Lecture 9

静态单赋值

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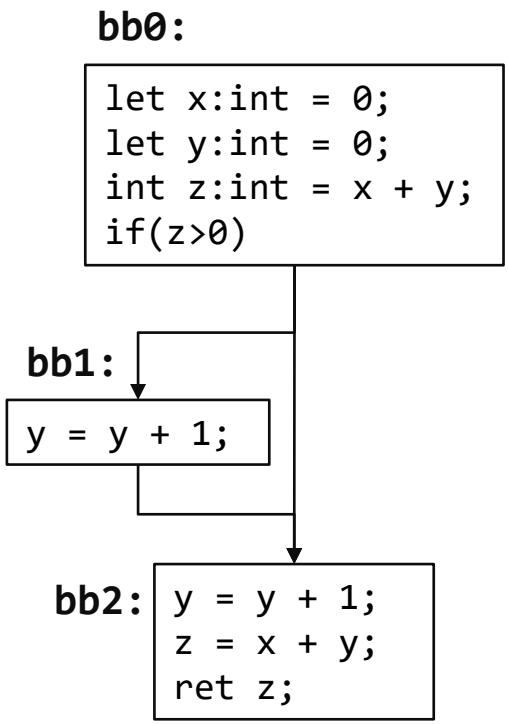
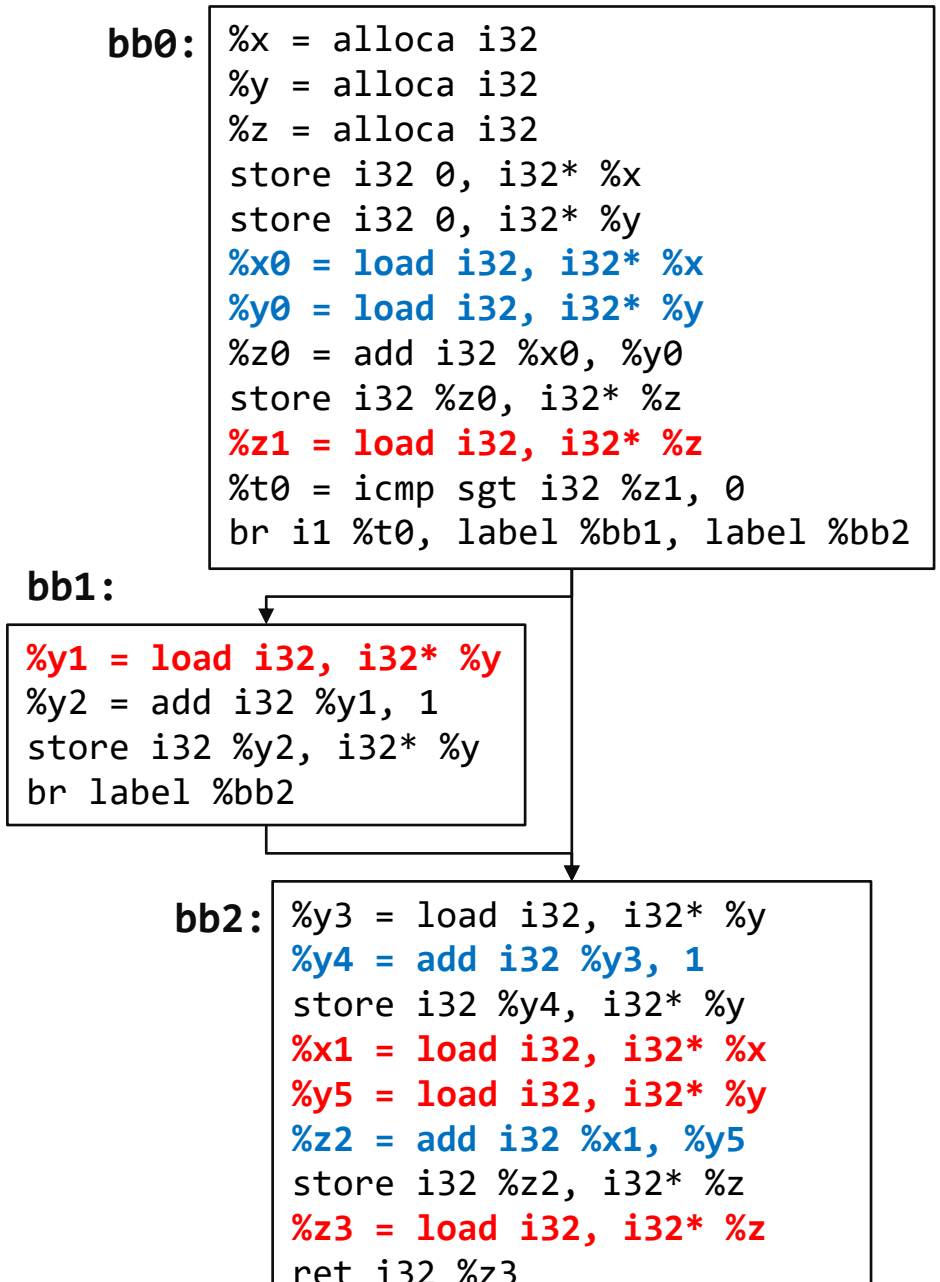
大纲

- 一、优化冗余Load指令
- 二、优化冗余Store指令
- 三、纯寄存器表示
- 四、Phi指令优化

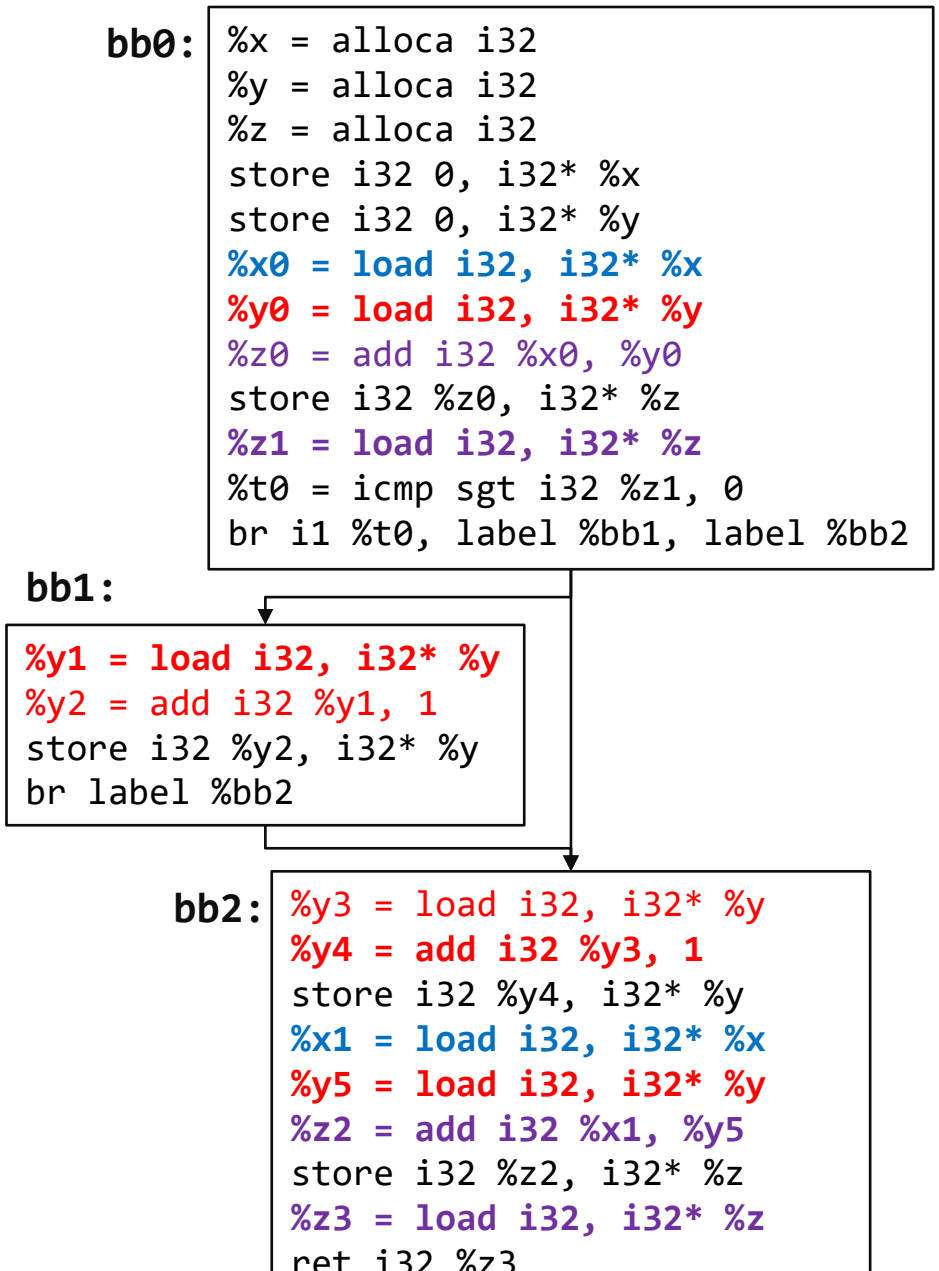
一、优化Load

线性IR中的Load冗余





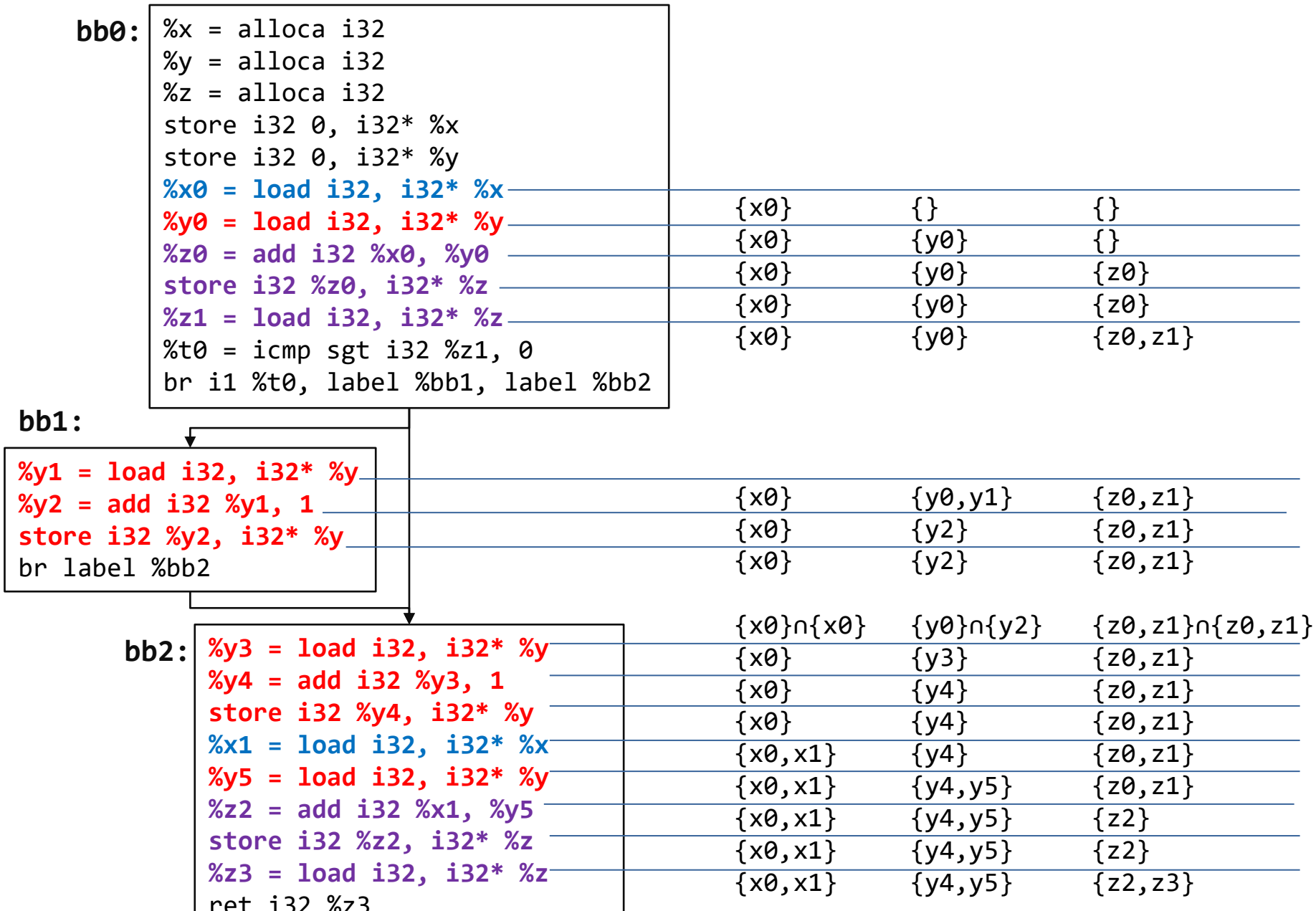
优化思路: 可用寄存器分析



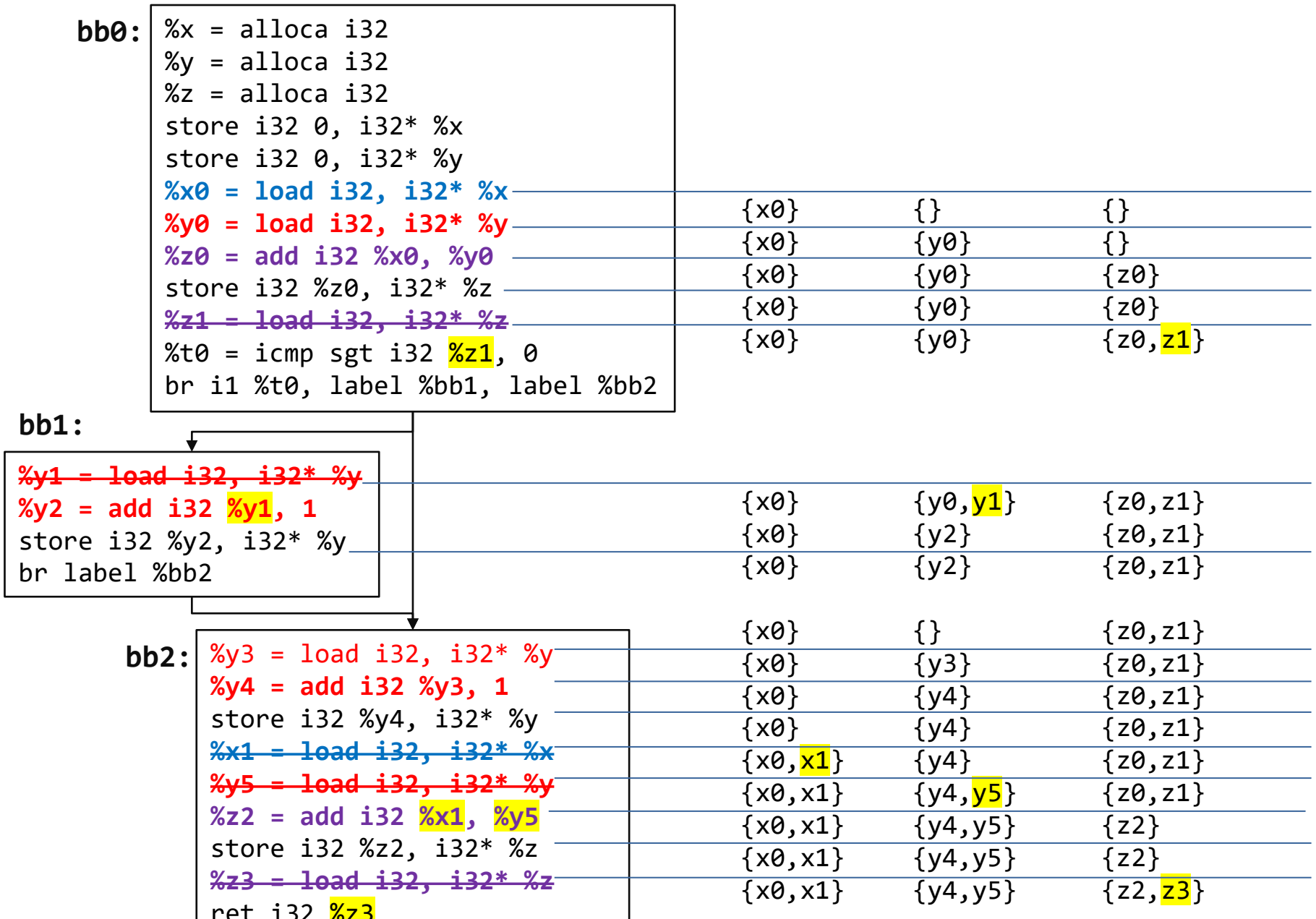
- 正向遍历控制流图
- Transfer函数定义：
  - `%t = load i32, i32* %x`
    - $S_x = S_x \cup \{t\}$
  - `%t = bop %t1, %t2`
    - $S_x = S_x \cup \{t\},\ \text{s.t. } t \in * x$
  - `store i32 %t, i32* %x`
    - $S_x = \{t\}$
- 遇到合并节点

$$\mathrm{IN}(n) = \bigcap_{n' \in \mathrm{predecessor}(n)} \mathrm{OUT}(n')$$

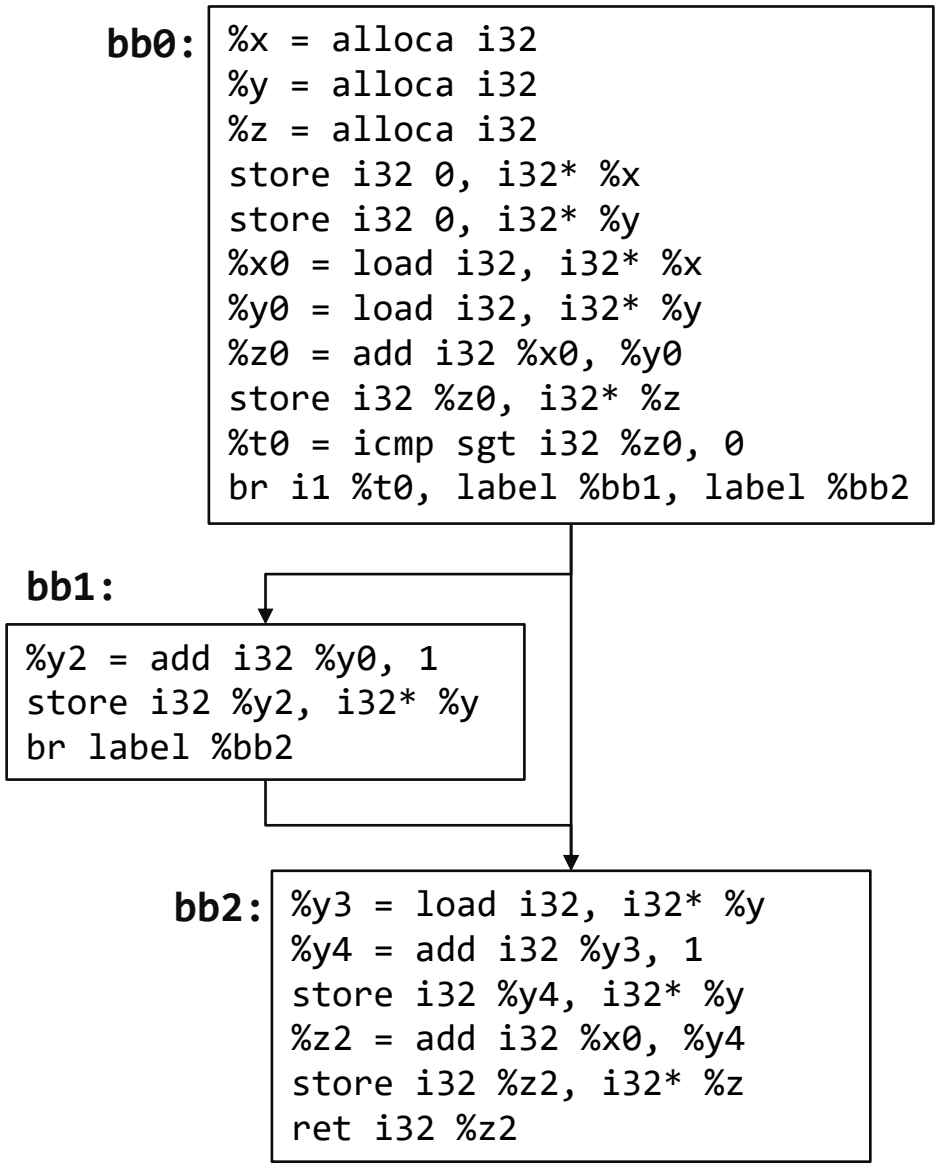
分析过程


bb0:
%x = alloca i32
%y = alloca i32
%z = alloca i32
store i32 0, i32* %x
store i32 0, i32* %y
%x0 = load i32, i32* %x
%y0 = load i32, i32* %y
%z0 = add i32 %x0, %y0
store i32 %z0, i32* %z
%z1 = load i32, i32* %z
%t0 = icmp sgt i32 %z1, 0
br i1 %t0, label %bb1, label %bb2
{x0} {} {}
{x0} {y0} {}
{x0} {y0} {z0}
{x0} {y0} {z0}
{x0} {y0} {z0,z1}
bb1:
%y1 = load i32, i32* %y
%y2 = add i32 %y1, 1
store i32 %y2, i32* %y
br label %bb2
{x0} {y0,y1} {z0,z1}
{x0} {y2} {z0,z1}
{x0} {y2} {z0,z1}
bb2:
%y3 = load i32, i32* %y
%y4 = add i32 %y3, 1
store i32 %y4, i32* %y
%x1 = load i32, i32* %x
%y5 = load i32, i32* %y
%z2 = add i32 %x1, %y5
store i32 %z2, i32* %z
%z3 = load i32, i32* %z
ret i32 %z3
{x0}∩{x0} {y0}∩{y2} {z0,z1}∩{z0,z1}
{x0} {y3} {z0,z1}
{x0} {y4} {z0,z1}
{x0} {y4} {z0,z1}
{x0,x1} {y4} {z0,z1}
{x0,x1} {y4,y5} {z0,z1}
{x0,x1} {y4,y5} {z2}
{x0,x1} {y4,y5} {z2}
{x0,x1} {y4,y5} {z2,z3}

分析结果


bb0:
%x = alloca i32
%y = alloca i32
%z = alloca i32
store i32 0, i32* %x
store i32 0, i32* %y
%x0 = load i32, i32* %x
%y0 = load i32, i32* %y
%z0 = add i32 %x0, %y0
store i32 %z0, i32* %z
%z1 = load i32, i32* %z
%t0 = icmp sgt i32 %z1, 0
br i1 %t0, label %bb1, label %bb2
{x0} {} {}
{x0} {y0} {}
{x0} {y0} {z0}
{x0} {y0} {z0}
{x0} {y0} {z0,z1}
bb1:
%y1 = load i32, i32* %y
%y2 = add i32 %y1, 1
store i32 %y2, i32* %y
br label %bb2
{x0} {y0,y1} {z0,z1}
{x0} {y2} {z0,z1}
{x0} {y2} {z0,z1}
bb2:
%y3 = load i32, i32* %y
%y4 = add i32 %y3, 1
store i32 %y4, i32* %y
%x1 = load i32, i32* %x
%y5 = load i32, i32* %y
%z2 = add i32 %x1, %y5
store i32 %z2, i32* %z
%z3 = load i32, i32* %z
ret i32 %z3
{x0} {} {z0,z1}
{x0} {y3} {z0,z1}
{x0} {y4} {z0,z1}
{x0} {y4} {z0,z1}
{x0,x1} {y4} {z0,z1}
{x0,x1} {y4,y5} {z0,z1}
{x0,x1} {y4,y5} {z2}
{x0,x1} {y4,y5} {z2}
{x0,x1} {y4,y5} {z2,z3}

优化结果

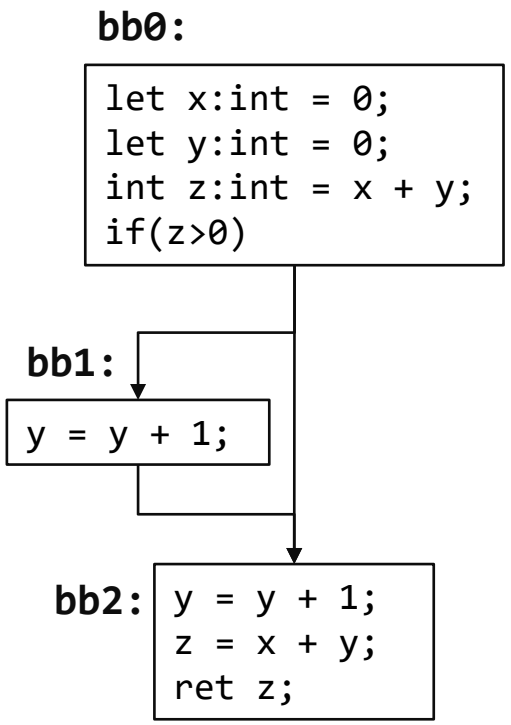

bb0:
%x = alloca i32
%y = alloca i32
%z = alloca i32
store i32 0, i32* %x
store i32 0, i32* %y
%x0 = load i32, i32* %x
%y0 = load i32, i32* %y
%z0 = add i32 %x0, %y0
store i32 %z0, i32* %z
%t0 = icmp sgt i32 %z0, 0
br i1 %t0, label %bb1, label %bb2
bb1:
%y2 = add i32 %y0, 1
store i32 %y2, i32* %y
br label %bb2
bb2:
%y3 = load i32, i32* %y
%y4 = add i32 %y3, 1
store i32 %y4, i32* %y
%z2 = add i32 %x0, %y4
store i32 %z2, i32* %z
ret i32 %z2

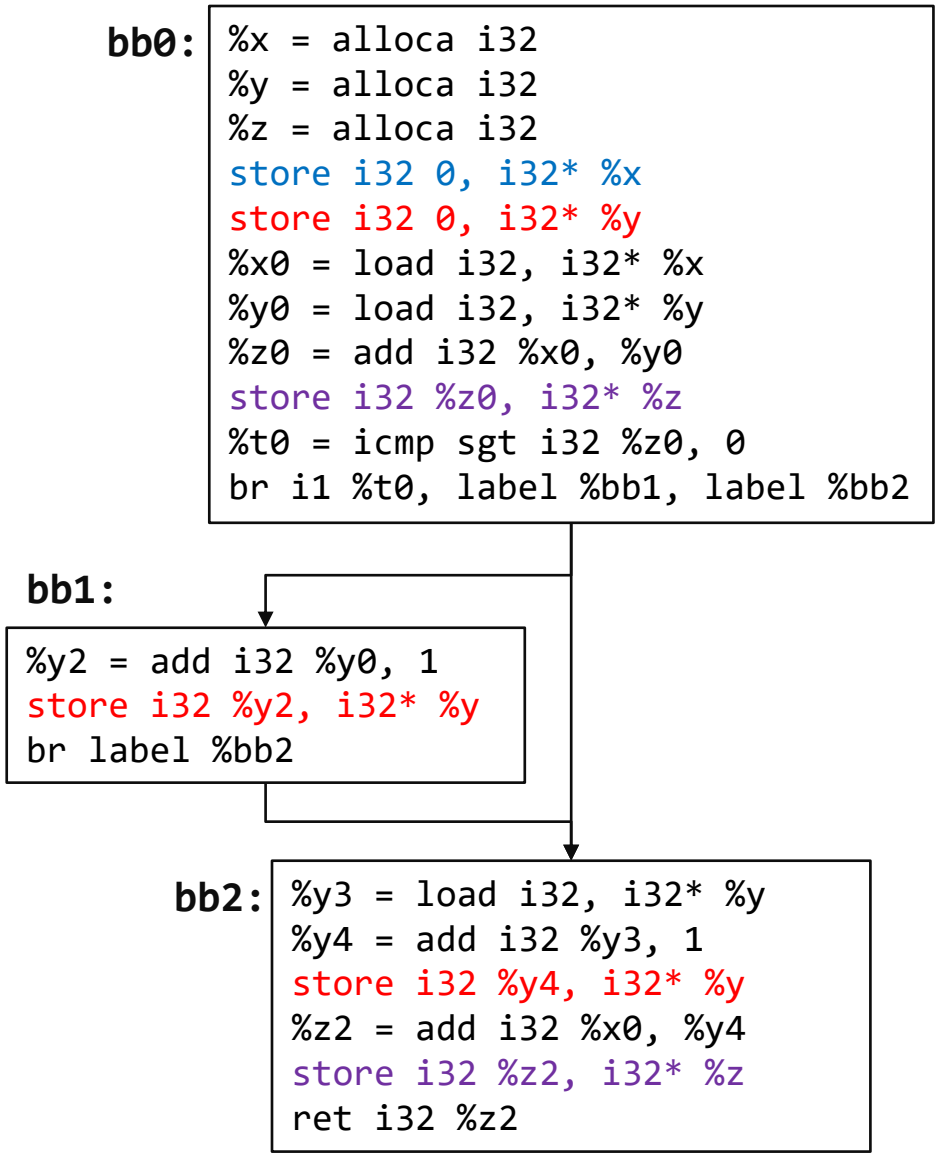
伪代码

```
For (each node n):
    IN[n] = {<v: ∅>: v is a program variable}
    OUT[n] = {<v: ∅>}
Repeat:
    For(each node n):
        For(each n's predecessor p)
            IN[n] = IN[n] ∩ OUT[p]
        OUT[n] = TRANSFER(n)
Until IN[n] and OUT[n] stops changing for all n
```

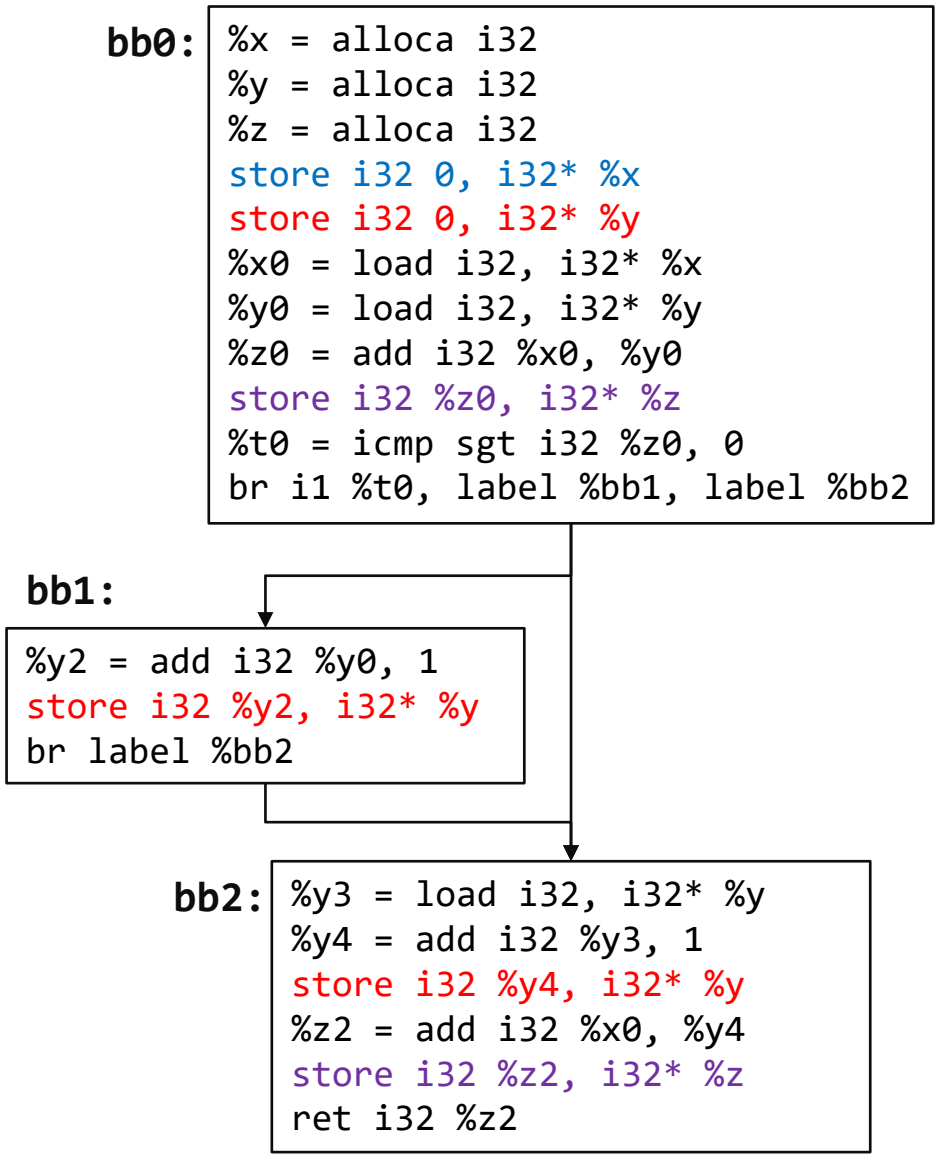
二、优化Store

线性IR中的Store冗余





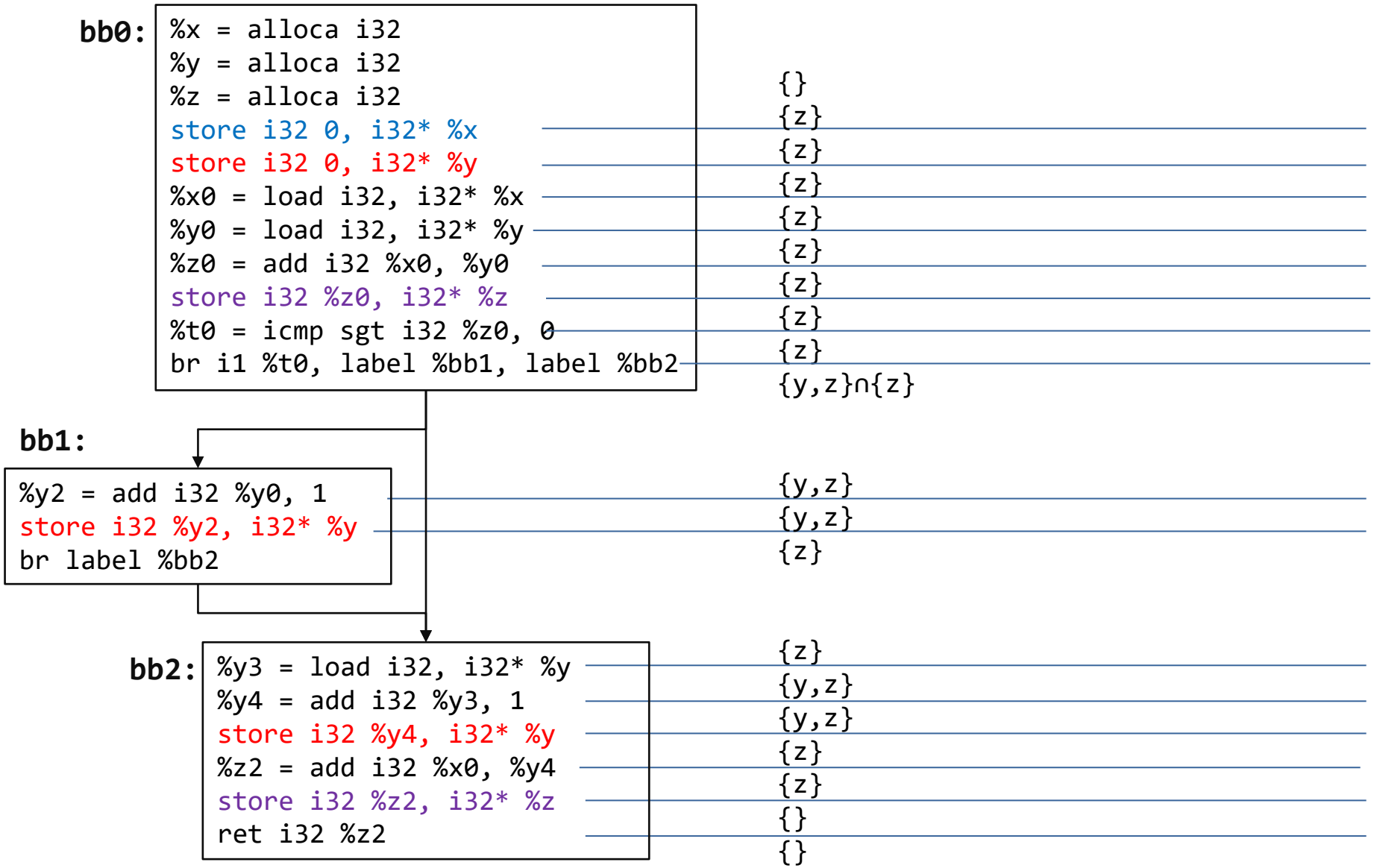
优化思路: 可用Store语句分析



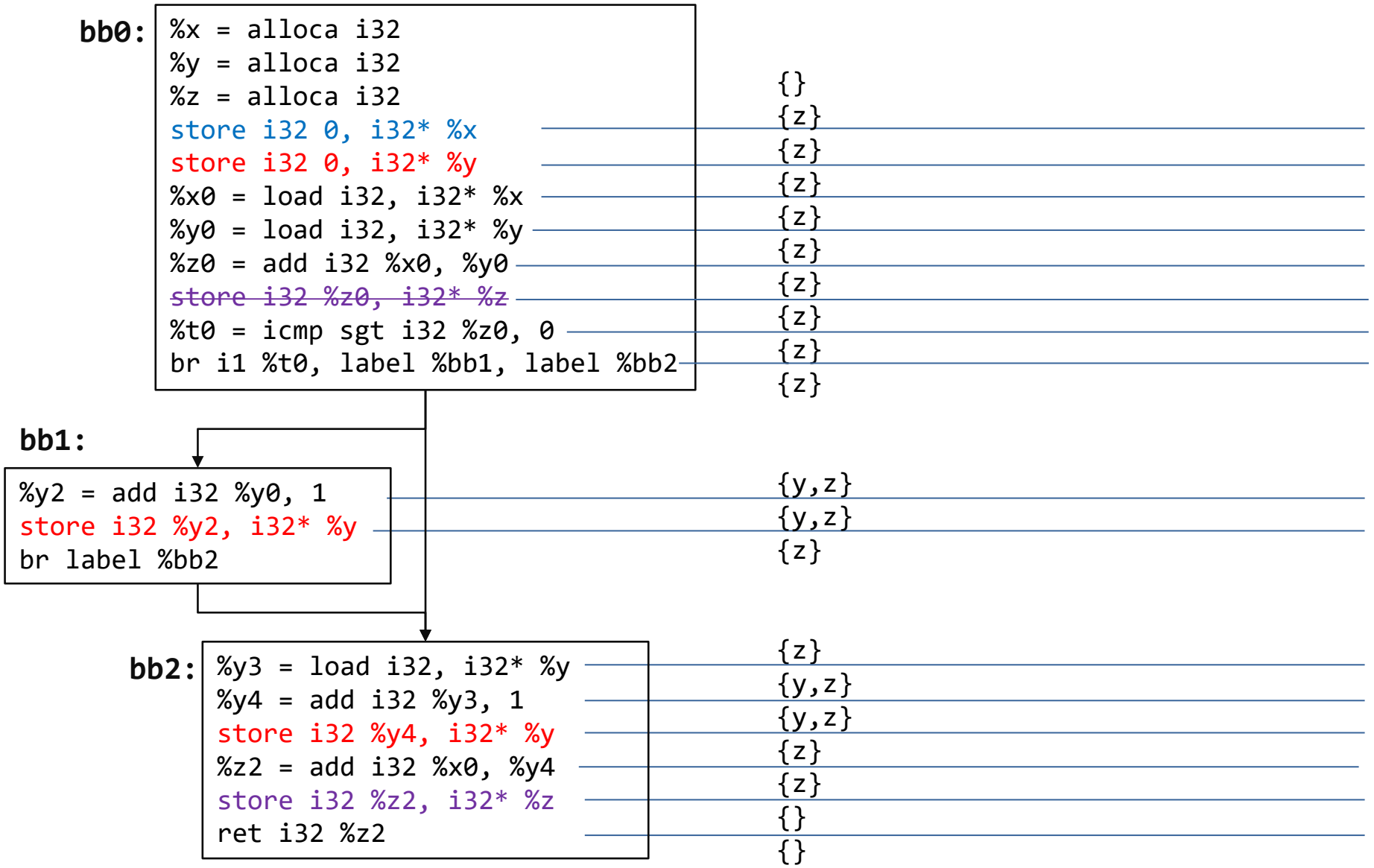
- 逆向遍历控制流图
- Transfer函数定义：
  - `store i32 %t, i32* %x`
    - $S = S \cup \{x\}$
  - `%t = load i32, i32* %x`
    - $S = S \backslash \{x\}$
  - `%t = alloc, i32* %x`
    - $S = S \backslash \{x\}$
- 遇到合并节点

$$\mathrm{OUT}(n) = \bigcap_{n' \in \mathrm{successor}(n)} \mathrm{IN}(n')$$

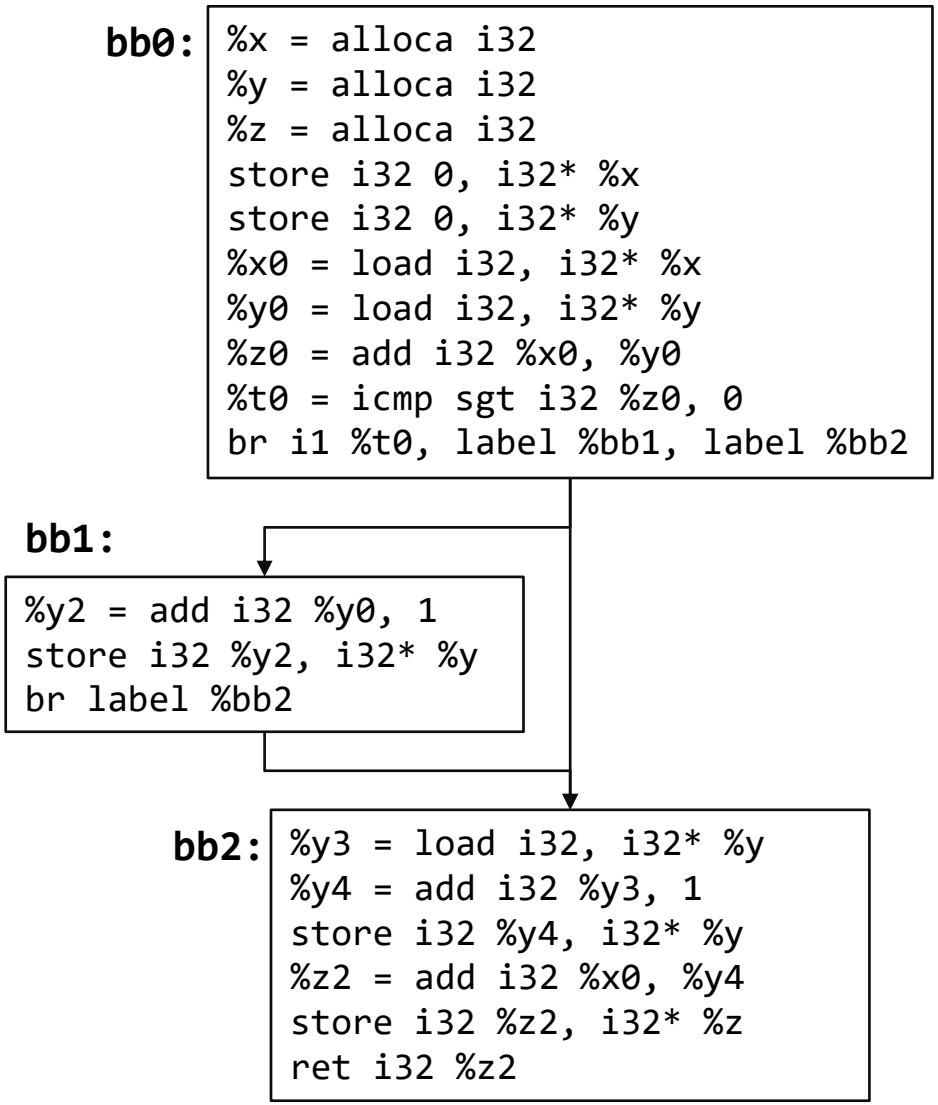
分析过程


bb0:
%x = alloca i32
%y = alloca i32
%z = alloca i32
store i32 0, i32* %x
store i32 0, i32* %y
%x0 = load i32, i32* %x
%y0 = load i32, i32* %y
%z0 = add i32 %x0, %y0
store i32 %z0, i32* %z
%t0 = icmp sgt i32 %z0, 0
br i1 %t0, label %bb1, label %bb2
{}
{z}
{z}
{z}
{z}
{z}
{z}
{z}
{y,z}∩{z}
bb1:
%y2 = add i32 %y0, 1
store i32 %y2, i32* %y
br label %bb2
{y,z}
{y,z}
{z}
bb2:
%y3 = load i32, i32* %y
%y4 = add i32 %y3, 1
store i32 %y4, i32* %y
%z2 = add i32 %x0, %y4
store i32 %z2, i32* %z
ret i32 %z2
{z}
{y,z}
{y,z}
{z}
{z}
{}
{}

分析结果

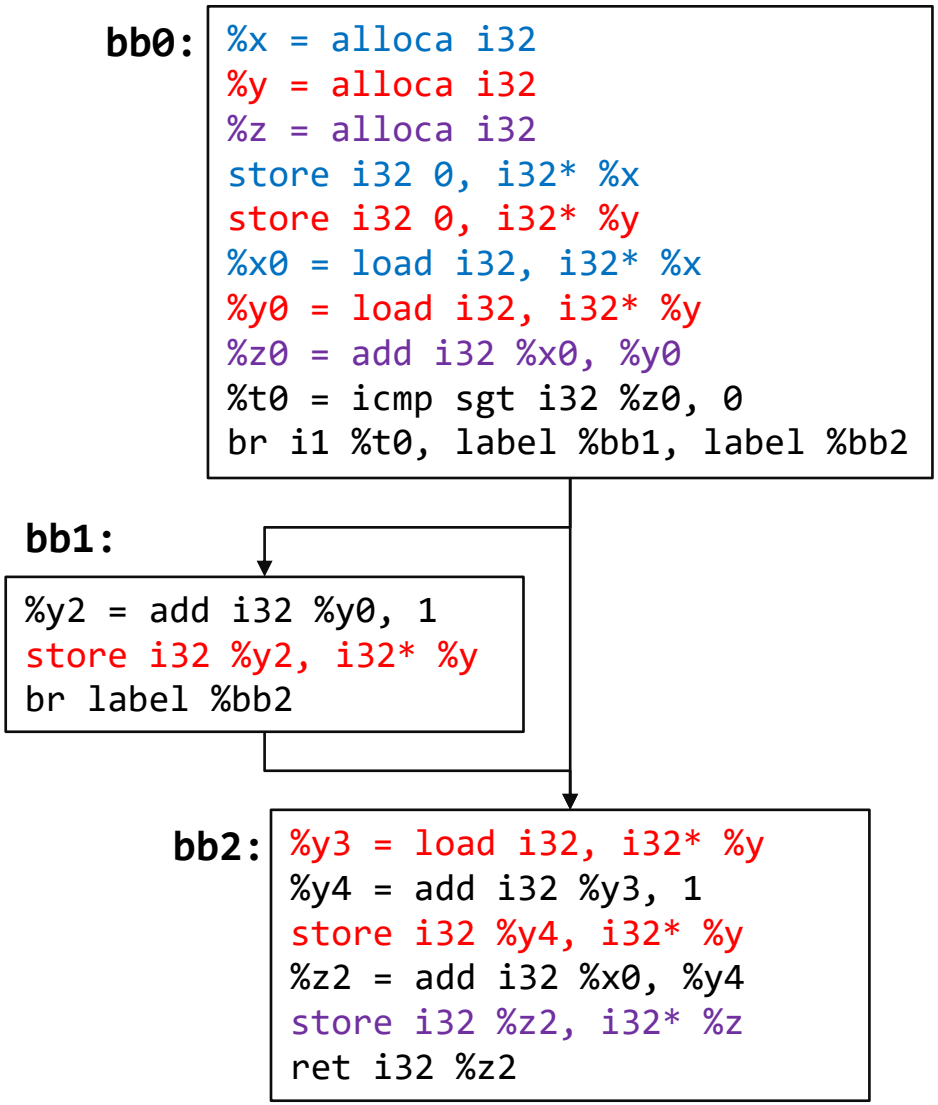

bb0:
%x = alloca i32
%y = alloca i32
%z = alloca i32
store i32 0, i32* %x
store i32 0, i32* %y
%x0 = load i32, i32* %x
%y0 = load i32, i32* %y
%z0 = add i32 %x0, %y0
store i32 %z0, i32* %z
%t0 = icmp sgt i32 %z0, 0
br i1 %t0, label %bb1, label %bb2
{}
{z}
{z}
{z}
{z}
{z}
{z}
{z}
{z}
bb1:
%y2 = add i32 %y0, 1
store i32 %y2, i32* %y
br label %bb2
{y,z}
{y,z}
{z}
bb2:
%y3 = load i32, i32* %y
%y4 = add i32 %y3, 1
store i32 %y4, i32* %y
%z2 = add i32 %x0, %y4
store i32 %z2, i32* %z
ret i32 %z2
{z}
{y,z}
{y,z}
{z}
{z}
{}
{}

优化结果

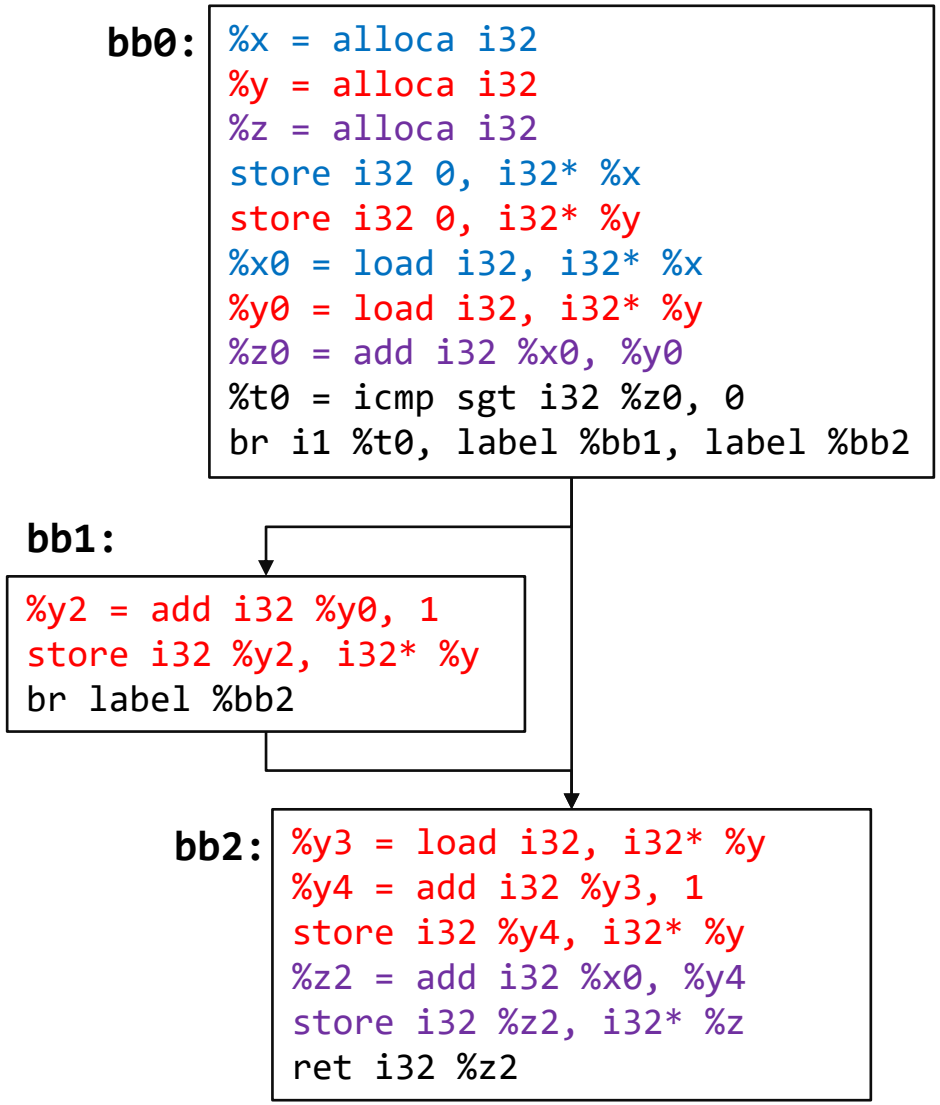

bb0:
%x = alloca i32
%y = alloca i32
%z = alloca i32
store i32 0, i32* %x
store i32 0, i32* %y
%x0 = load i32, i32* %x
%y0 = load i32, i32* %y
%z0 = add i32 %x0, %y0
%t0 = icmp sgt i32 %z0, 0
br i1 %t0, label %bb1, label %bb2
bb1:
%y2 = add i32 %y0, 1
store i32 %y2, i32* %y
br label %bb2
bb2:
%y3 = load i32, i32* %y
%y4 = add i32 %y3, 1
store i32 %y4, i32* %y
%z2 = add i32 %x0, %y4
store i32 %z2, i32* %z
ret i32 %z2

三、纯寄存器表示

消除内存存取


bb0:
%x = alloca i32
%y = alloca i32
%z = alloca i32
store i32 0, i32* %x
store i32 0, i32* %y
%x0 = load i32, i32* %x
%y0 = load i32, i32* %y
%z0 = add i32 %x0, %y0
%t0 = icmp sgt i32 %z0, 0
br i1 %t0, label %bb1, label %bb2
bb1:
%y2 = add i32 %y0, 1
store i32 %y2, i32* %y
br label %bb2
bb2:
%y3 = load i32, i32* %y
%y4 = add i32 %y3, 1
store i32 %y4, i32* %y
%z2 = add i32 %x0, %y4
store i32 %z2, i32* %z
ret i32 %z2

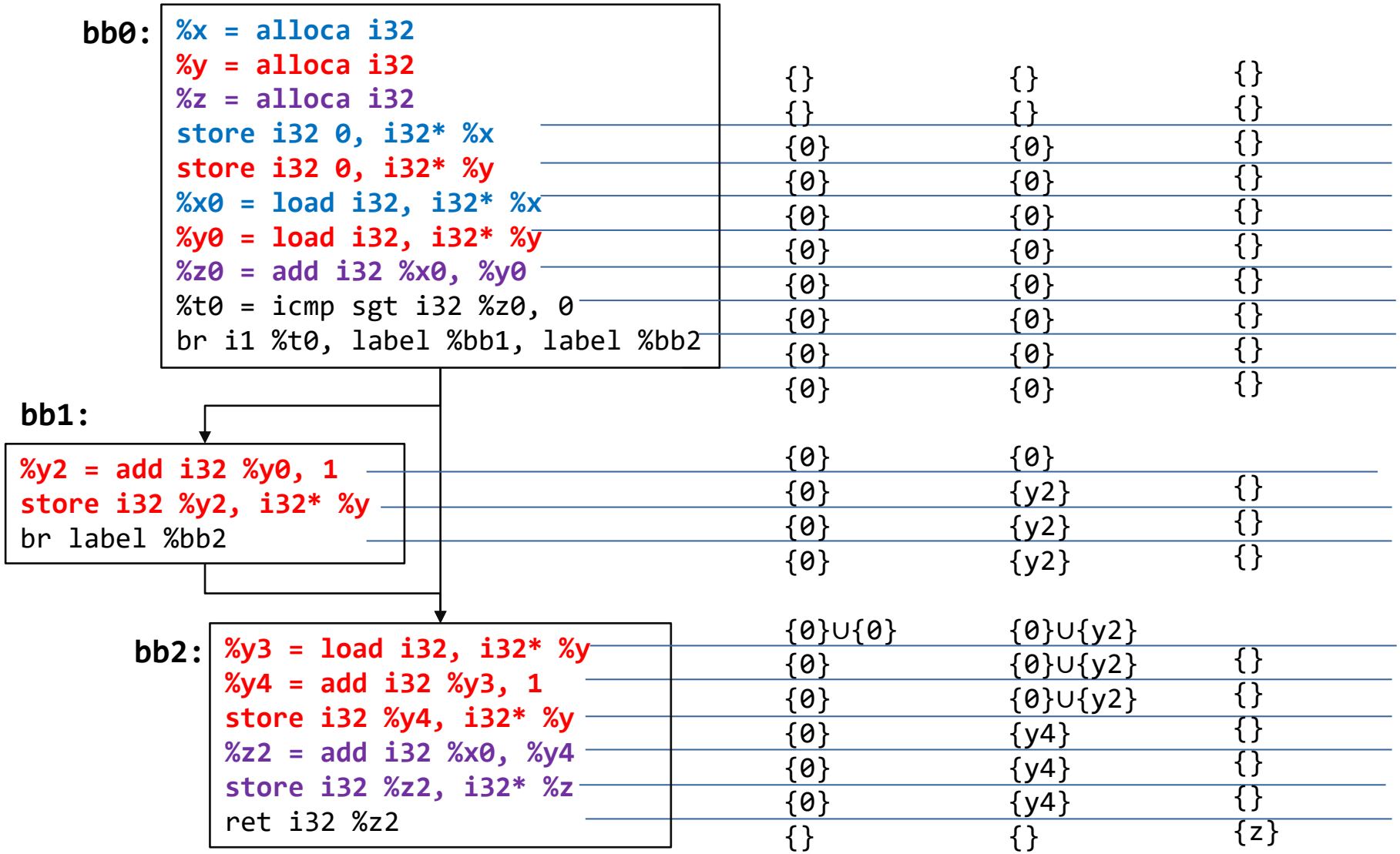
分析方法：数值流分析



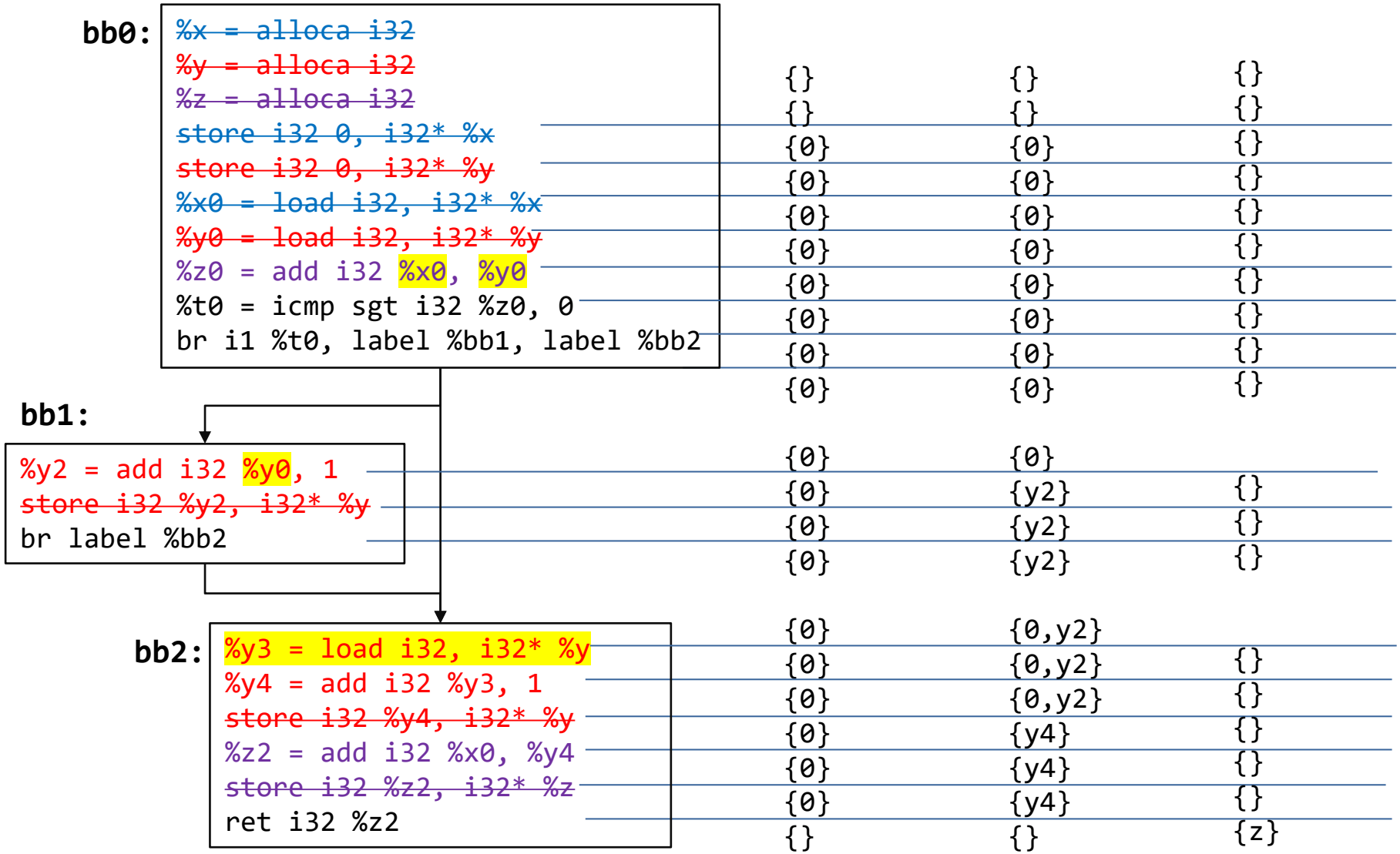
- 正向遍历控制流图
- Transfer函数定义：
  - store i32 %t, i32* %x
    - $S_x = \{t\}$
- 遇到合并节点

$$\mathrm{IN}(n) = \bigcup_{n' \in \mathrm{predecessor}(n)} \mathrm{OUT}(n')$$

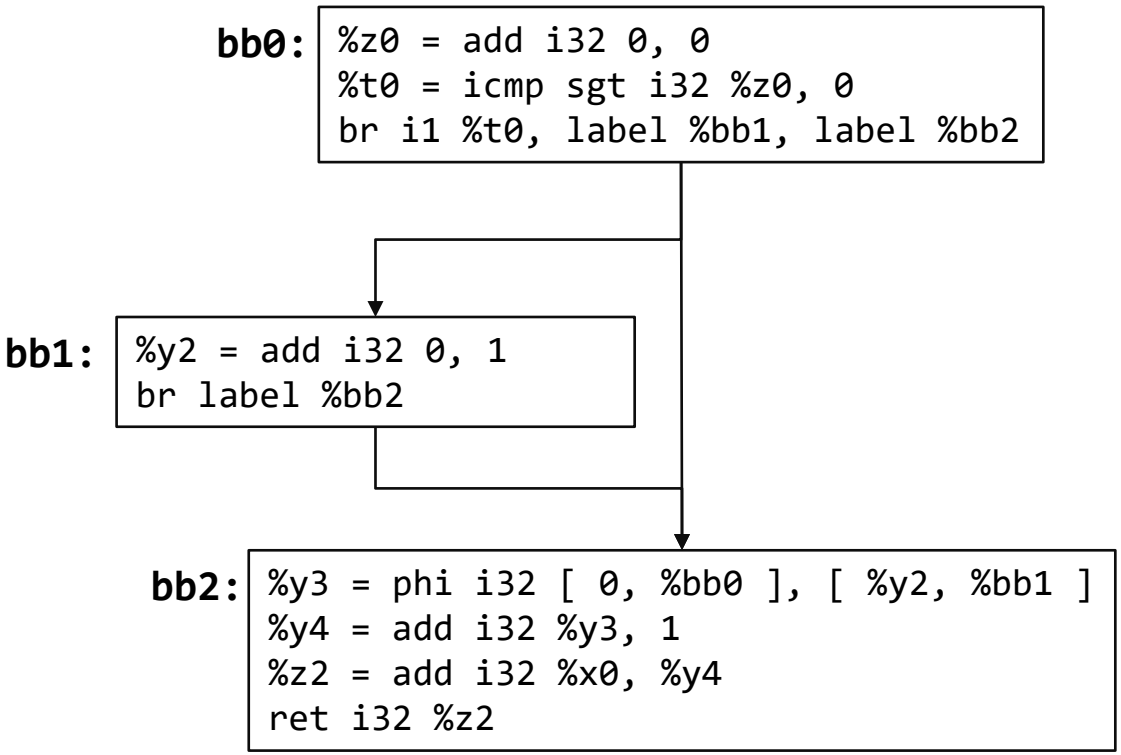
分析过程


bb0:
%x = alloca i32
%y = alloca i32
%z = alloca i32
store i32 0, i32* %x
store i32 0, i32* %y
%x0 = load i32, i32* %x
%y0 = load i32, i32* %y
%z0 = add i32 %x0, %y0
%t0 = icmp sgt i32 %z0, 0
br i1 %t0, label %bb1, label %bb2
bb1:
%y2 = add i32 %y0, 1
store i32 %y2, i32* %y
br label %bb2
bb2:
%y3 = load i32, i32* %y
%y4 = add i32 %y3, 1
store i32 %y4, i32* %y
%z2 = add i32 %x0, %y4
store i32 %z2, i32* %z
ret i32 %z2
{} {} {}
{} {} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0}
{0} {y2} {}
{0} {y2} {}
{0} {y2} {}
{0}∪{0} {0}∪{y2}
{0} {0}∪{y2} {}
{0} {0}∪{y2} {}
{0} {y4} {}
{0} {y4} {}
{0} {y4} {}
{} {} {z}

分析结果

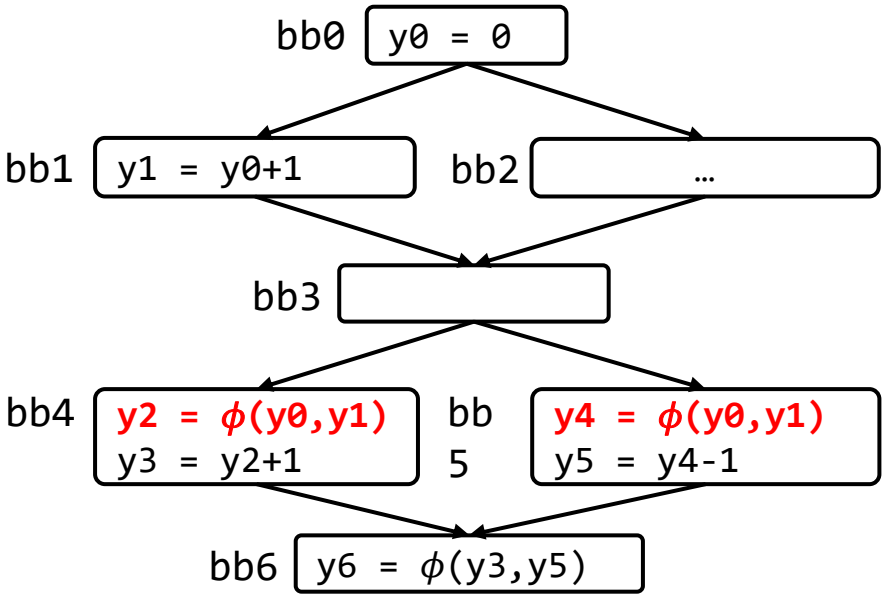

bb0:
%x = alloca i32
%y = alloca i32
%z = alloca i32
store i32 0, i32* %x
store i32 0, i32* %y
%x0 = load i32, i32* %x
%y0 = load i32, i32* %y
%z0 = add i32 %x0, %y0
%t0 = icmp sgt i32 %z0, 0
br i1 %t0, label %bb1, label %bb2
bb1:
%y2 = add i32 %y0, 1
store i32 %y2, i32* %y
br label %bb2
bb2:
%y3 = load i32, i32* %y
%y4 = add i32 %y3, 1
store i32 %y4, i32* %y
%z2 = add i32 %x0, %y4
store i32 %z2, i32* %z
ret i32 %z2
{} {} {}
{} {} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0} {}
{0} {0}
{0} {y2} {}
{0} {y2} {}
{0} {y2} {}
{0} {0,y2}
{0} {0,y2} {}
{0} {0,y2} {}
{0} {y4} {}
{0} {y4} {}
{0} {y4} {}
{} {} {z}

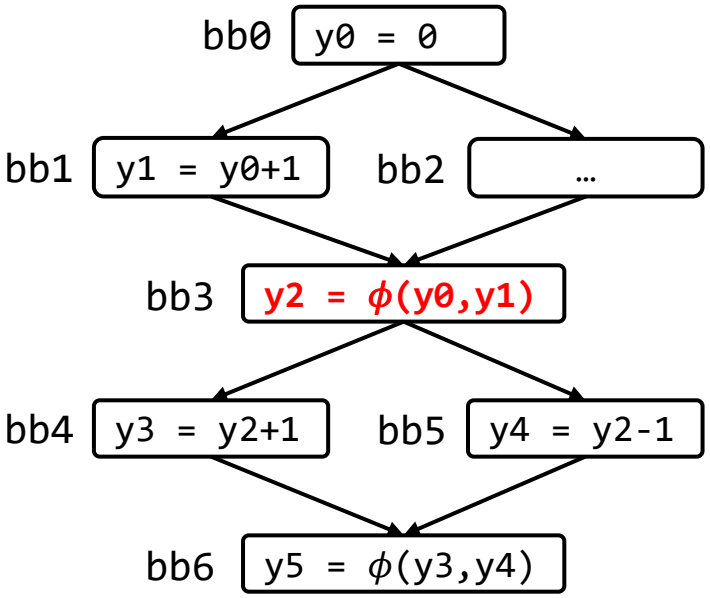
纯寄存器表示


bb0:
%z0 = add i32 0, 0
%t0 = icmp sgt i32 %z0, 0
br i1 %t0, label %bb1, label %bb2
bb1:
%y2 = add i32 0, 1
br label %bb2
bb2:
%y3 = phi i32 [0, %bb0], [%y2, %bb1]
%y4 = add i32 %y3, 1
%z2 = add i32 %x0, %y4
ret i32 %z2

四、Phi指令优化

哪个Phi指令方案更优？

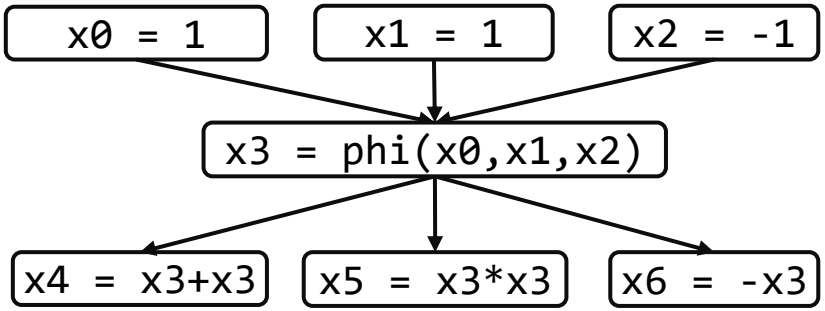




SSA简化def-use关系

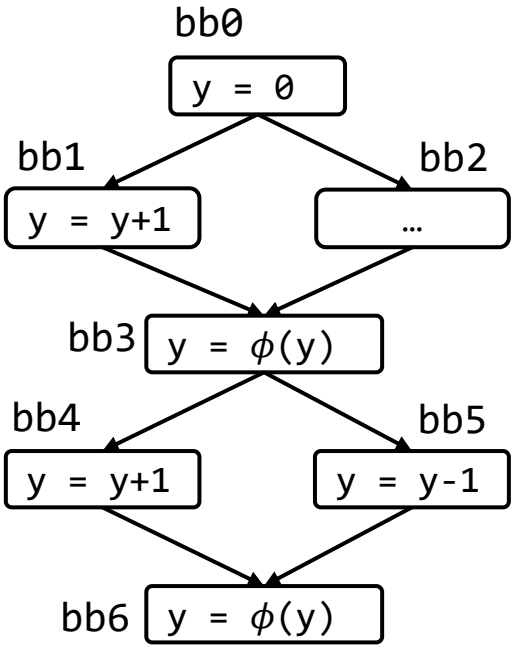
- 原始程序的def-use关系数量是$O(m \times n)$;
- SSA的def-use数量减少为$O(m + n)$。

```
match v1:
    0 => { x = 0; }
    1 => { x = 1; }
    _ => { x = -1; }
...
match v2:
    0 => { x = x + x; }
    1 => { x = x * x; }
    _ => { x = -x; }
```



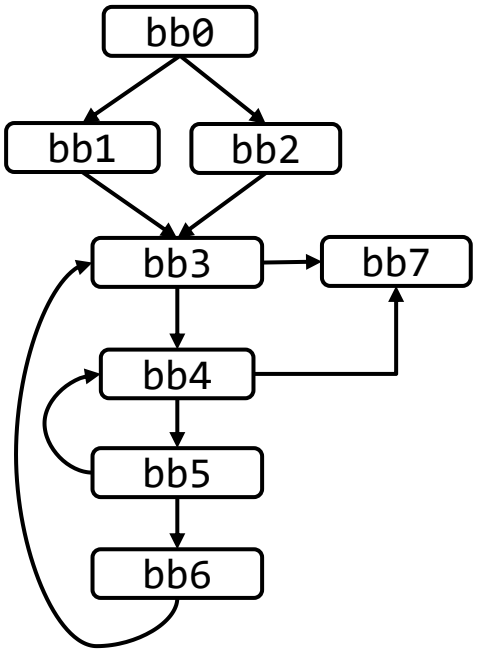
优化思路：基于支配边界优化Phi指令

- bb0支配bb2，bb1和bb2的支配边界都是bb3
- 如果bb1和bb2中都没有def(x)，bb3不需要phi(x)，可直接使用bb0中的def(x)
- 如果bb1中有def(y)，bb3中一定需要phi(y)



支配的基本概念

- 给定有向图$G(V,E)$与起点v_0，如果从v_0到某个点v_j均需要经过点v_i，则称v_i支配v_j或v_i是v_j 的一个支配点
  - $v_i \in Dom(v_j)$
- 如果$v_i \neq v_j$，则称v_i严格支配v_j



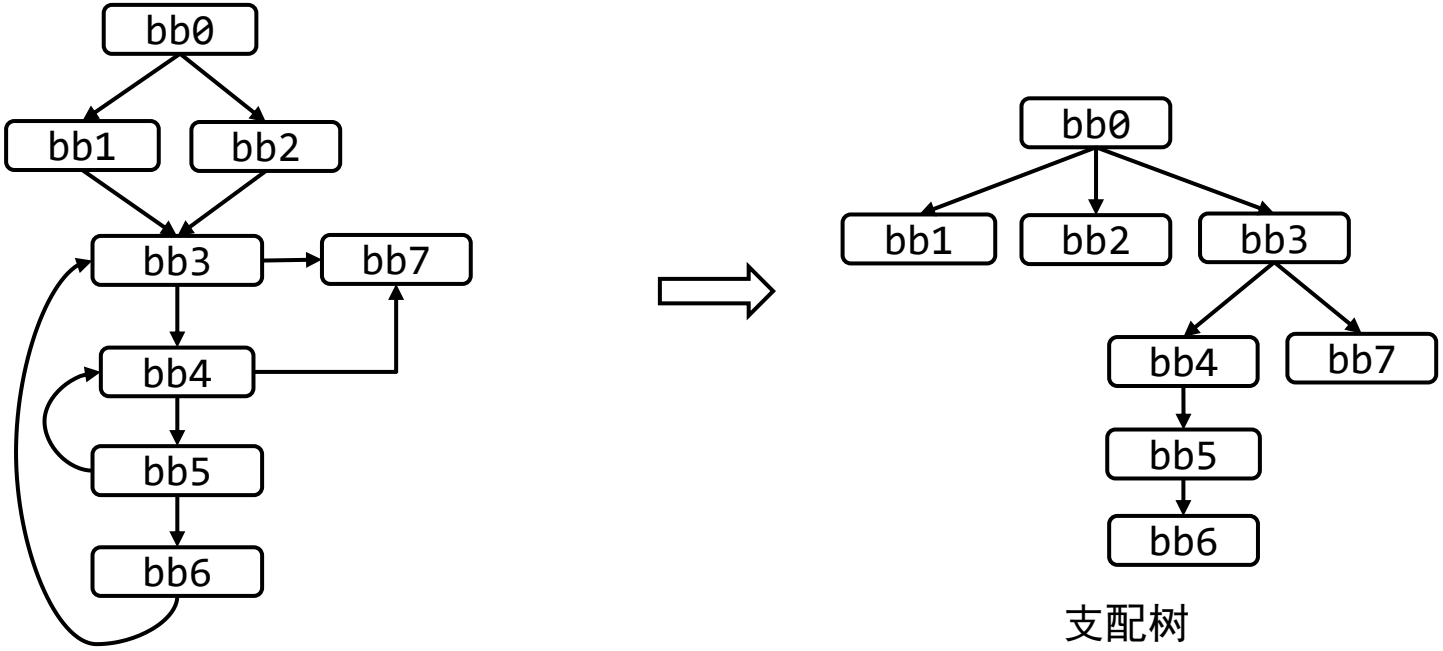
控制流图

$$Dom(bb_0) = \{bb_0\}$$
$$Dom(bb_1) = \{bb_0, bb_1\}$$
$$Dom(bb_2) = \{bb_0, bb_2\}$$
$$Dom(bb_3) = \{bb_0, bb_3\}$$
$$Dom(bb_4) = \{bb_0, bb3, bb_4\}$$
$$Dom(bb_5) = \{bb_0, bb3, bb_4, bb_5\}$$
$$Dom(bb_6) = \{bb_0, bb3, bb_4, bb5, bb_6\}$$
$$Dom(bb_7) = \{bb_0, bb_3\}$$

$$Dom(v) = \begin{cases} \{v\}, & if\ v = v_0 \\ \{v\} \cup \left(\bigcap_{p \in pred(v)} Dom(p) \right), & if\ v \neq v_0 \end{cases}$$

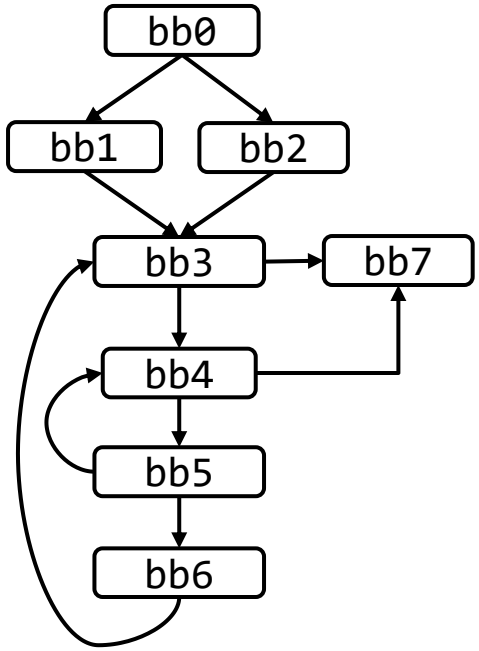
支配树的基本概念

- 所有v_j的严格支配点中与v_j最接近的点成为v_j的最近支配点
  - $Idom(v_j) = v_i$，v_j的其它严格支配点均严格支配v_i
- 连接接所有的最近支配关系，形成一棵支配树
  - 根节点外的每一点均存在唯一的最近支配点



支配边界Dominance Frontier

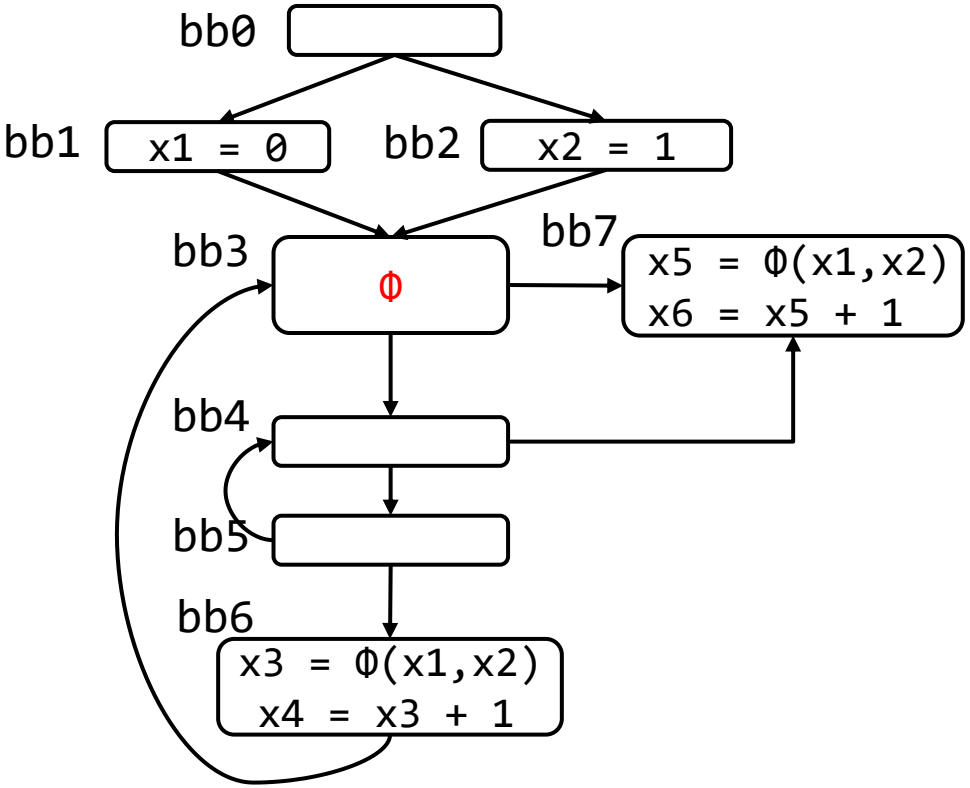
- v_i的支配边界是所有满足条件的v_j的集合
  - v_i支配v_j的一个前序节点
  - v_i并不严格支配v_j



$$DF(bb_0) = \{\}$$
$$DF(bb_1) = \{bb_3\}$$
$$DF(bb_2) = \{bb_3\}$$
$$DF(bb_3) = \{bb_3\}$$
$$DF(bb_4) = \{bb_4, bb_7\}$$
$$DF(bb_5) = \{bb_4\}$$
$$DF(bb_6) = \{bb_3\}$$
$$DF(bb_7) = \{\}$$

利用支配边界设置Phi指令

- 初始化：枚举所有变量的def-sites
  - def-sites(x) = {bb1,bb2,bb6,bb7}
- 为每个变量在bb_j增加phi节点：
  - $bb_i \in$ def-sites(x)
  - $bb_j \in DF(bb_i)$
- 在bb3增加phi指令的phi(x)



$$DF(bb_0) = \{\}$$
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$$DF(bb_2) = \{bb_3\}$$
$$DF(bb_3) = \{bb_3\}$$
$$DF(bb_4) = \{bb_4, bb_7\}$$
$$DF(bb_5) = \{bb_4\}$$
$$DF(bb_6) = \{bb_3\}$$
$$DF(bb_7) = \{\}$$

优化结果

- 重新编号
- 删除只有一个元素的phi指令