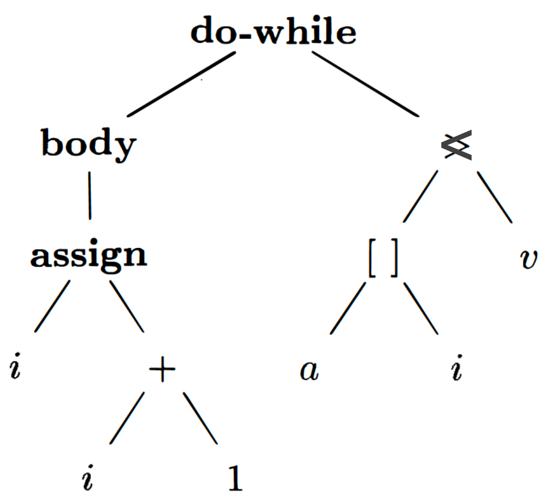
- high-level and closed to grammar structure
- usually language dependent
- suitable for fast type checking
- lack of control flow information

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

`“do i=i+1; while(a[i]<v);”`

AST



IR

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

(“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 ⇨ t1 = a + b
t2 = t1 + 3

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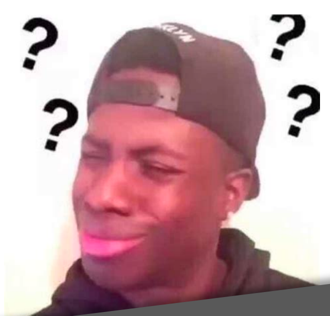
Each 3AC contains at most 3 addresses



Why called 3-address?

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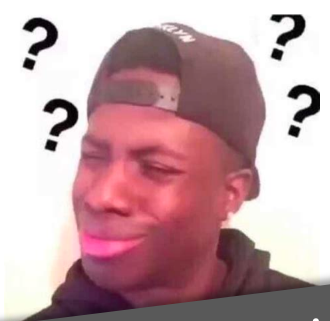

Why called 3-address?

Address can be one of the following:

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

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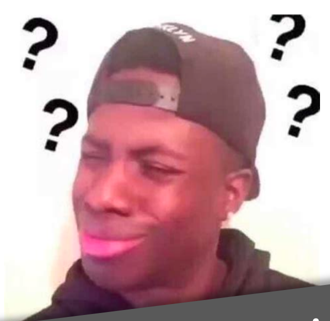

Why called 3-address?

Address can be one of the following:

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

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

```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

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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

Method Call

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package nju.sa.examples;
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    }
}
```

Java Src

```
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

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package nju.sa.examples;
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    String foo(String para1, String para2) {
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    public static void main(String[] args) {
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        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)

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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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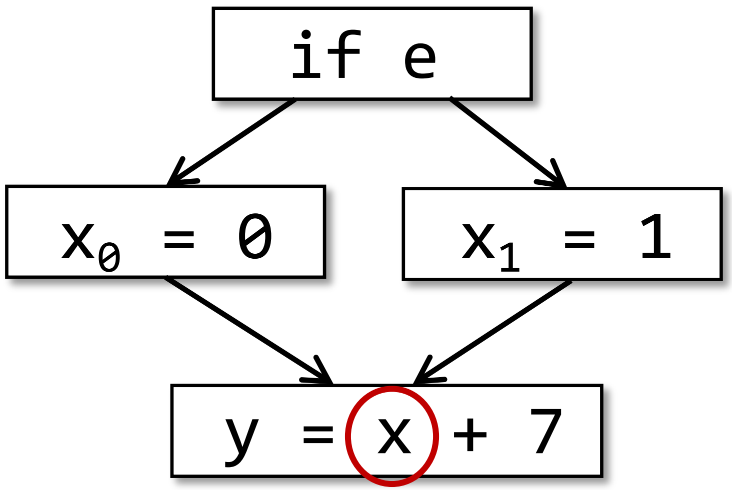
SSA

Static Single Assignment (SSA)

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



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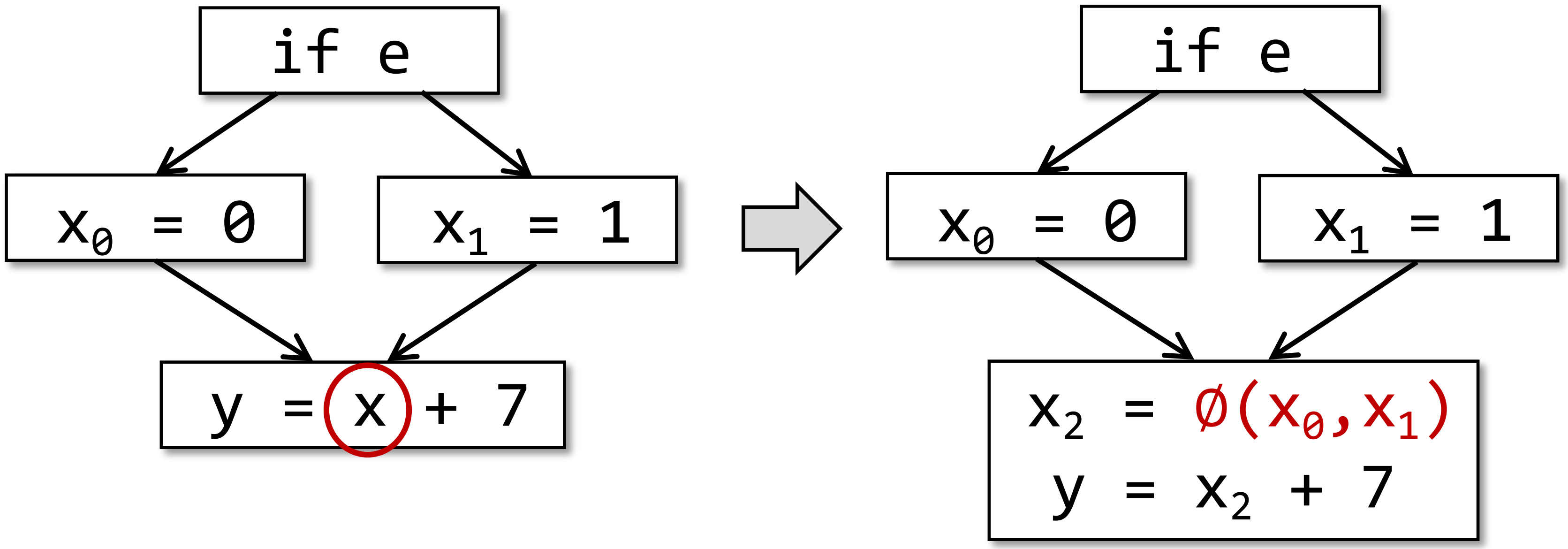

- A special merge operator, Ø (called phi-function), is introduced to select the values at merge nodes
- $Ø(x_0,x_1)$ has the value x_0 if the control flow passes through the true part of the conditional and the value x_1 otherwise

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

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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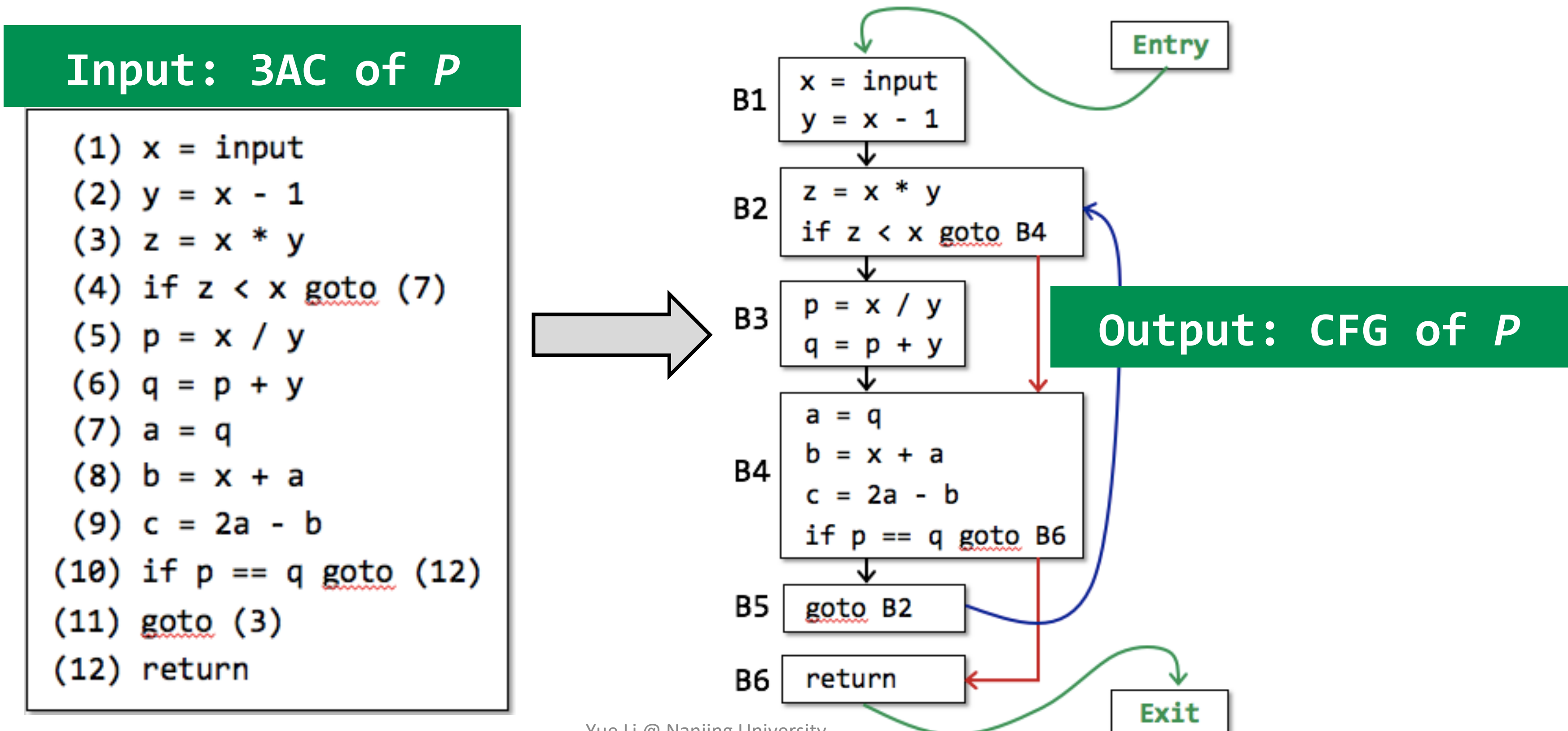

Control Flow Analysis

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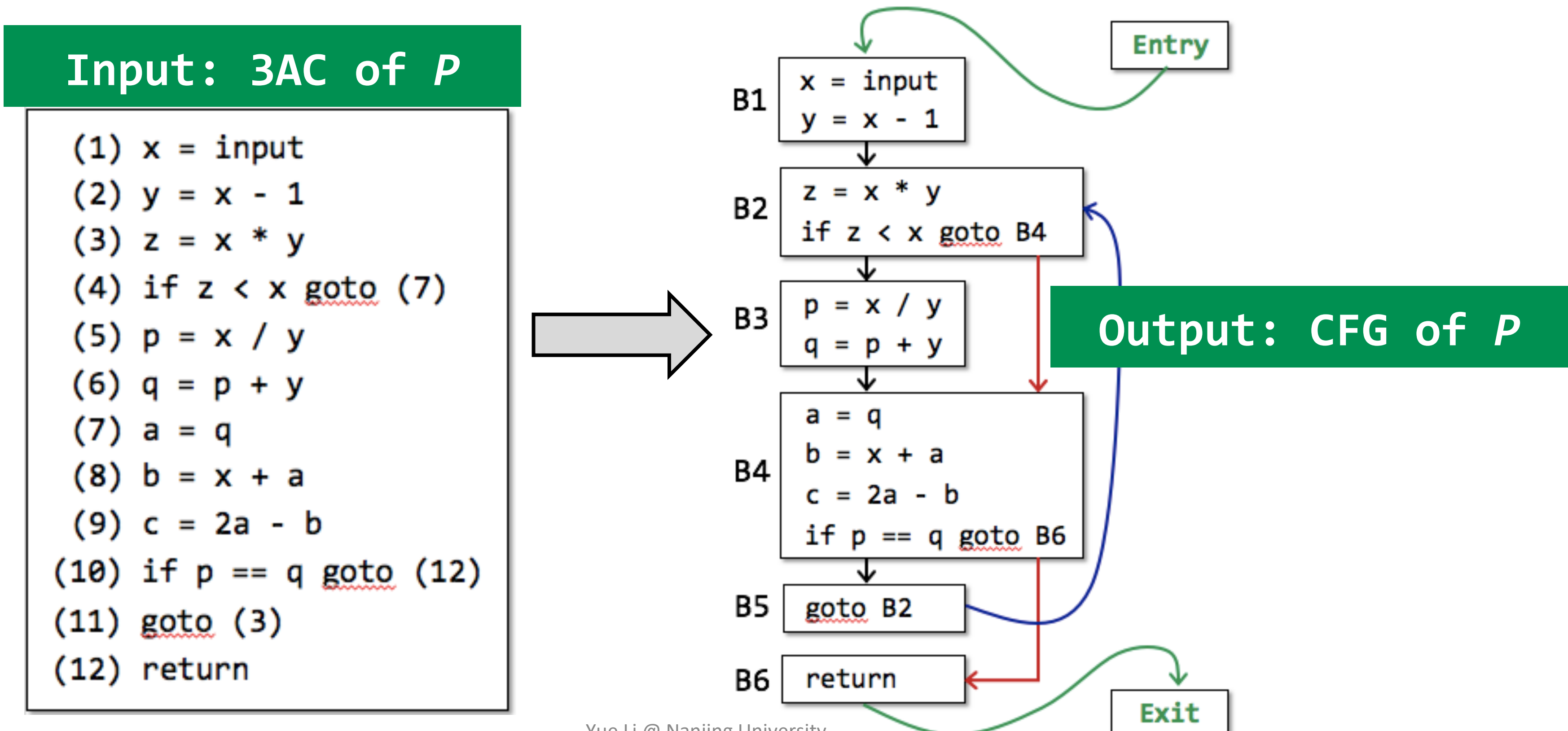
- CFG serves as the basic structure for static analysis



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
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(10) if p == q goto (12)
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```

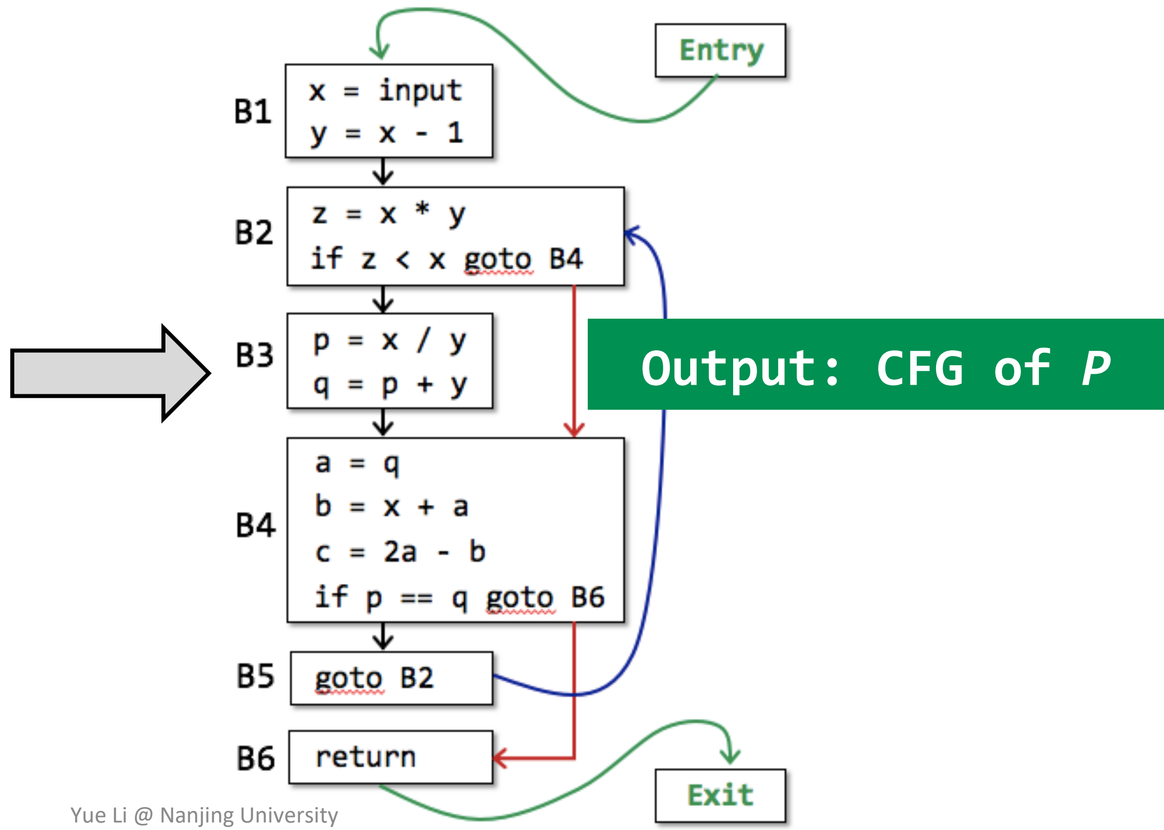

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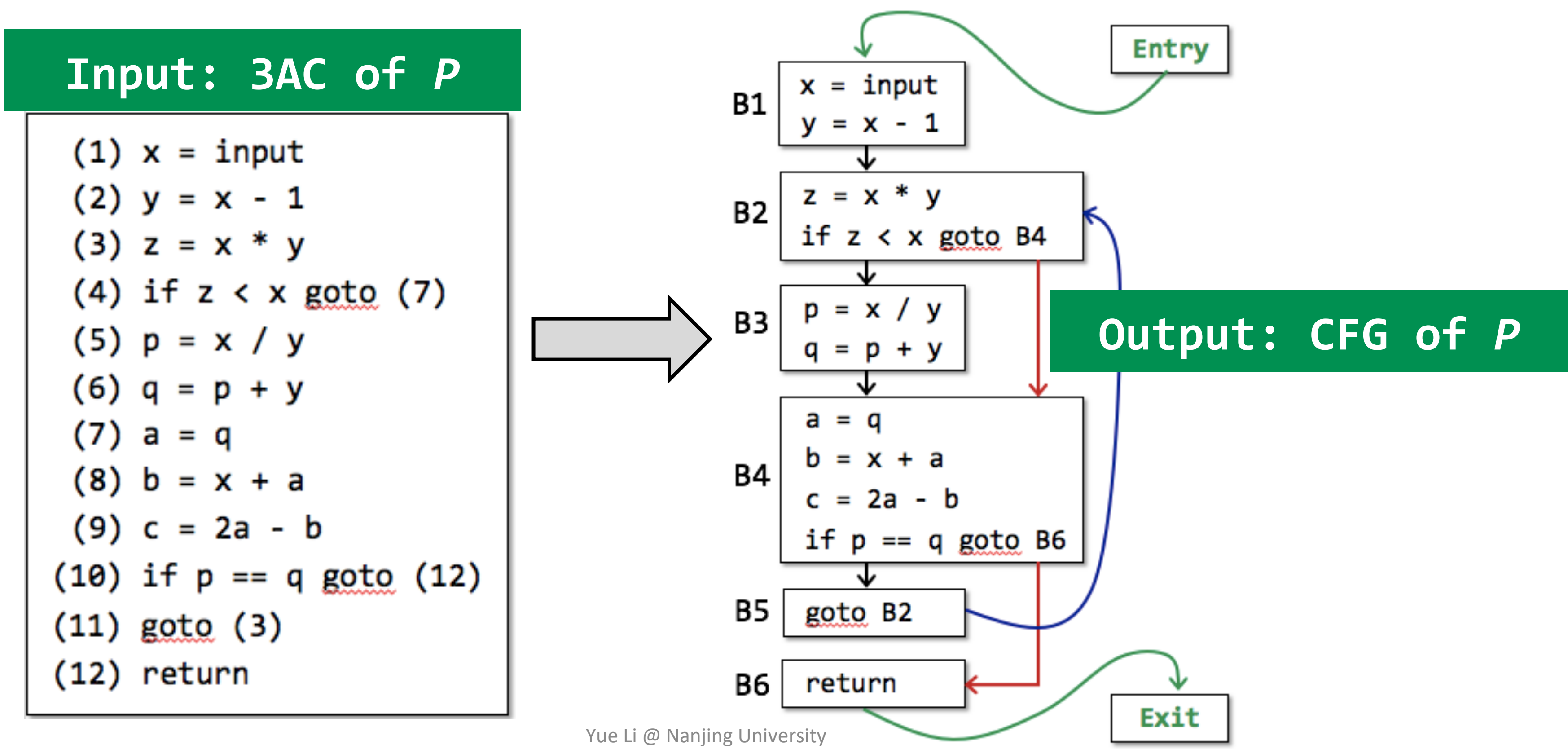

Basic Blocks (BB)

- 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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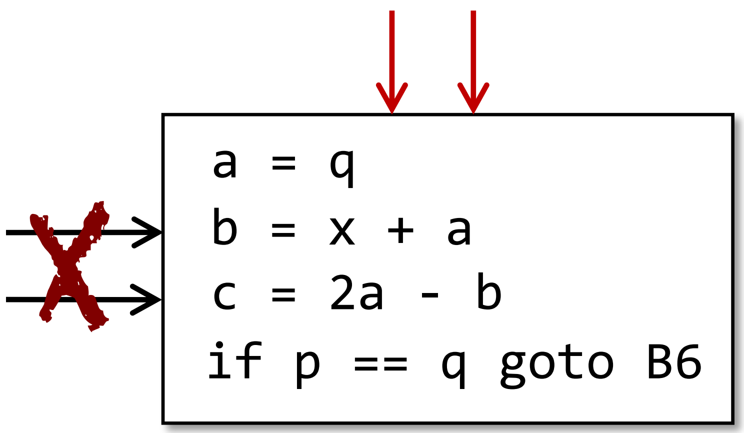

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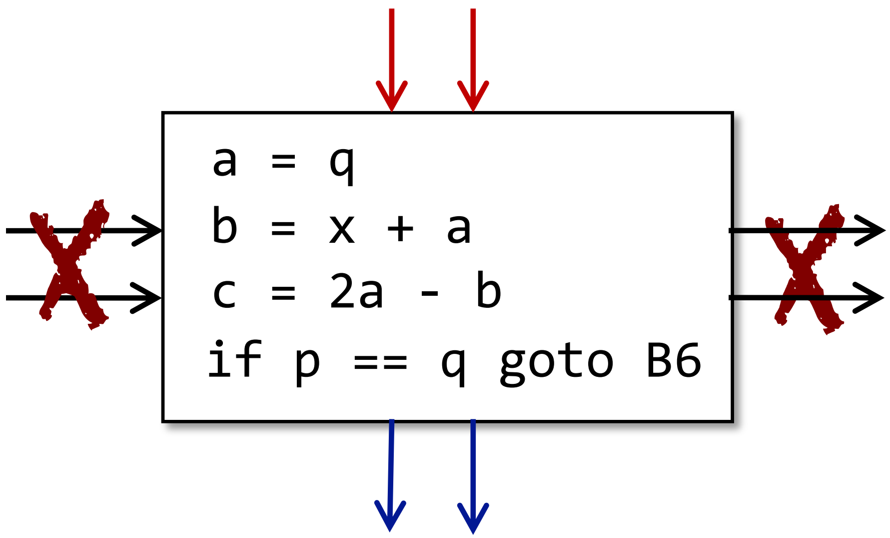
  - It can be entered only at the beginning, i.e., *the first instruction in the block*
  - It can be exited only at the end, i.e., *the last instruction in the block*



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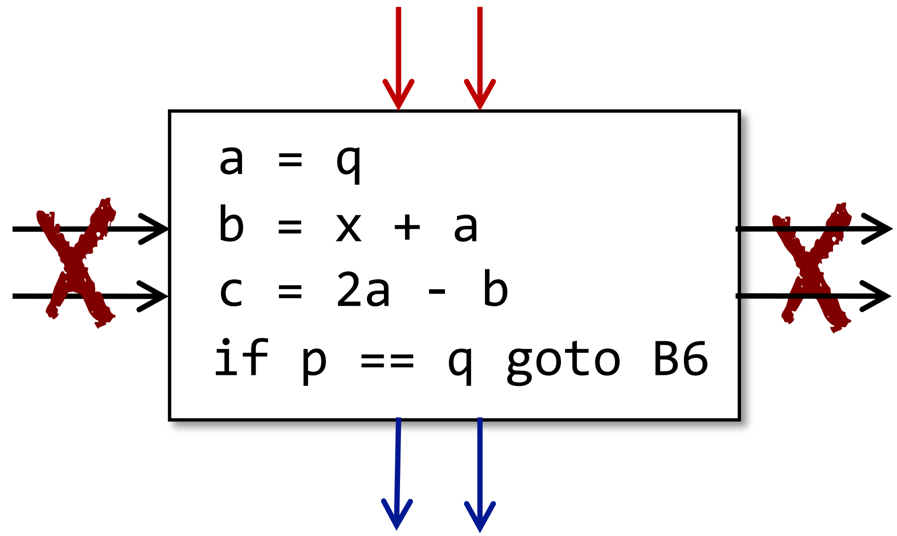
Now try to design the algorithm to build BBs by yourself!



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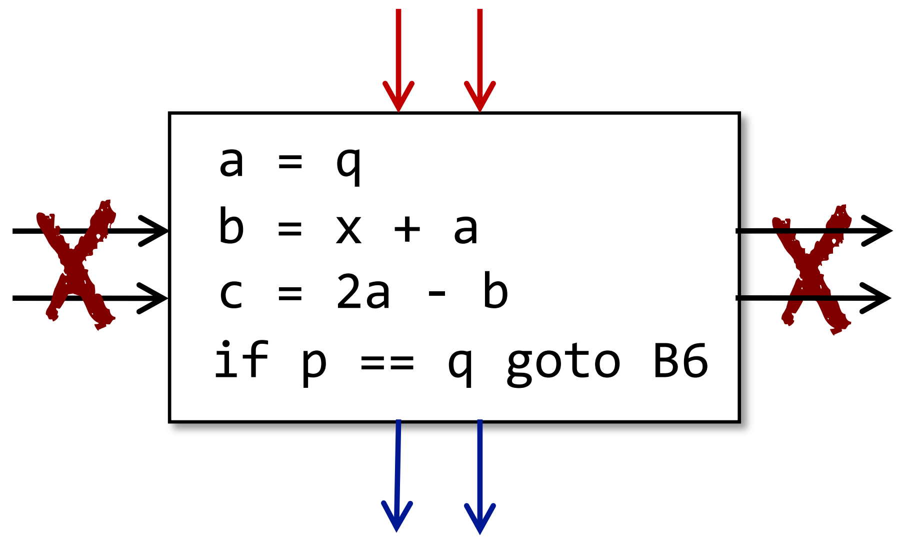

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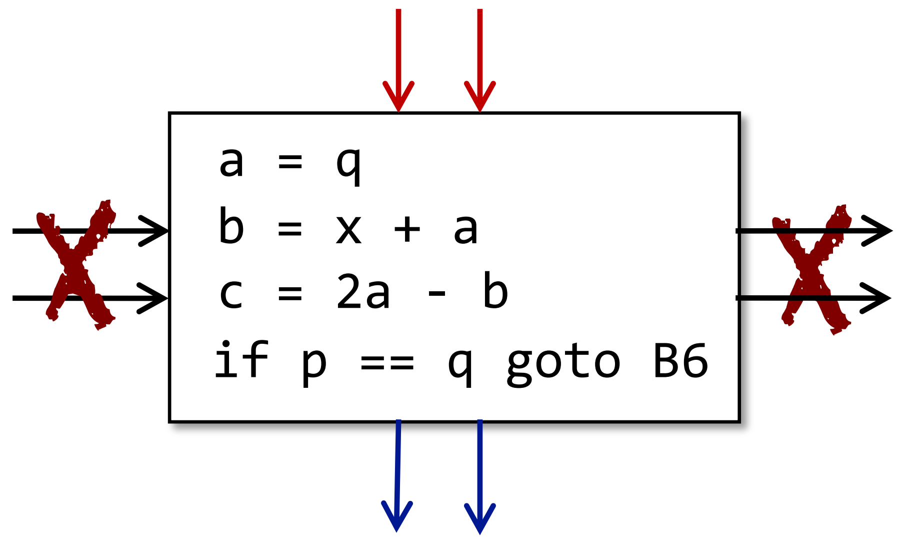

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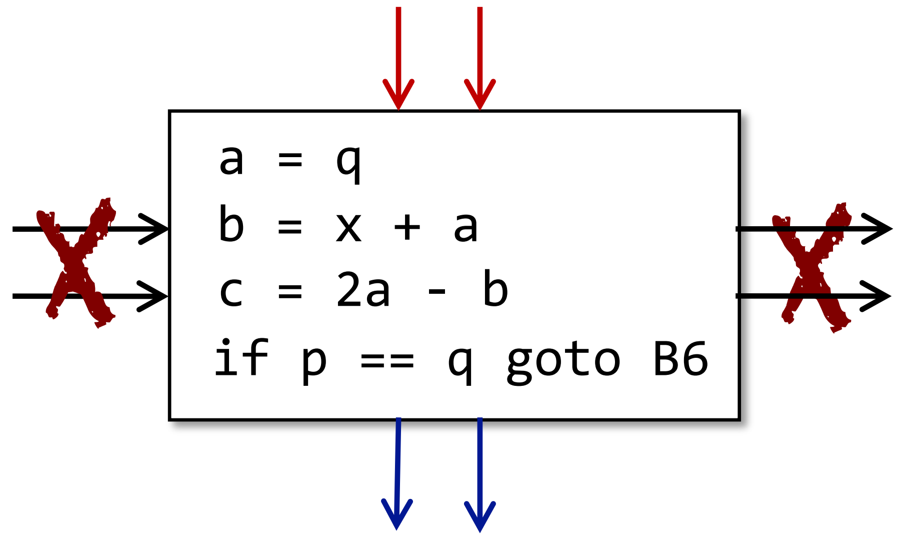

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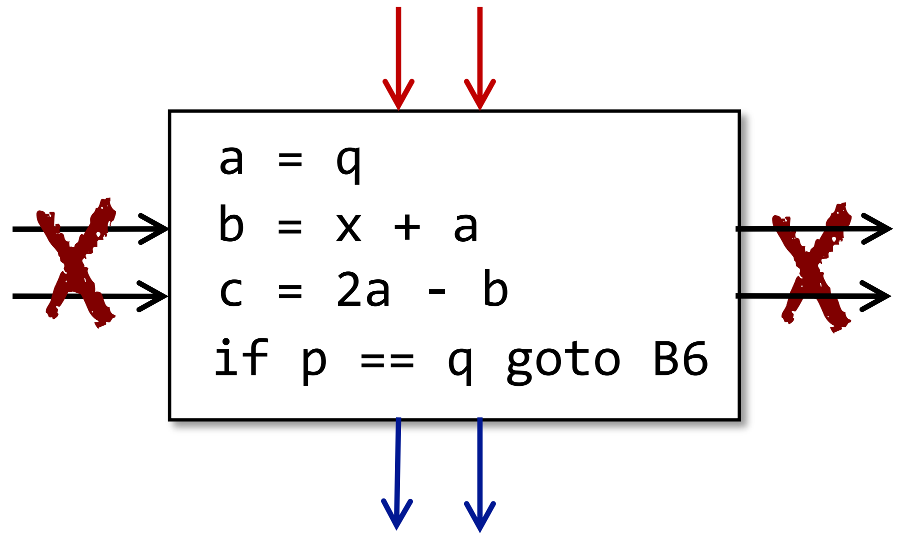

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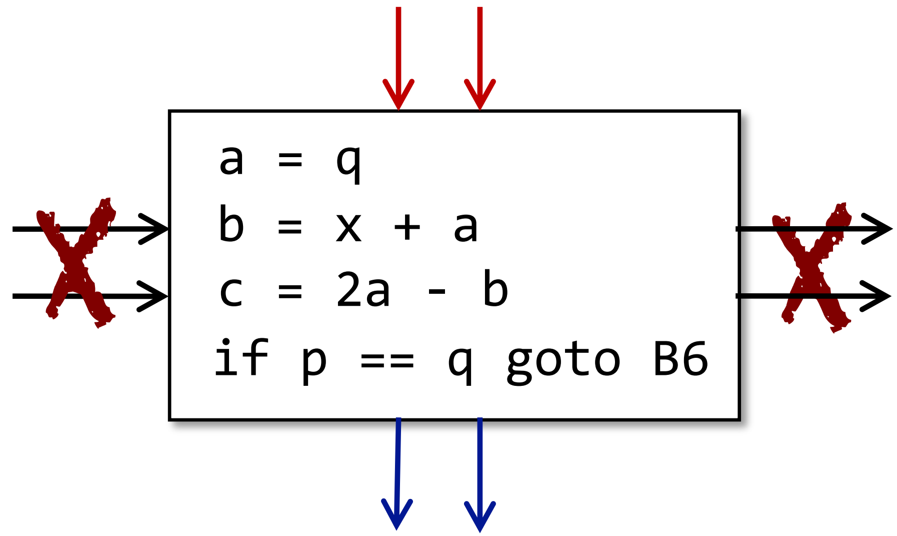

Now try to design the algorithm to build BBs by yourself!

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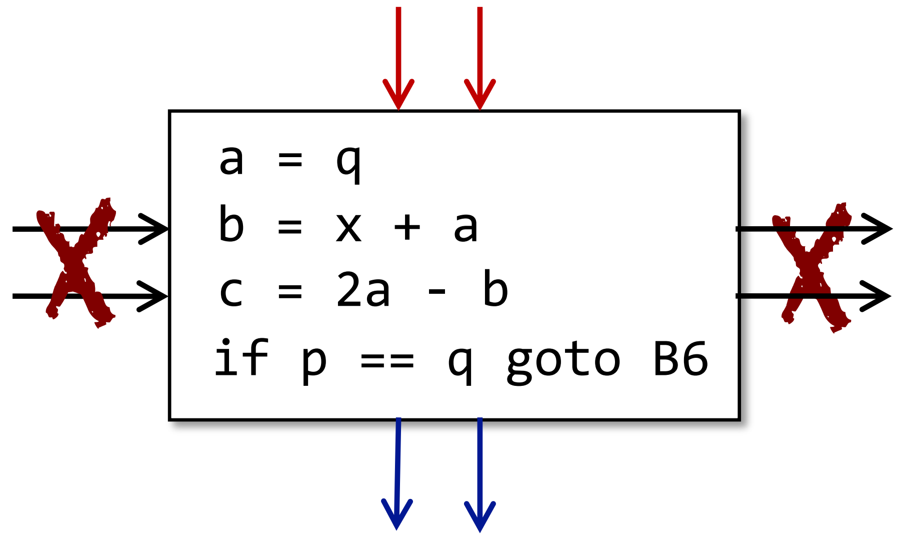

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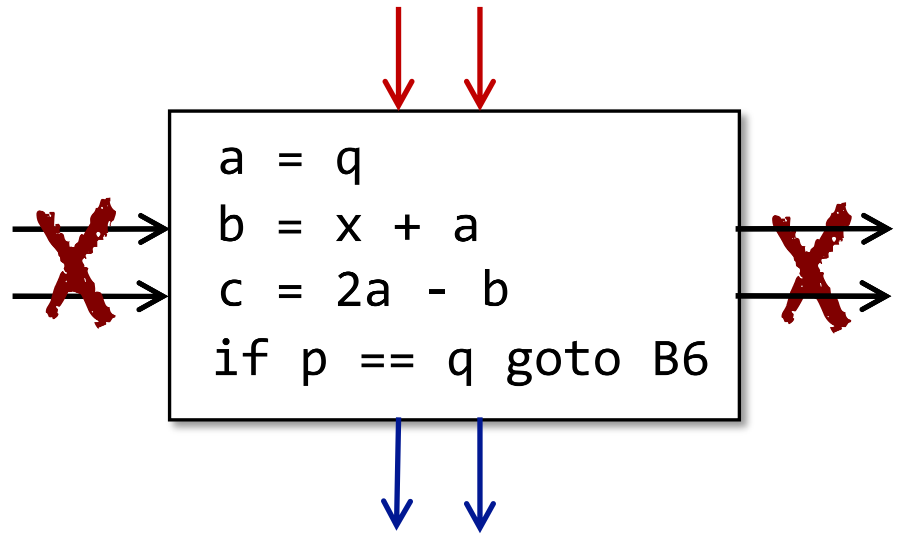

How to build Basic Blocks?

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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Output: BBs of *P*

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How to build CFG on top of BBs?

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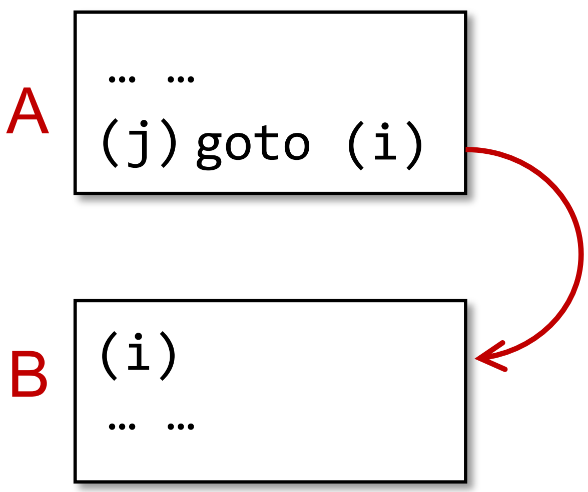

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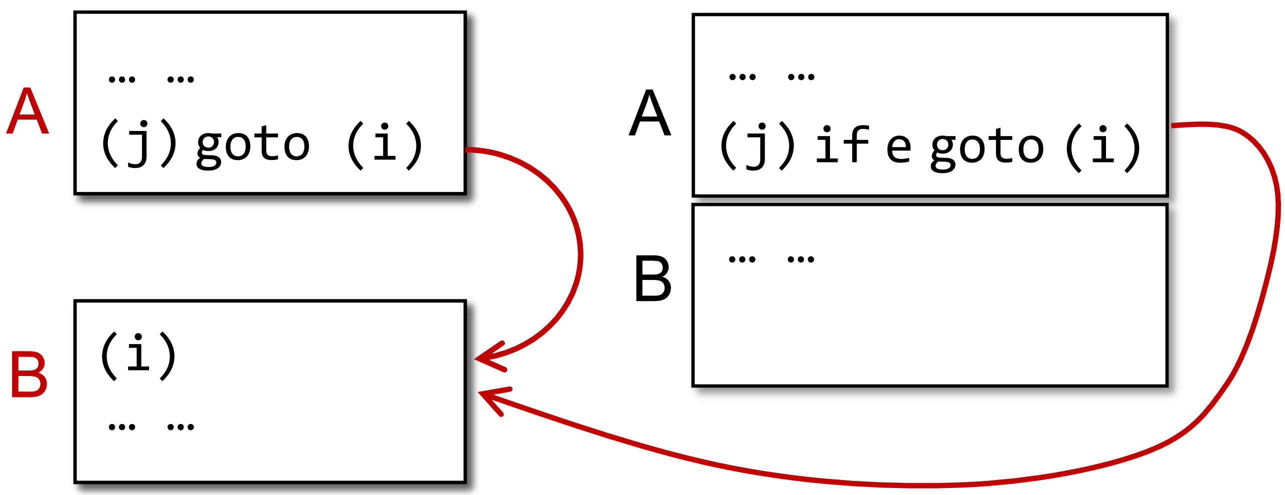

Control Flow Graph (CFG)

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- There is an edge from block A to block B if and only if
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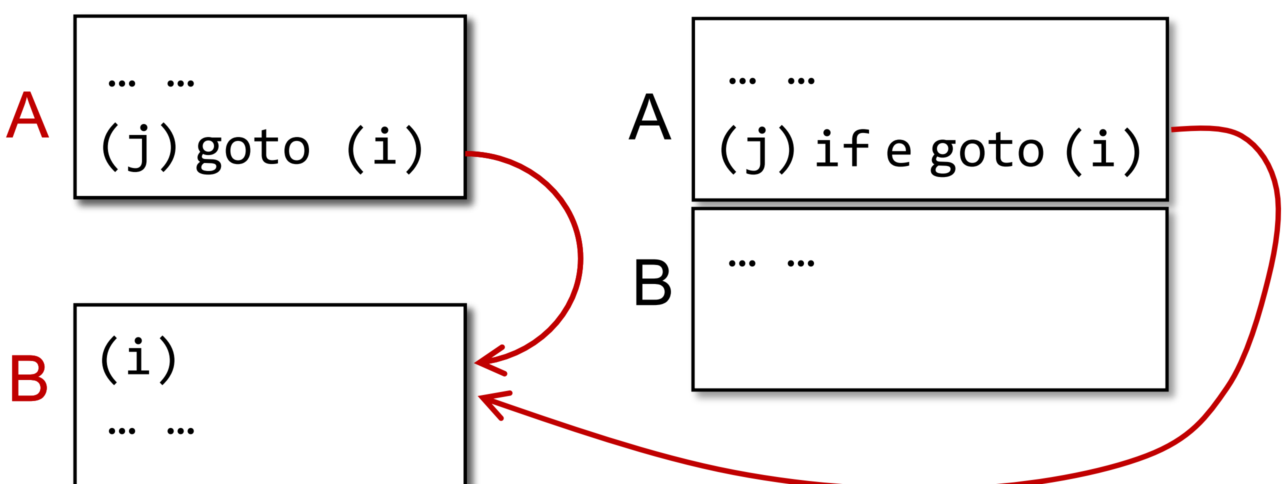

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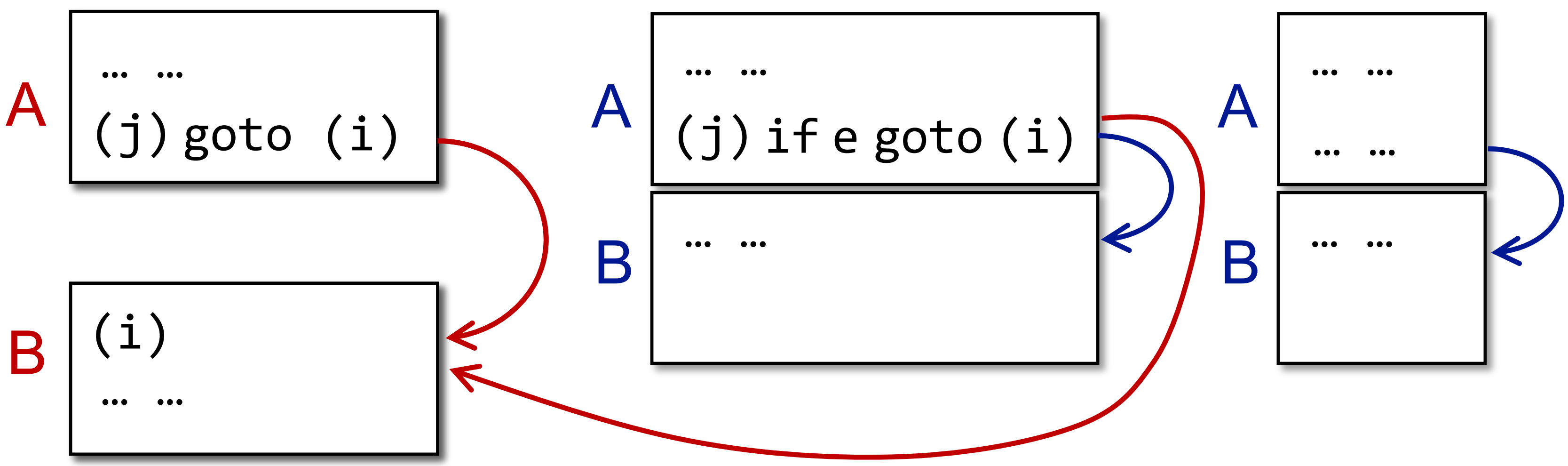

Control Flow Graph (CFG)

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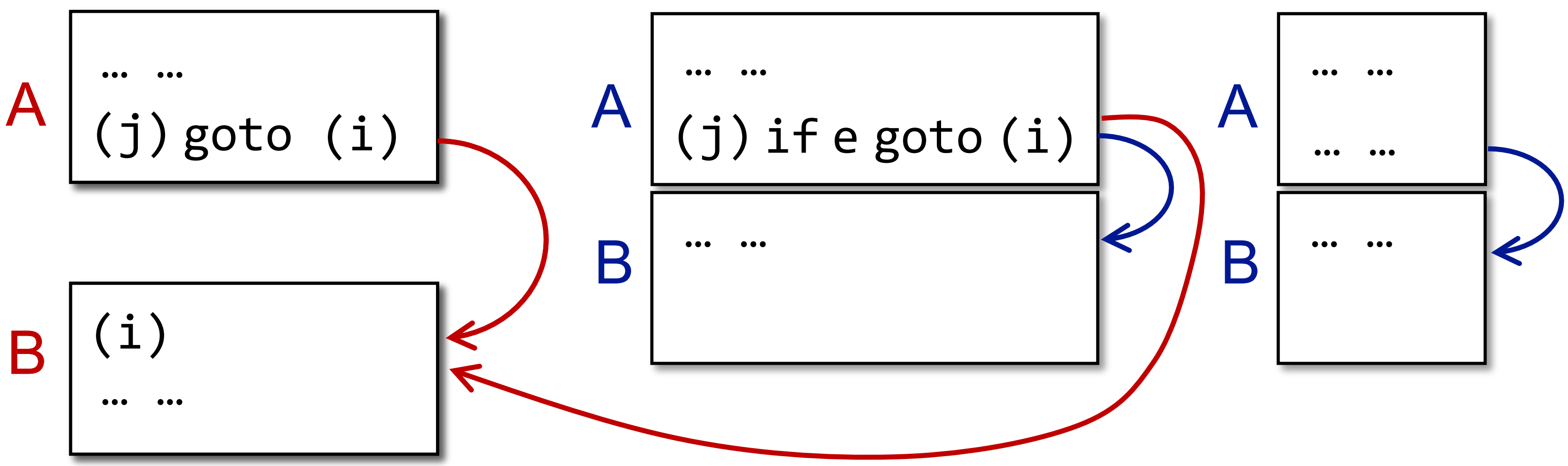

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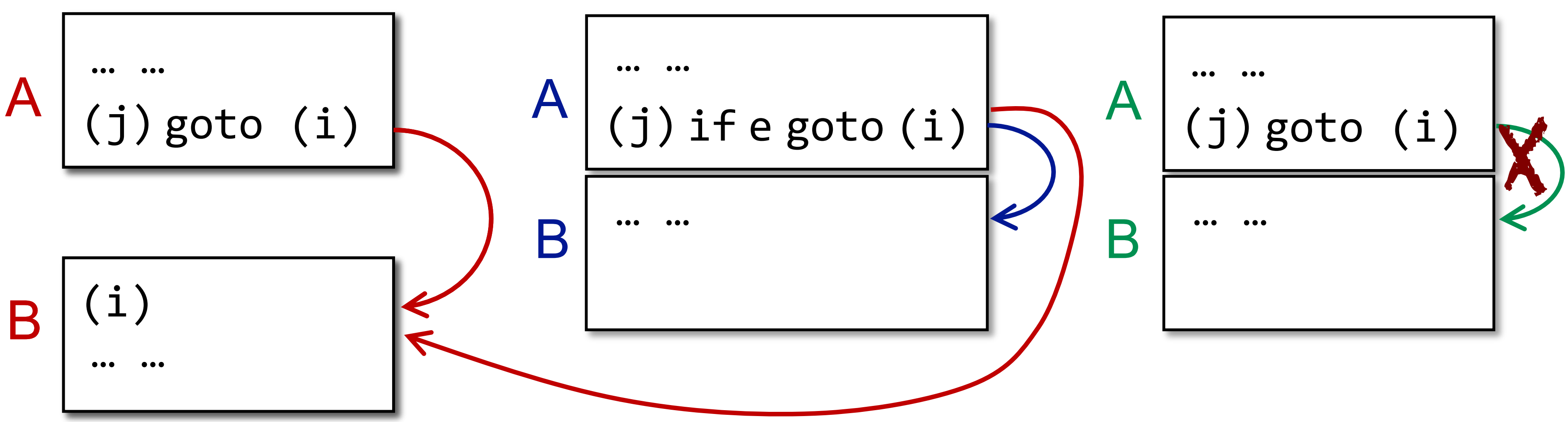

Control Flow Graph (CFG)

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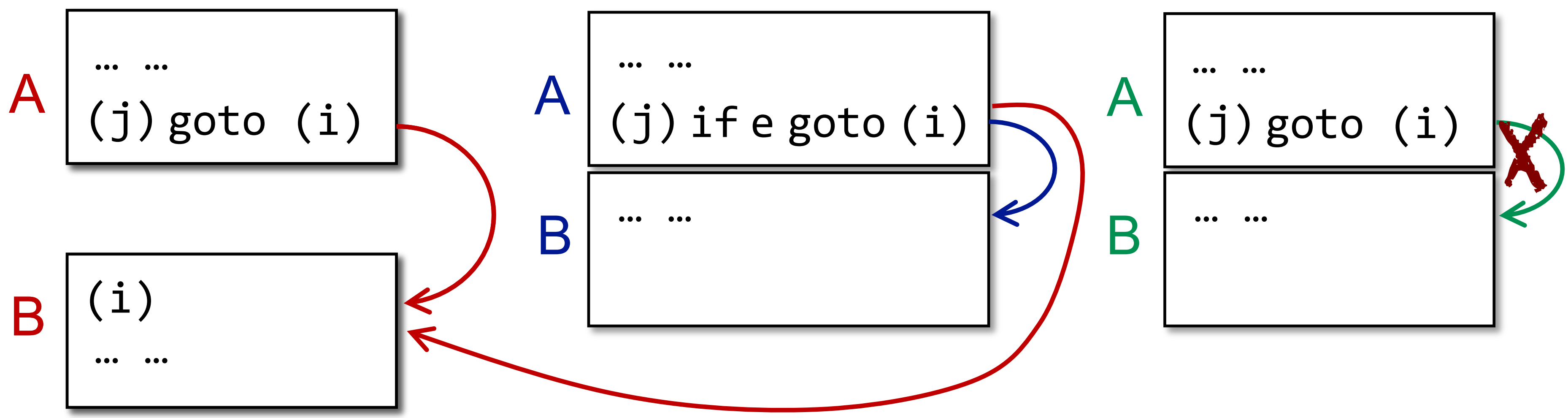
  - B immediately follows A in the original order of instructions and A does not end in an unconditional jump



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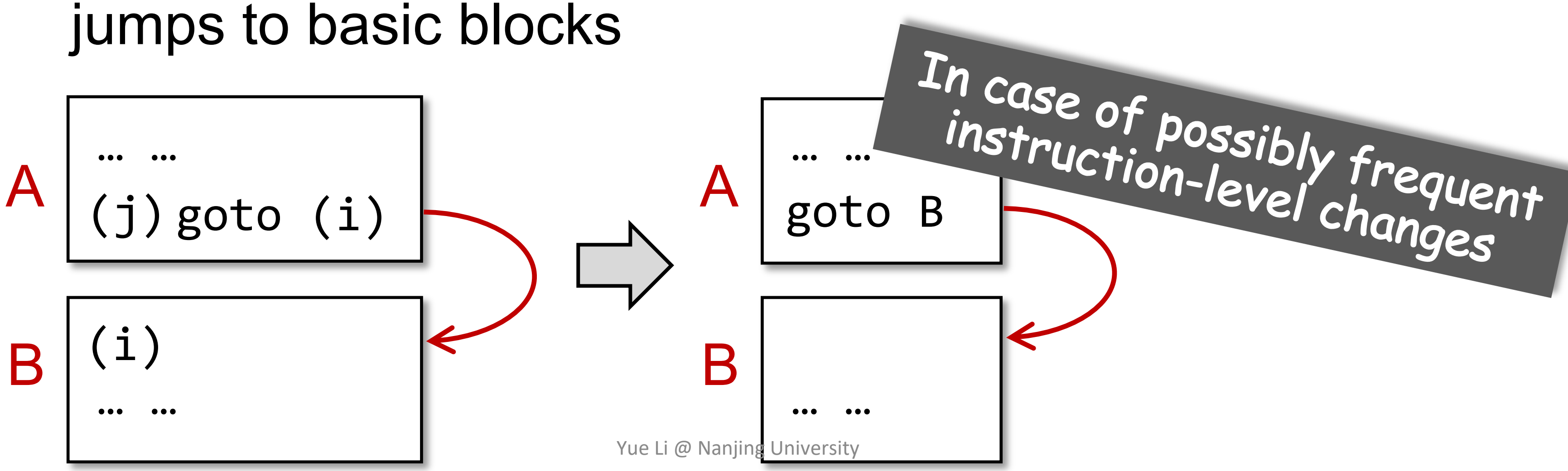
- It is normal to replace the jumps to instruction labels by jumps to basic blocks



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⇒

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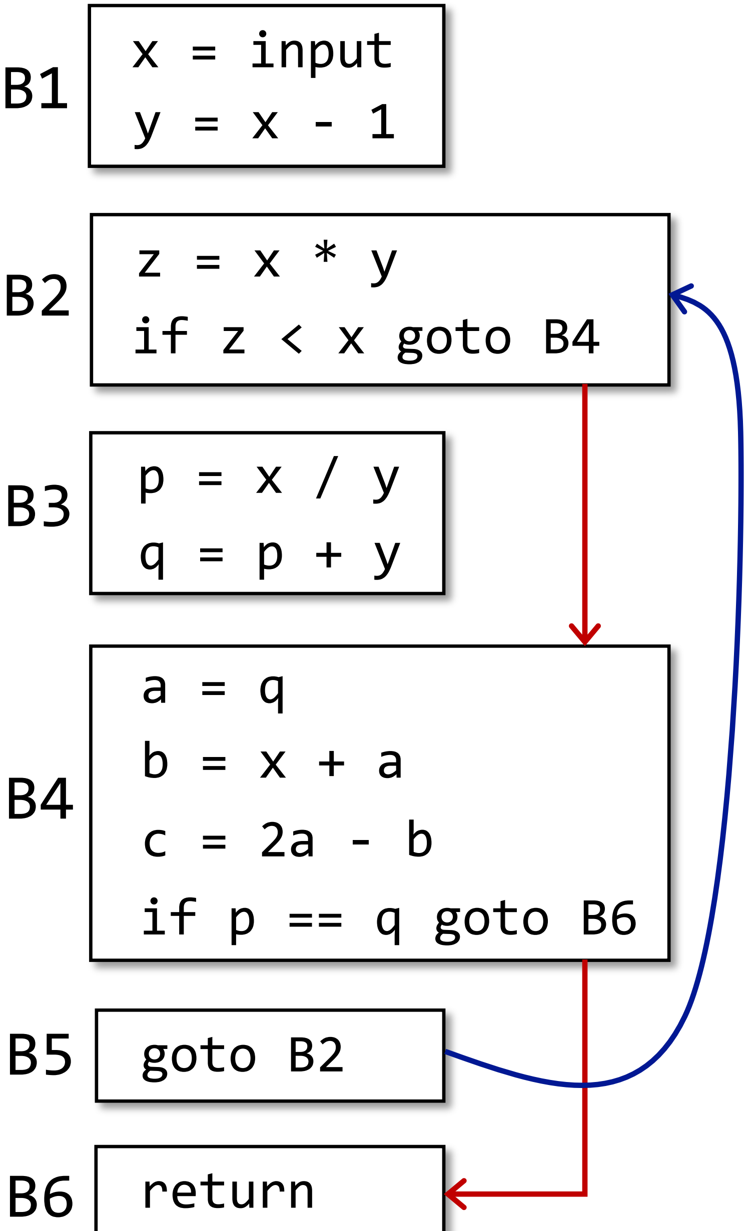

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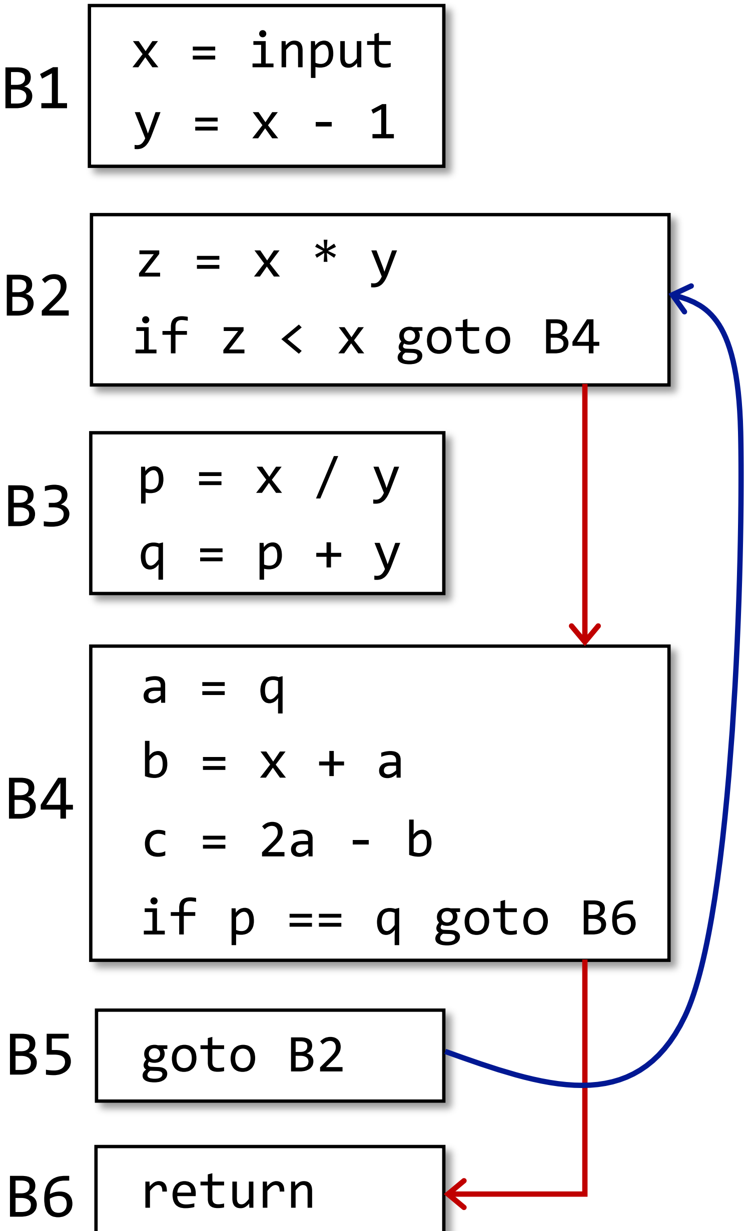

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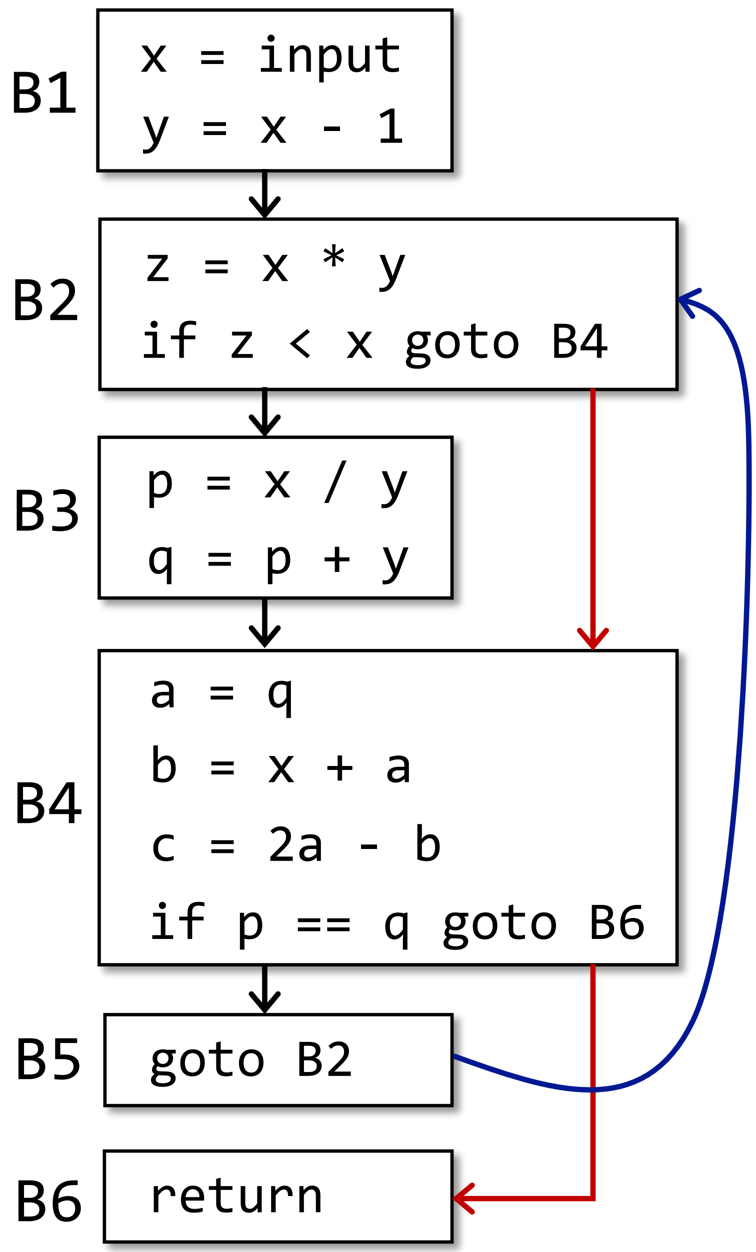
B immediately follows **A** in the original order of instructions and **A** does not end in an unconditional jump



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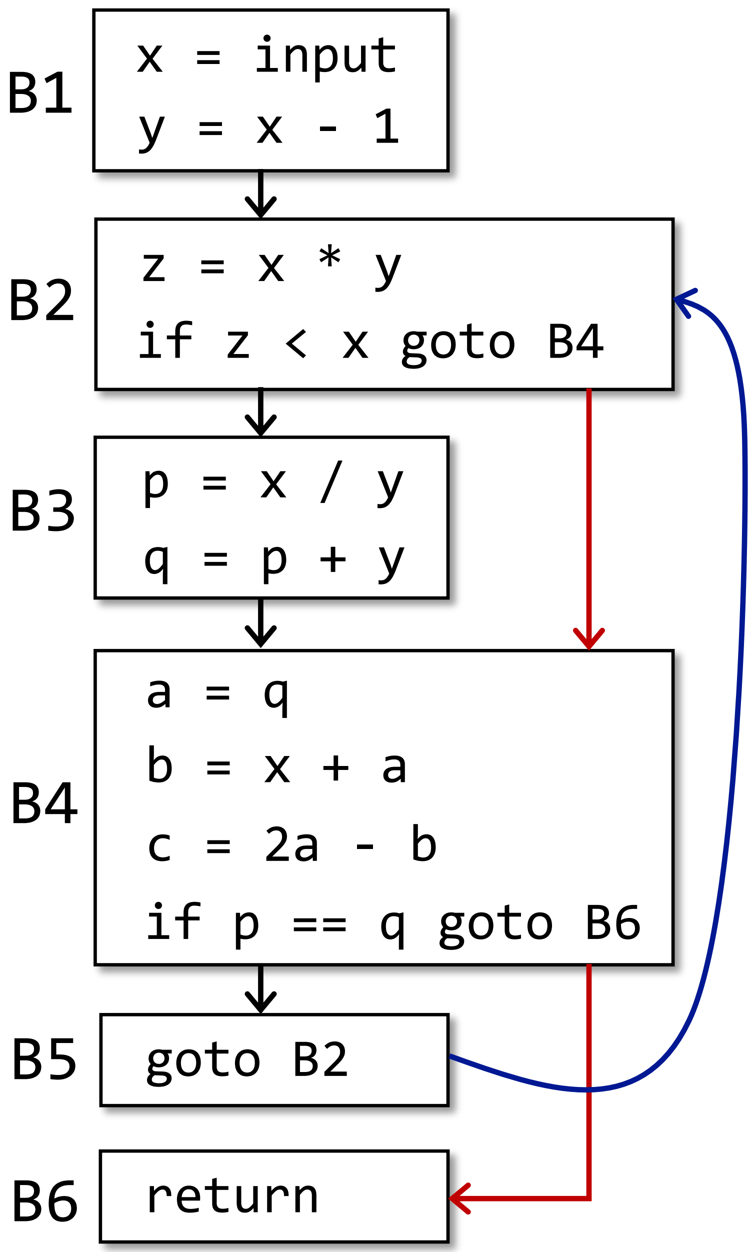

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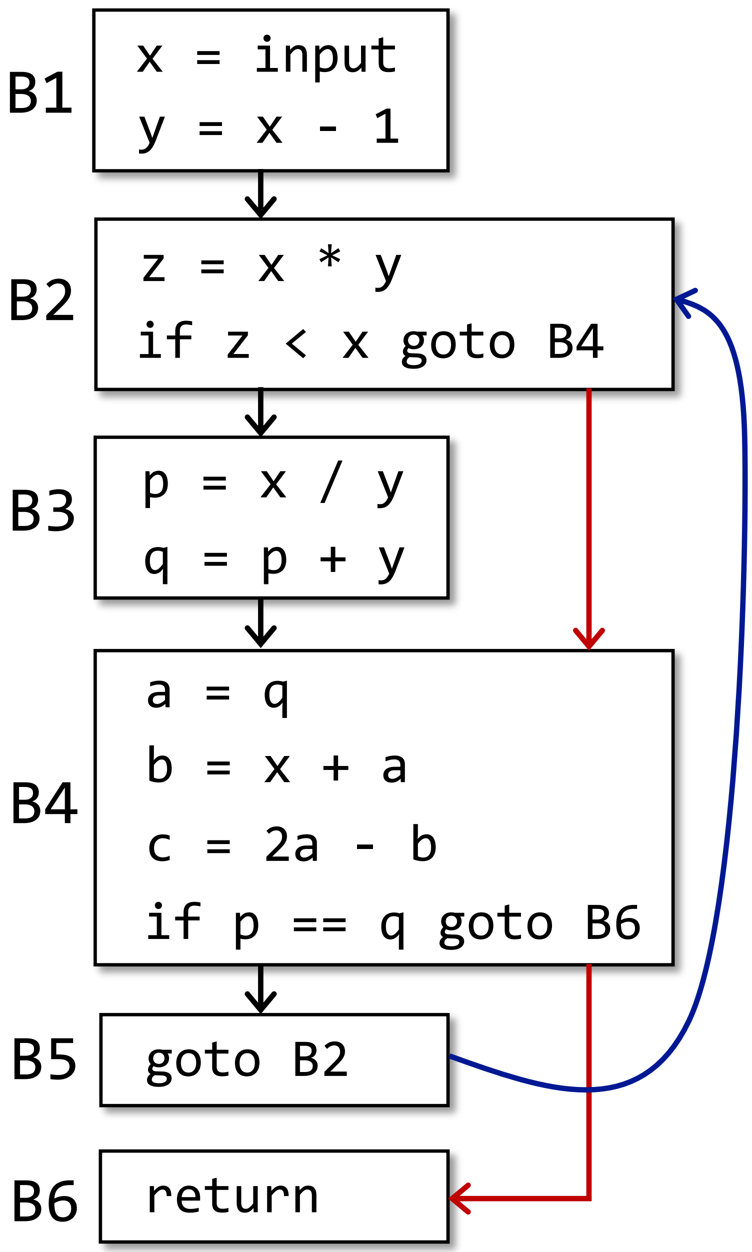
We say that **A** is a **predecessor** of **B**, and **B** is a **successor** of **A**



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

- They do not correspond to executable IR
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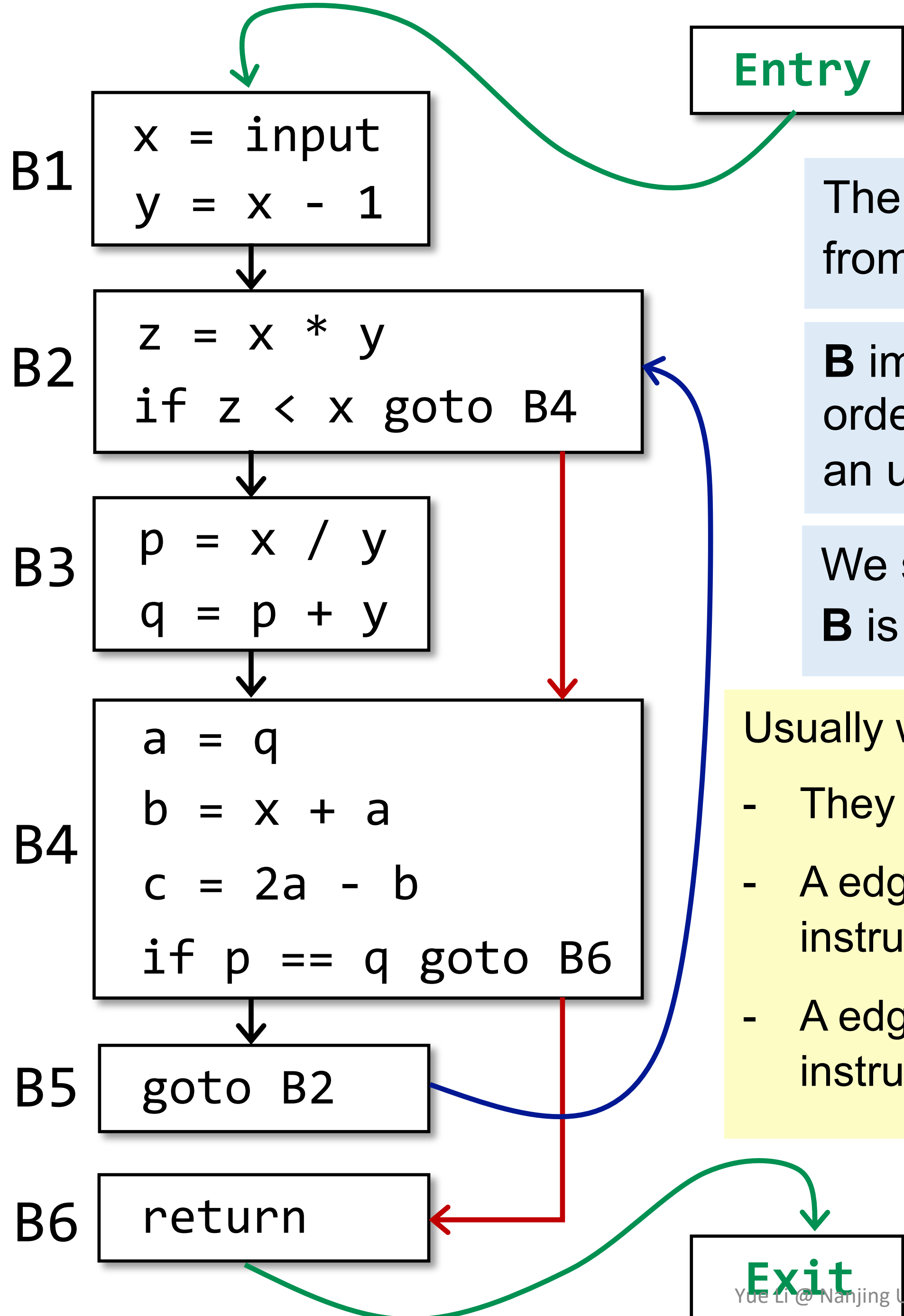

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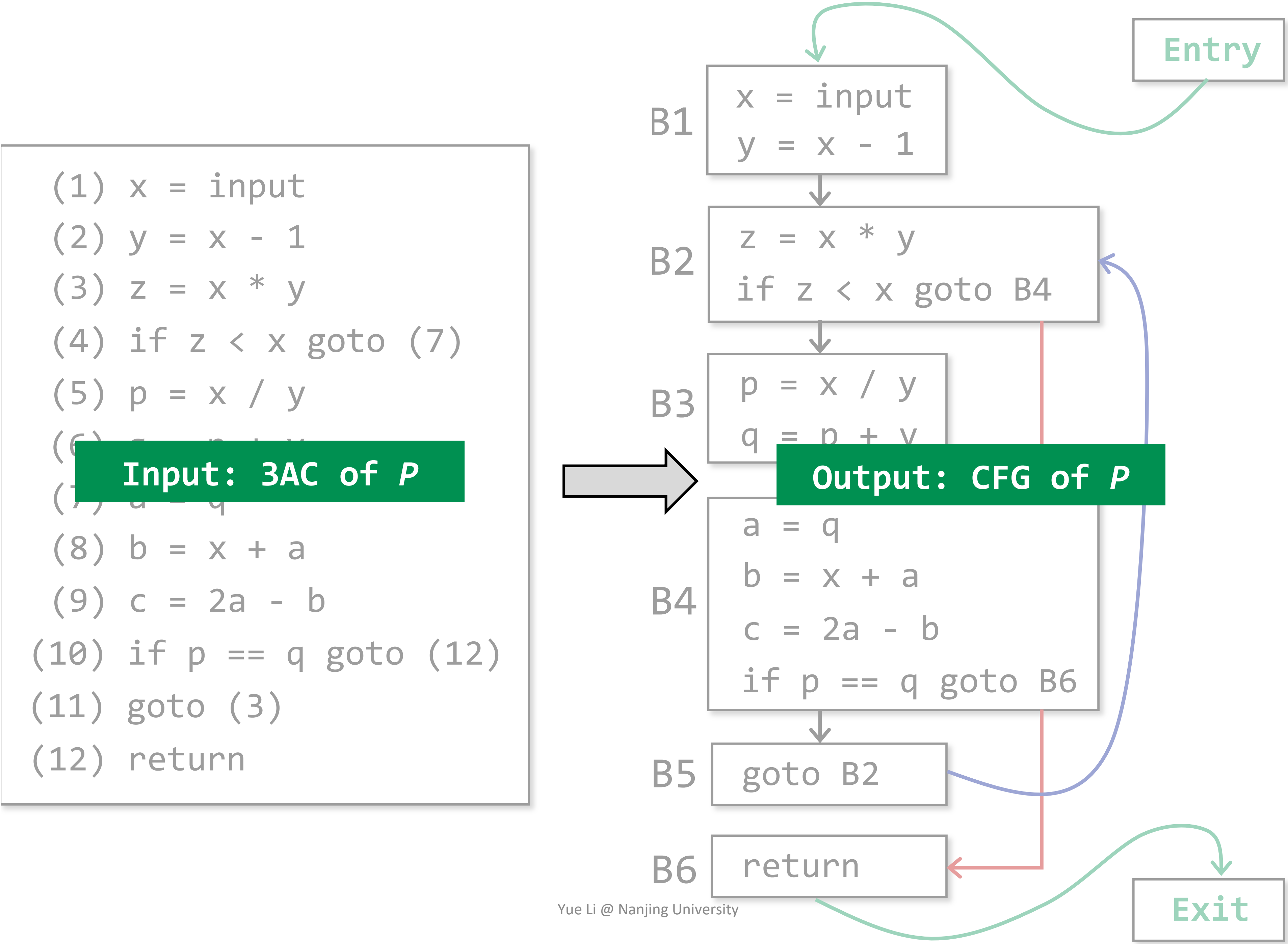
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Input: 3AC of *P*
Output: CFG of *P*
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B2
z = x * y
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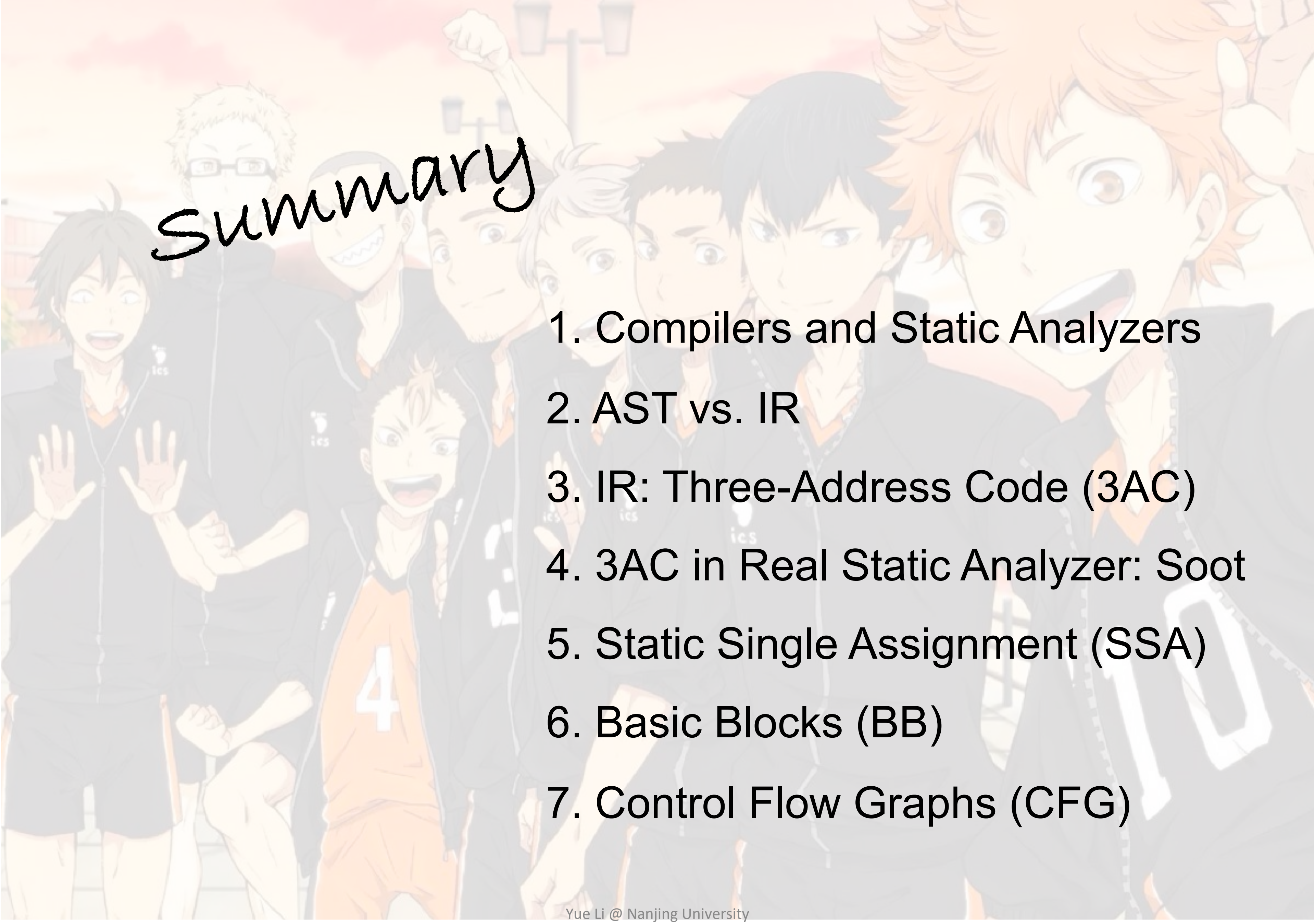
B3
p = x / y
B4
a = q
b = x + a
c = 2a - b
if p == q goto B6
B5
goto B2
B6
return
Exit



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