Lecture 10

基于IR的优化

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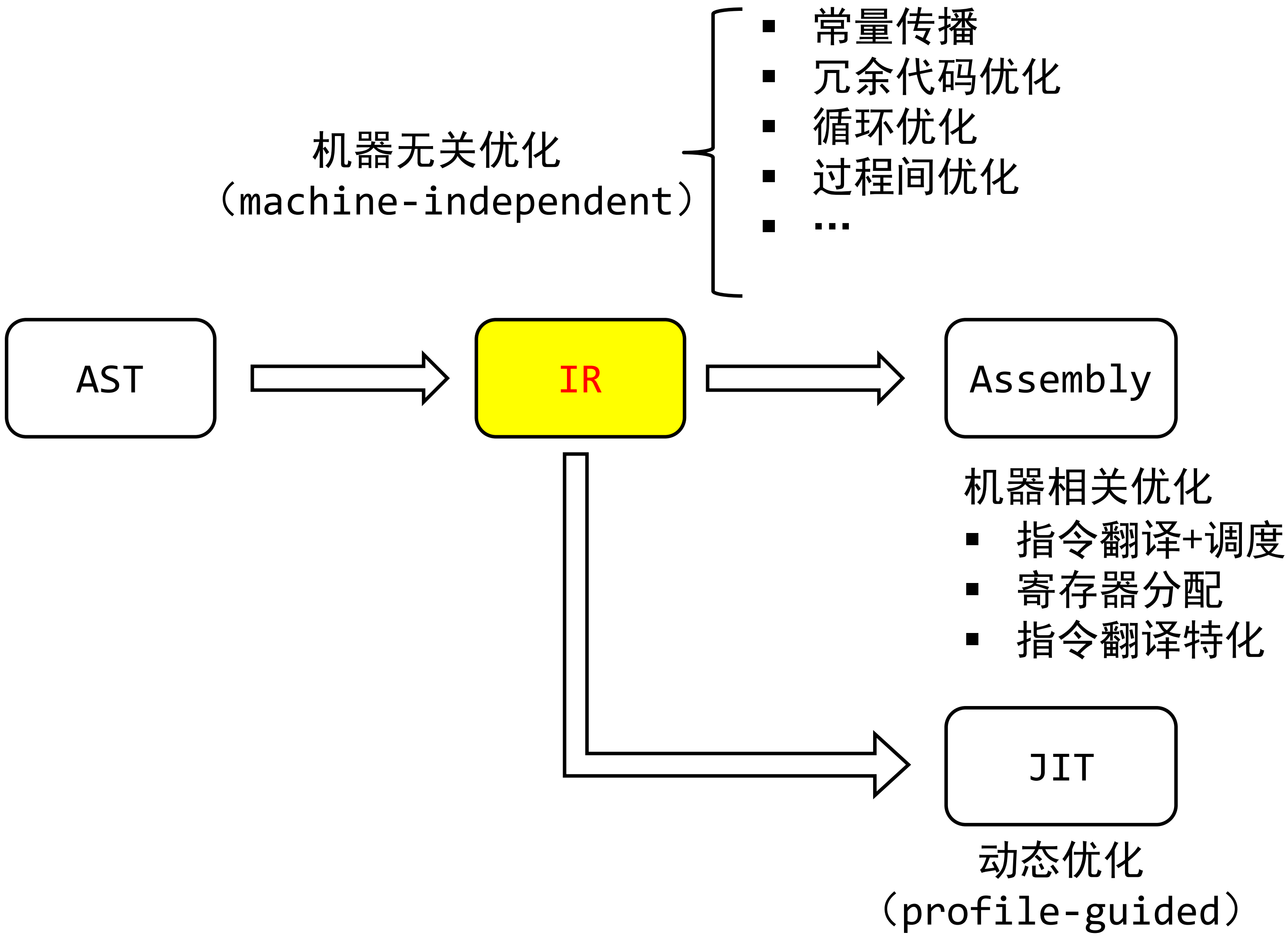
优化策略



机器无关优化
（machine-independent）
常量传播
冗余代码优化
循环优化
过程间优化
…
AST
IR
Assembly
机器相关优化
指令翻译+调度
寄存器分配
指令翻译特化
JIT
动态优化
（profile-guided）

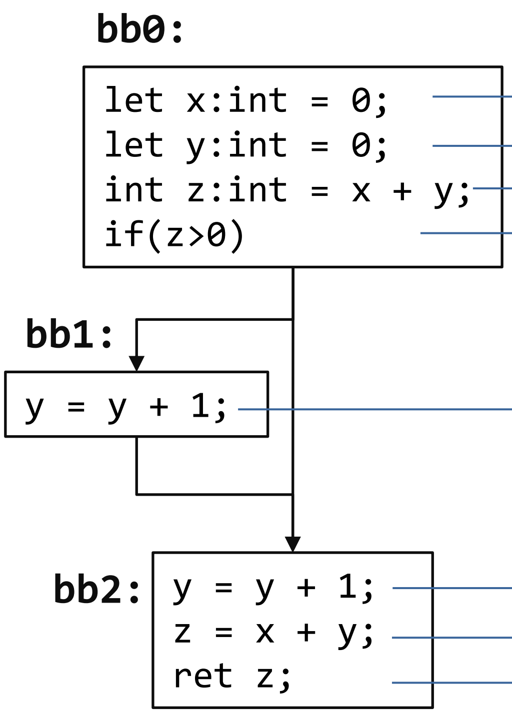
IR优化

- 一、基于常量传播的优化
- 二、面向冗余代码的优化
- 三、循环优化
- 四、过程间优化

一、基于常量传播的优化

常量分析问题

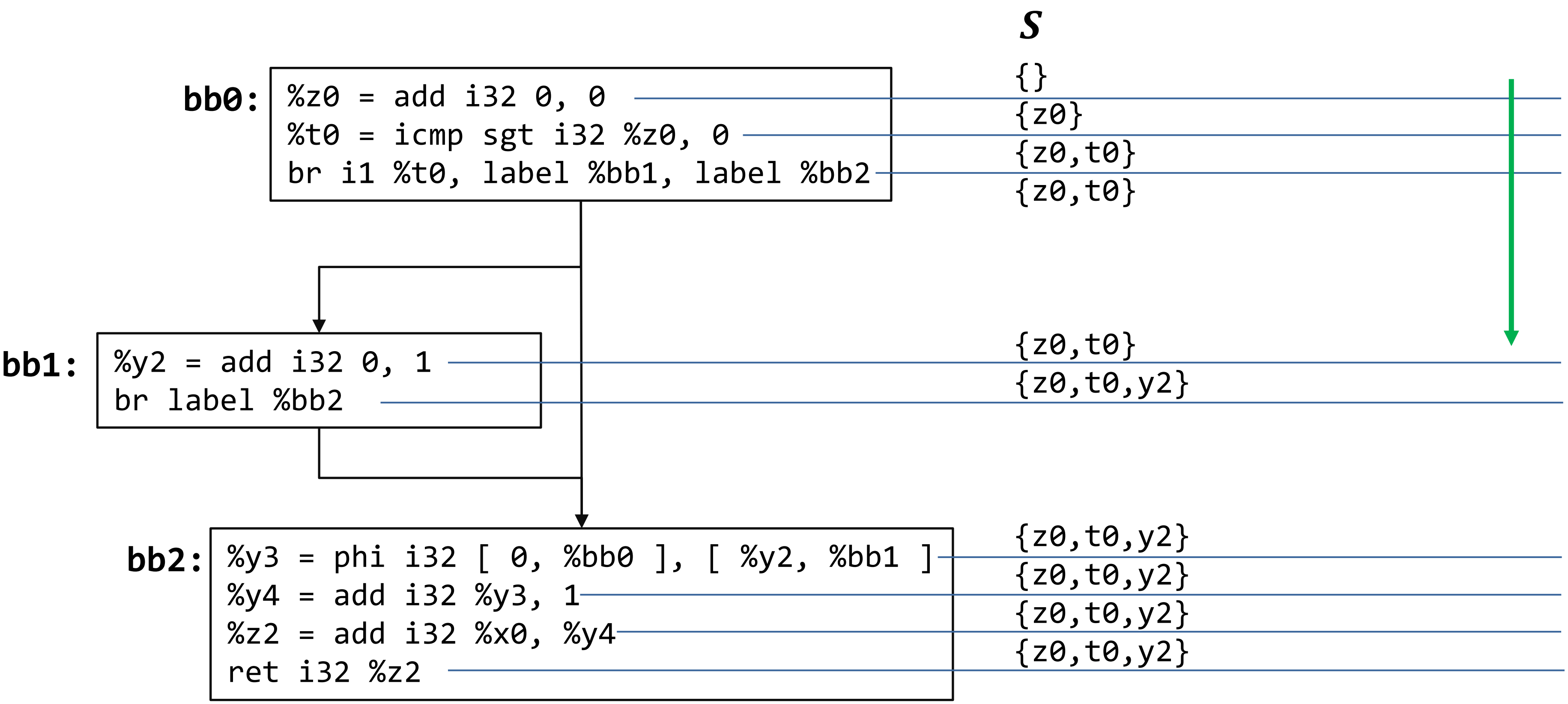
- 分析变量x在特定程序节点p是否为常量



S_x	S_y	S_z
{}	{}	{}
{0}	{}	{}
{0}	{0}	{0}
{0}	{0}	{0}
{0}	{0}	{0}
{0}	{0}	{0}
{0}	{1}	{0}
{0}	{0∪1}	{0}
{0}	{0∪1}	{0∪1}
{0}	{0∪1}	{0∪1}

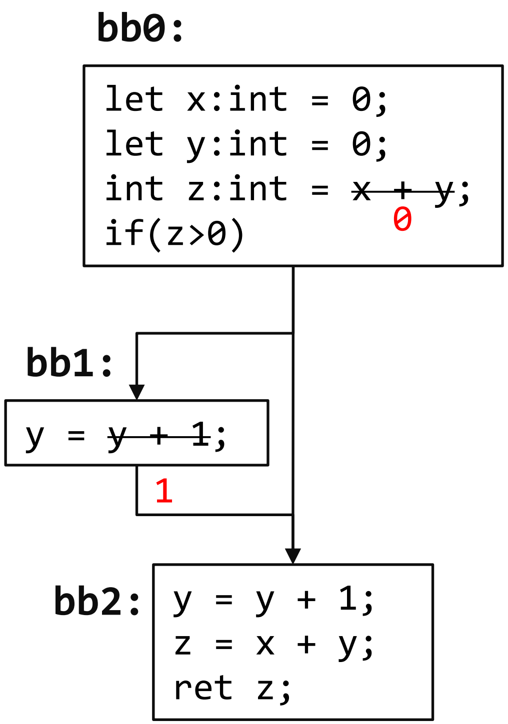
基于SSA的常量分析

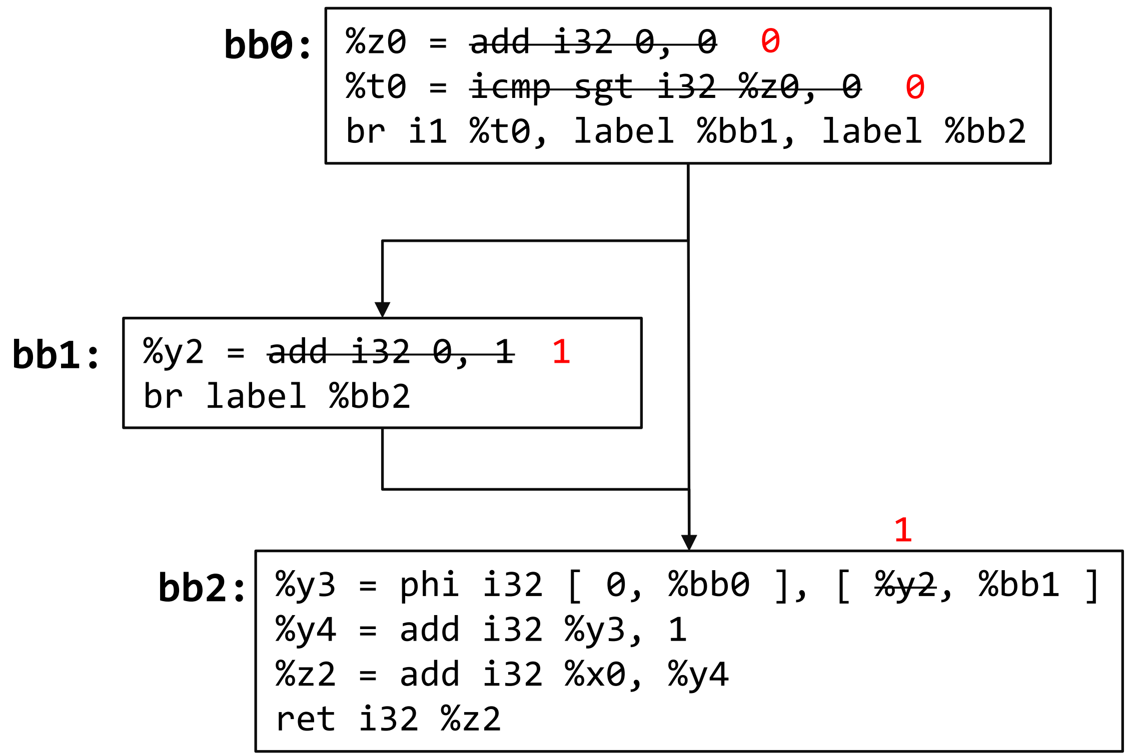
- 分析哪些寄存器内容为常量



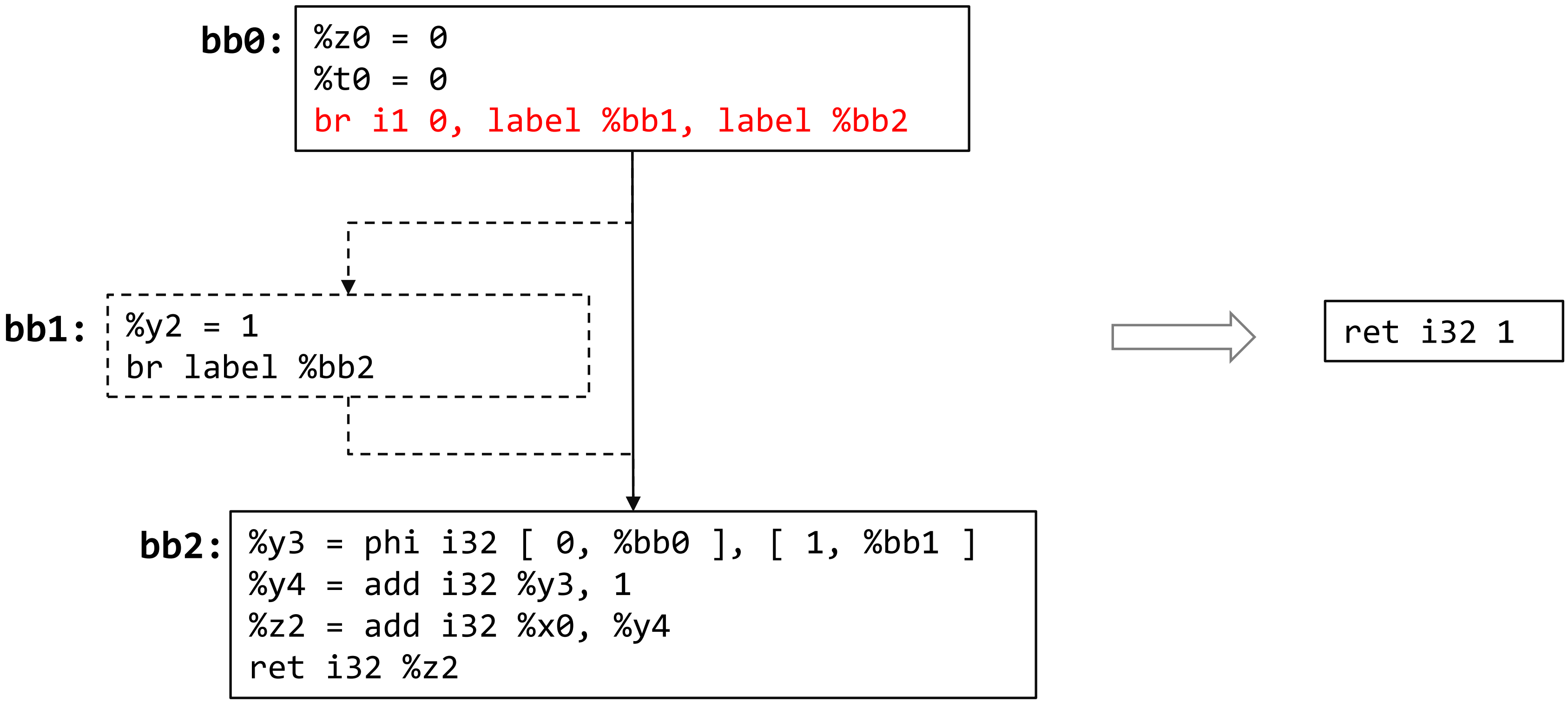
主要思想：在编译时完成常量相关的计算

- 常量传播：识别常量并将相应的变量替换为常量
- 常量折叠：编译时完成对常量表达式的计算





继续对代码进行优化


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

指令合并

- 两条二元运算指令可以合并的条件：
  - 指令1：一个运算数为常量，另一个为变量
  - 指令2：一个运算数为常量，另一个为指令1的运算结果

```
y = x + 1;
...
y = y + 2;
...
z = y + 3;
```

⇩

```
y = x + 1;
...
y = x + 3;
...
z = x + 6;
```

```
%y0 = add i32 %x0, 1
...
%y1 = add i32 %y0, 2
...
%z0 = add i32 %y1, 3
```

⇩

```
%y0 = add i32 %x0, 1
...
%y1 = add i32 %x0, 3
...
%z0 = add i32 %x1, 6
```

二、冗余代码优化

全局值编号（Global Value Numbering）

- 相同的运算（运算符、运算数）只算一次即可

```
%y0 = add i32 %x0, 1
...
%y1 = add i32 %x0, 1
...
%z0 = add i32 %x0, 1
```

```
%y0 = add i32 %x0, 1
...
%y1 = %y0
...
%z0 = %y0
```

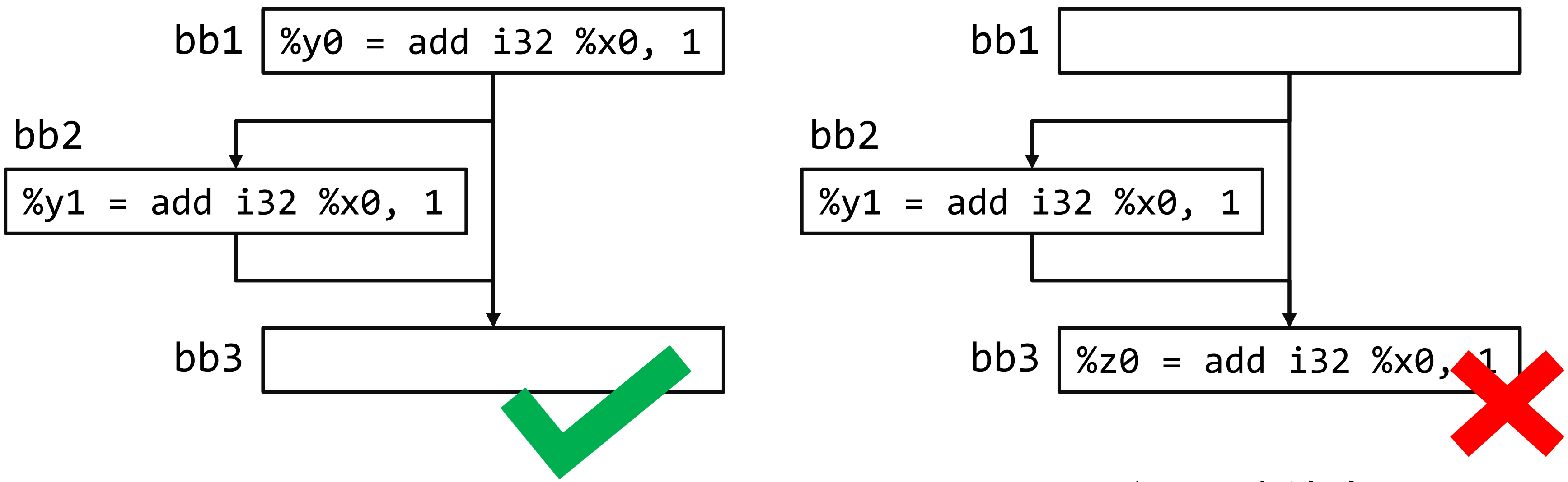
- 非LLVM IR；必须以指令开头
- 直接替换USE(%y1)为USE(%y0)

```
%y0 = add i32 %x0, 1
...
%x0 = bitcast i32 %y0 to i32
...
%y0 = bitcast i32 %y0 to i32
```

等价LLVM IR

GVN：公共表达式（可用表达式）

- 该表达式在存在支配关系的两条指令中重复出现

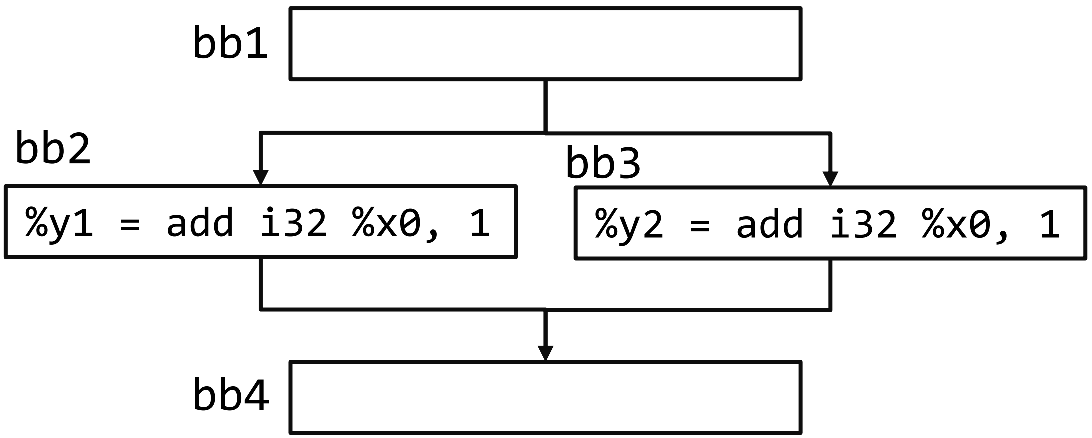


弱公共子表达式

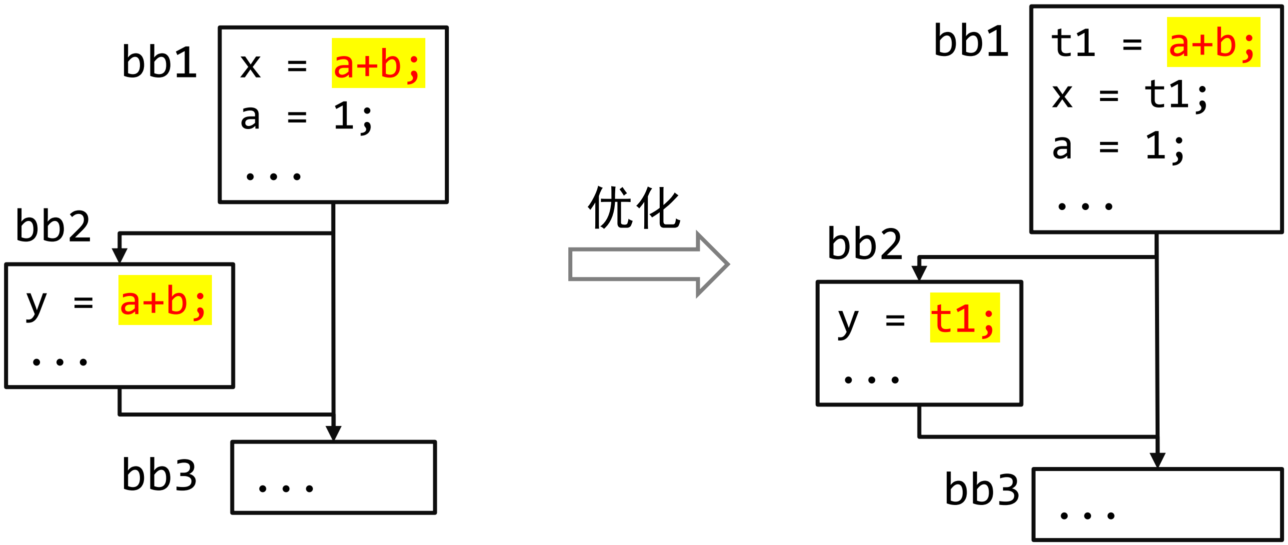
逆向数据流分析=>代码提升

GVN：繁忙表达式

- 不同代码分支中都存在的表达式
- 可以优化代码体积



基于非SSA形式做可用表达式分析？



- 正向遍历控制流图
  - 如遇到指令：x = a + b
    - $\text{Gen}(n) = \{< a + b >\}$
    - $\text{KILL}(n) = \{< \varepsilon >: \text{表达式}\varepsilon\text{包含}x\}$
  - ...
  - $\text{OUT}(n) = (\text{IN}(n) - \text{KILL}(n)) \cup \text{Gen}(n)$

死代码

- 无用代码块：代码块不可达（条件语句恒真或恒假）
- 无用计算：缺少use的def
- 无用参数：IR中没有use/store该参数
- 无用局部变量：IR中没有load该局部变量

三、循环优化

循环中的不变代码

- 出现位置：循环条件、循环体中都可能出现

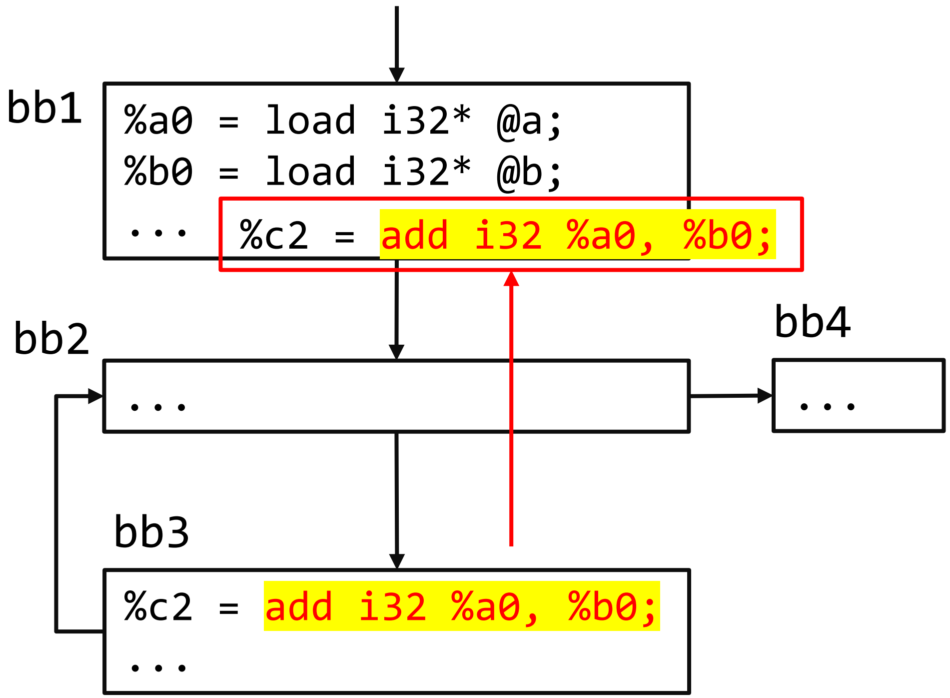
```
let a = ...;
let b = ...;
let s:list = ...;
for i in 1..100 {
    let t = (a + b)*i;
    s.push(t);
}
```

```
let a = ...;
let b = ...;
let s:list = ...;
for i in 1..s.len() {
    let t = (a + b)*i;
    s[i] = t;
}
```

```
let a = ...;
let b = ...;
let s:list = ...;
for i in 1..100 {
    let t = foo();
    s.push(t);
}
```

```
let a = ...;
let b = ...;
let s:list = ...;
for i in 1..s.len() {
    let t = s.pop();
    s[i] = t;
}
```

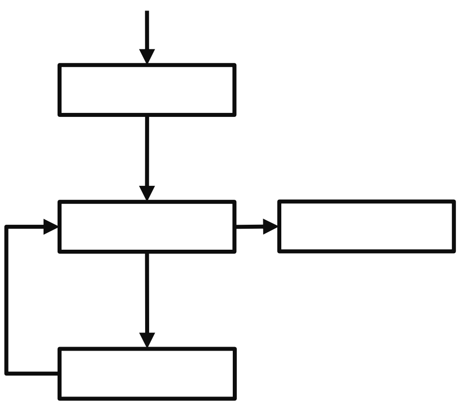
循环不变代码



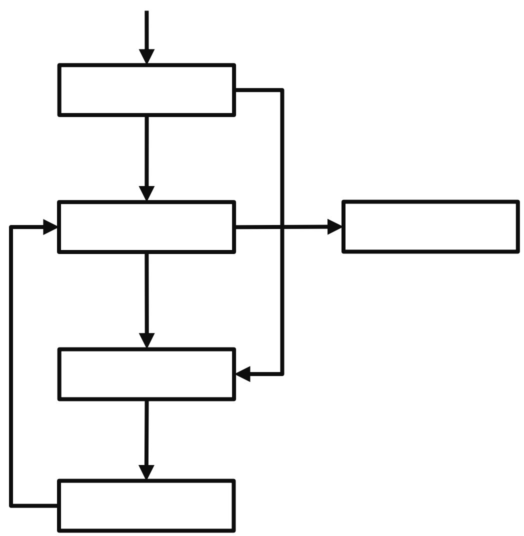
- 检测循环不变代码
  - 操作数定义自循环外部
  - 如何检测循环？
- 前移到循环外部
  - 支配节点

自然循环natural loop

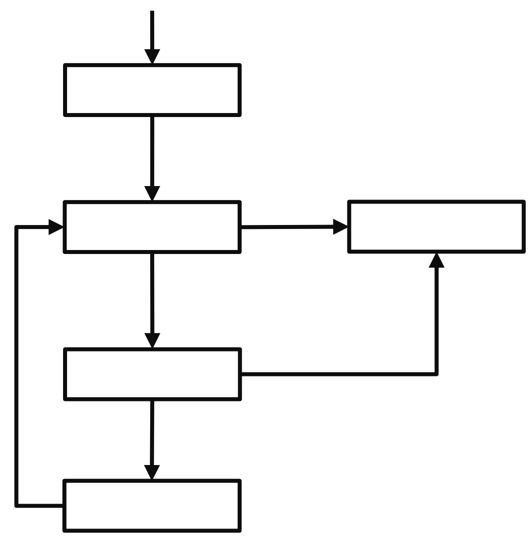
- 一个循环是自然循环的条件：
  - 有唯一的入口（支配所有节点）
  - 返回入口节点的返回边
- 一般正常的控制流语句形成的环：while、if-else、for
  - goto语句会造成非自然循环



自然循环



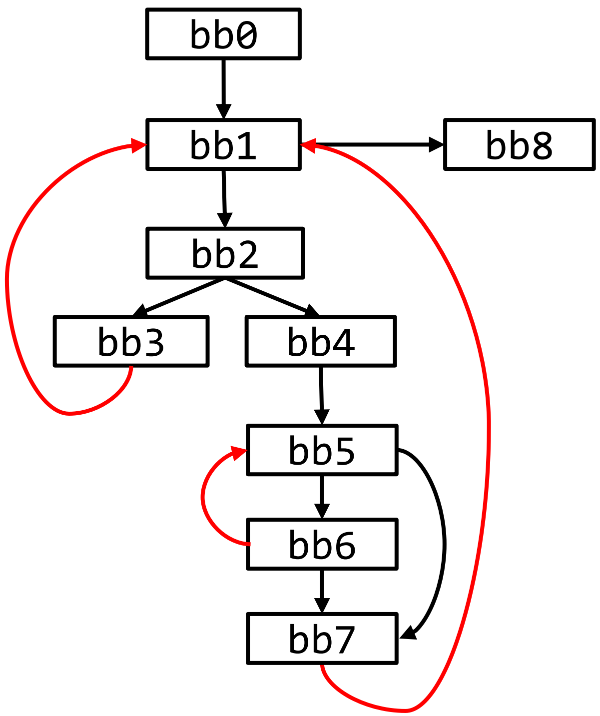
非自然循环



自然循环

自然循环的性质

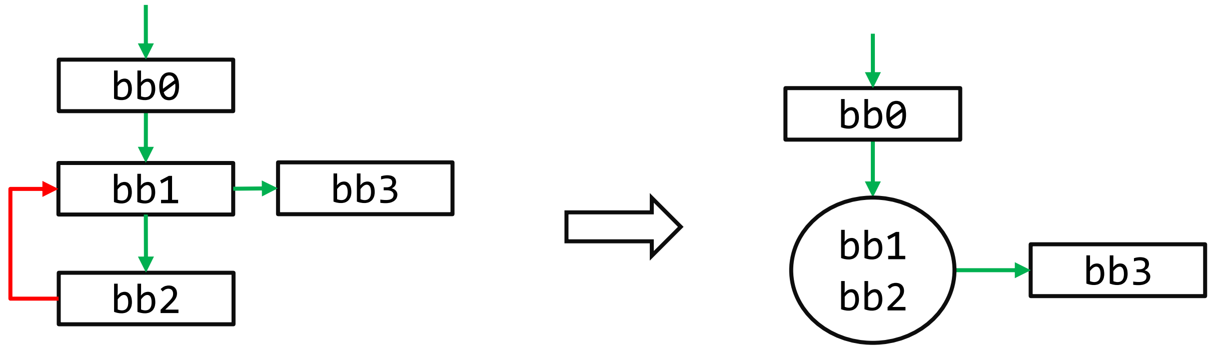
- 两个自然循环之间不相交：相切、嵌套、分离
- 两个首节点相同的自然循环：嵌套、相切
- 自然循环标识：每条返回边对应一个自然循环



bb3->bb1：1-2-3
bb6->bb5：5-6
bb7->bb1：1-2-4-5-6-7

可规约控制流图：Reducible CFG

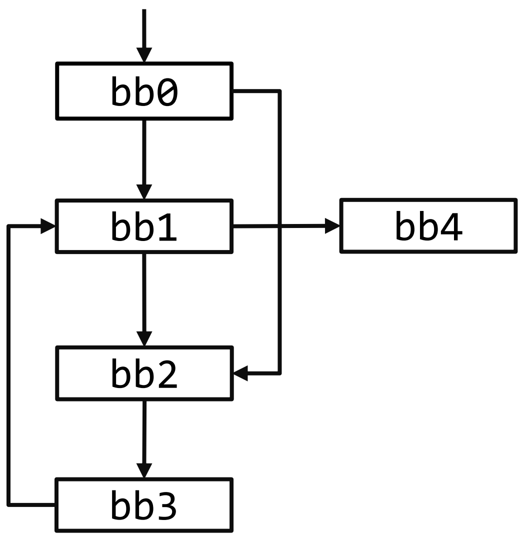
- 可规约CFG的所有循环都是自然循环
- 边可以分为前进边和返回边两个不交集=>可以缩环



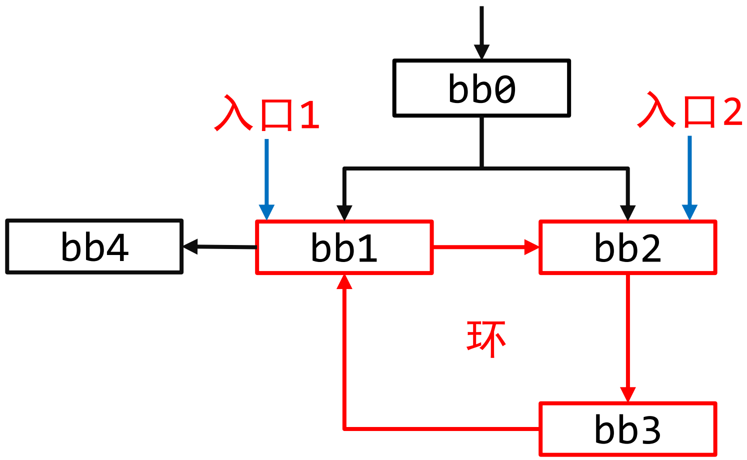
入边：
出边：

不可规约控制流图

- 无法确定循环入口和返回边



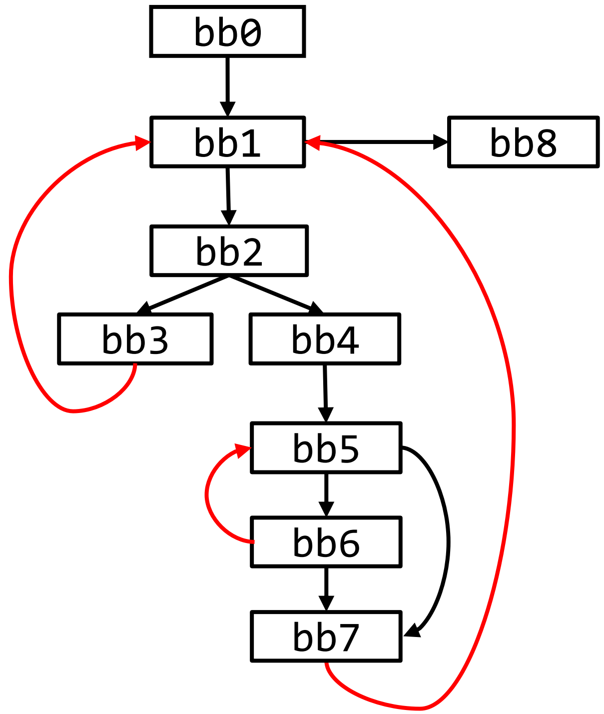
非自然循环



同态图
isomorphic

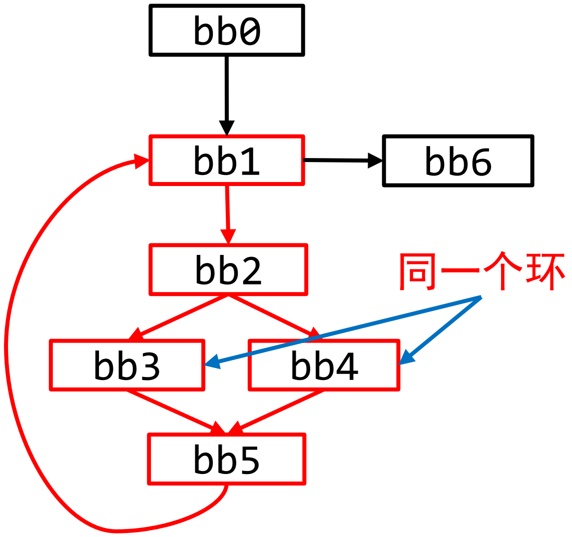
自然循环检测算法

- 基本思路：
  1) 遍历CFG=>支配关系矩阵M1
  2) 比对图邻接表M2=>检测返回边
  3) 识别每一条回边对应的环
- DFS检测环
  - 如果栈中已存在节点=>返回边
  - 若干栈顶元素组成环
  - 相同返回边的环需要合并



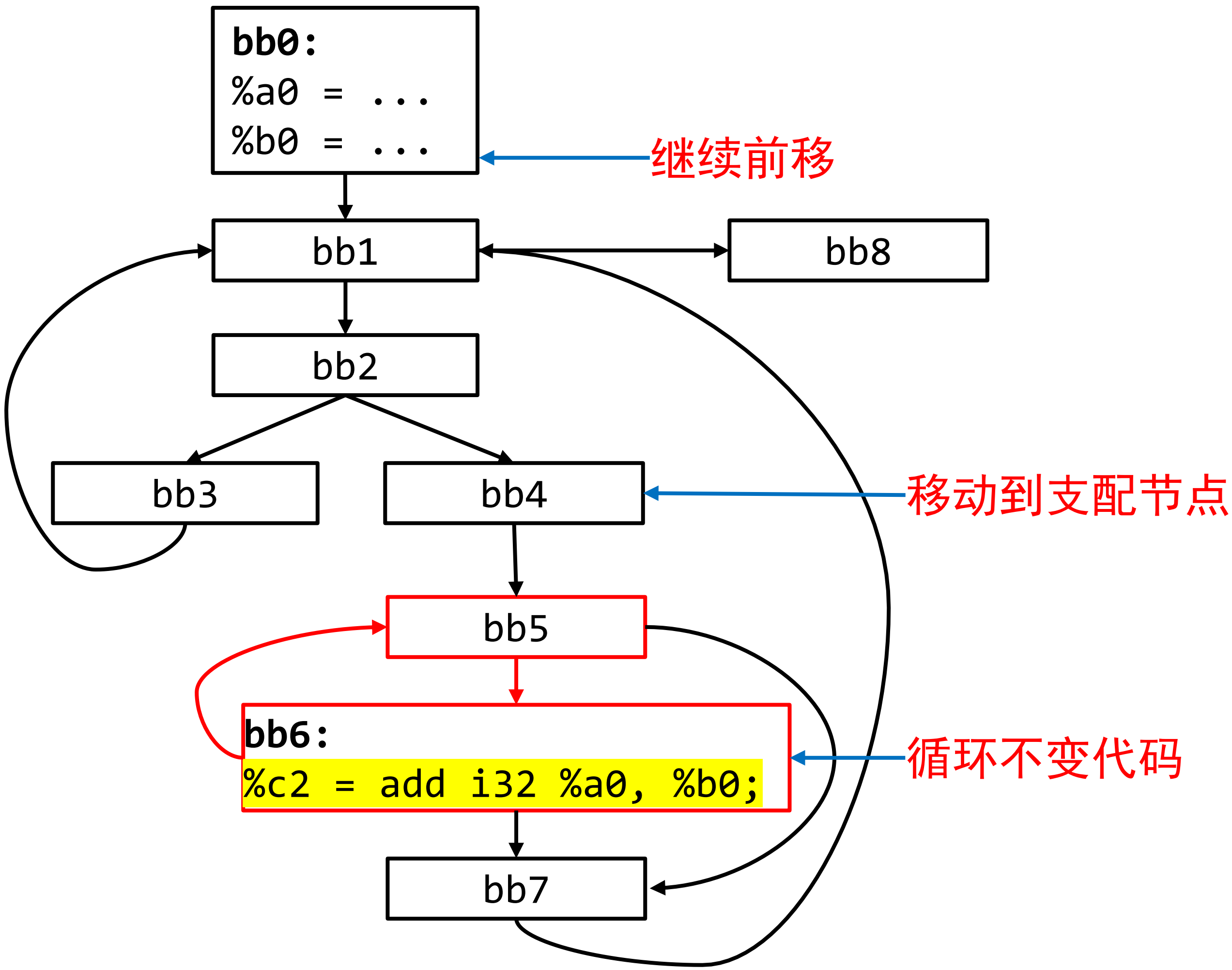
DFS检测环

```
stack s;
DFSVisit(v) {
    s.push(v);
    for each w in OUT(v) {
        if s.contains(w) {//找到回边
            AddLoopback(w,v);
        }  else {
           DFSVisit(w);
        }
    }
}
AddLoopback(v,w) {
    new = CreateLoop(top n items of s untill w);
    old = Findloop(v, w)
    merge(old,new)
}
```



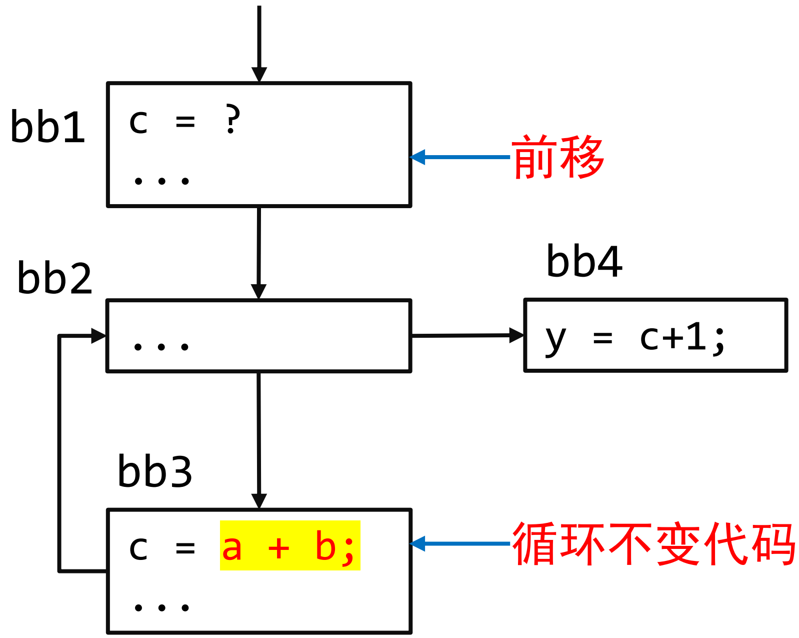
前移位置

- 单层循环：前移到最近的支配节点
- 多层循环：前移至不能移动为止

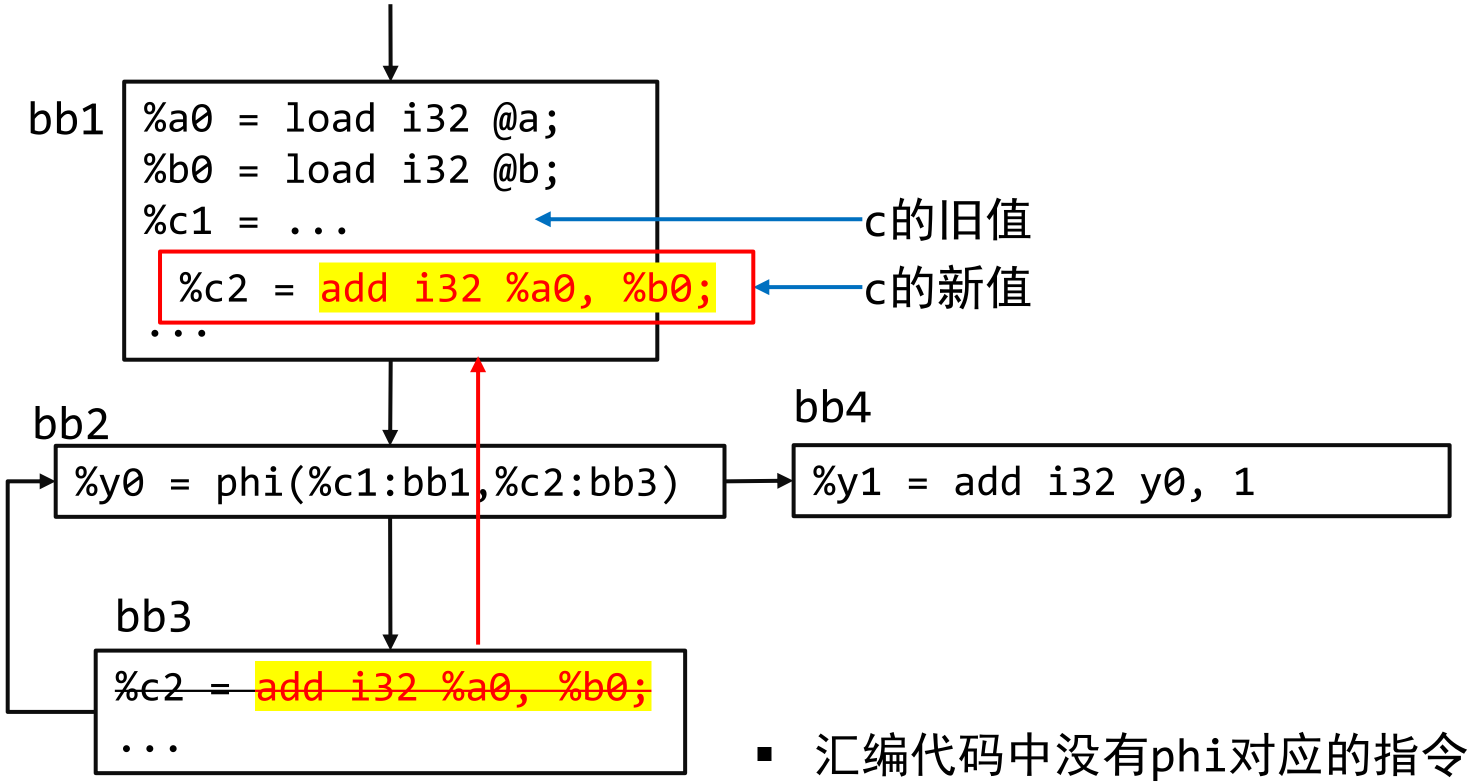


可能会有副作用？

- 如未进入循环，会错误修改x的值



SSA形式会有副作用吗？



- 汇编代码中没有phi对应的指令
- 翻译汇编前用store替代phi

归纳变量

- 变量x的值每轮循环增加固定值，则称x为归纳变量
  - 基本归纳变量x
  - 依赖归纳变量y = ax + b，a和b为常量

```
for i in 1..100 {
    y = 10 * i + 1;
    s[i] = y;
}
```

⇒

```
t1 = 1;
for i in 1..100 {
    t1 = t1 + 10;
    s[i] = t1;
}
```

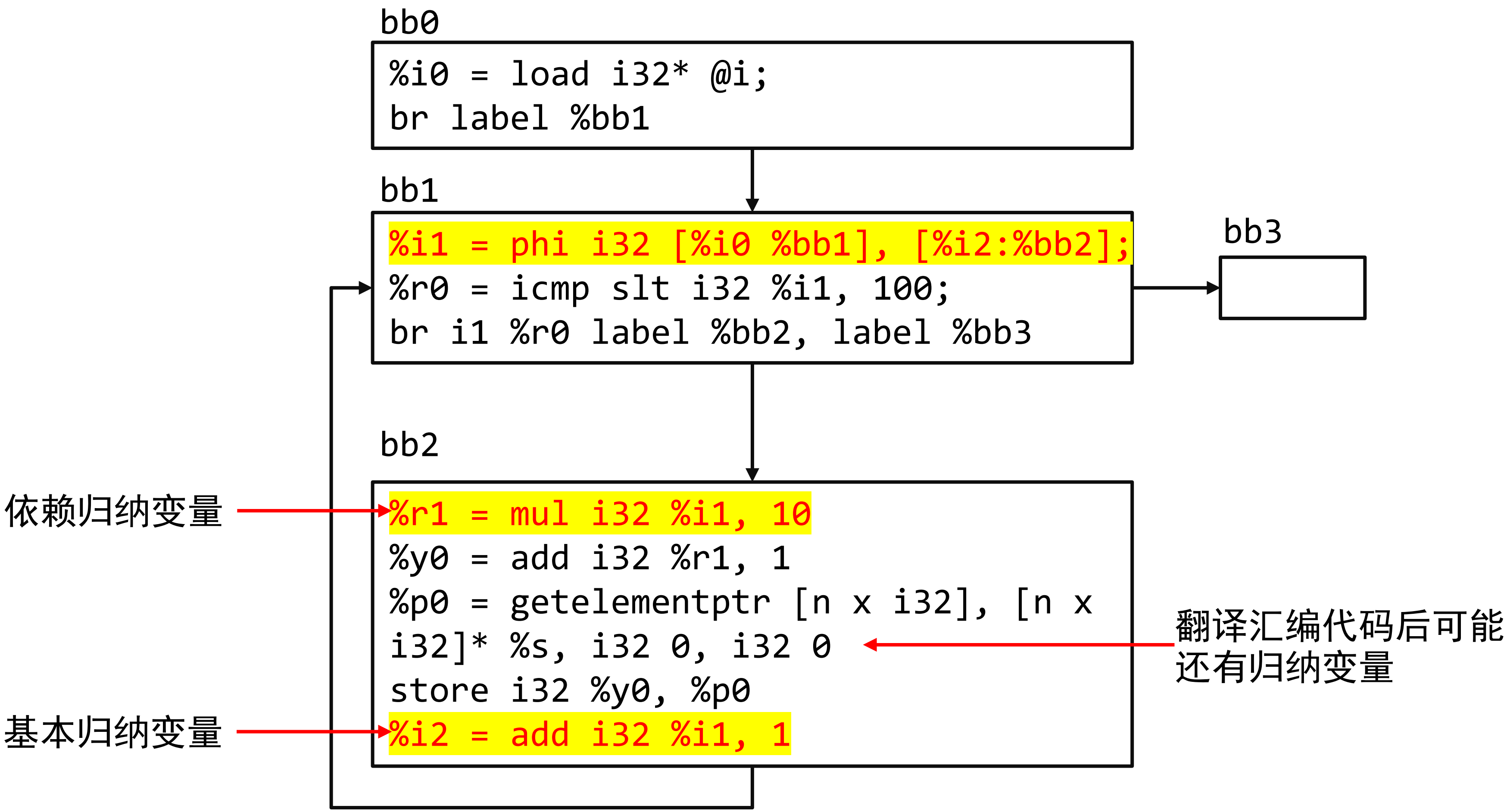
‖

```
let i:int = 1;
while(i<100) {
    y = 10 * i + 1;
    s[i] = y;
    i = i + 1;
}
```

⇒

```
let i:int = 1;
let t1 = 1;
while(i<100) {
    y = t1 + 10;
    s[i] = y;
    i = i + 1;
}
```

基于IR识别归纳变量


bb0
%i0 = load i32* @i;
br label %bb1
bb1
%i1 = phi i32 [%i0 %bb1], [%i2:%bb2];
%r0 = icmp slt i32 %i1, 100;
br i1 %r0 label %bb2, label %bb3
bb3
bb2
%r1 = mul i32 %i1, 10
%y0 = add i32 %r1, 1
%p0 = getelementptr [n x i32], [n x i32]* %s, i32 0, i32 0
store i32 %y0, %p0
%i2 = add i32 %i1, 1
依赖归纳变量
基本归纳变量
翻译汇编代码后可能还有归纳变量

标量替换：Scala Replacement

- 使用标量替换循环内部的频繁内存读写操作
- 在IR层自动替换R[i][j]的难点？R[i][j]和i可能是alias

```
for i in 0..rowA {
    for j in 0..colB {
        for k in 0..colA {
            R[i][j] = R[i][j] + A[i][k]*B[k][j];
        }
    }
}
```

每次从内存或cache读写R[i][j]会影响性能

⇩

```
for i in 0..rowA {
    for j in 0..colB {
        t = R[i][j];
        for k in 0..colA {
            t = t + A[i][k]*B[k][j];
        }
        R[i][j] = t;
    }
}
```

使用临时变量替换，可直接使用寄存器中的值

降低分支预测的代价

- Loop unswitching：外提（减少）循化内条件判断
- Loop unroll：将循环体复制多遍

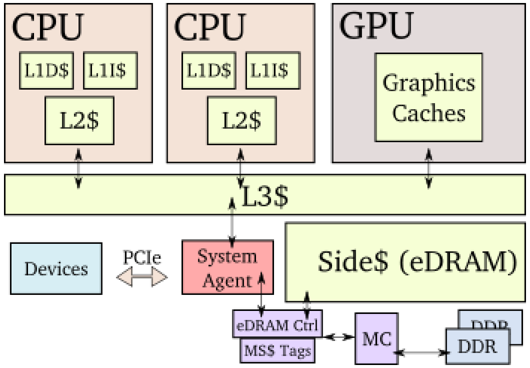
```
void testbrpred(int* a, int len,  int x){
    unsigned long long cycle = rdtsc();
    while(len>-1){
        len-=1;
        if(a[len]>x) ;
        else ;
    }
    unsigned long long cycl = rdtsc()- cycle;
    printf("x = %d, cycles = %d\n", x, cycl);
}

int main(int argc, char** argv){
    int a[1000];
    srand(time(NULL));
    for(int i = 0; i< 1000; i++) a[i] = rand()%1000;
    testbrpred(a,1000,100);
    testbrpred(a,1000,300);
    testbrpred(a,1000,500);
    testbrpred(a,1000,700);
    testbrpred(a,1000,900);
}
```

```
x = 100, cycles = 23630
x = 300, cycles = 47175
x = 500, cycles = 63744
x = 700, cycles = 49642
x = 900, cycles = 26301
```

Cache

- Cache访问速度优于内存访问速度
- 最小单位是cache line
- 通过降低cache miss提升代码性能

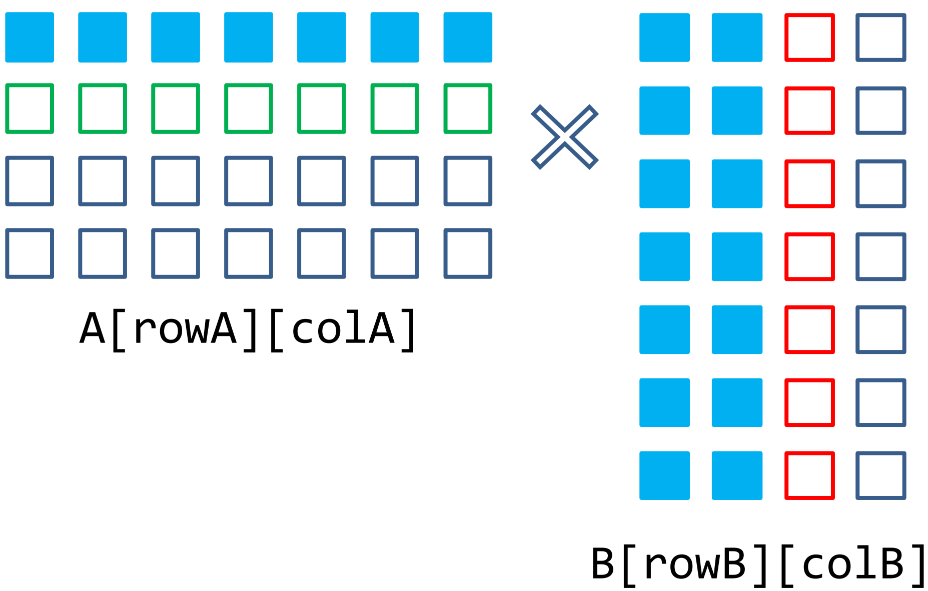


index	valid	tag	data
001	0x...		64 B
002	0x...		64 B
003	0x...		64 B
...	0x...		64 B

cache	size	line	speed
L1	32 KB + 32 KB	64 B	4-5 cycles
L2	256 KB	64 B	12 cycles
L3	up to 2 MB	64 B	30-50 cycles

矩阵乘法：循环分块

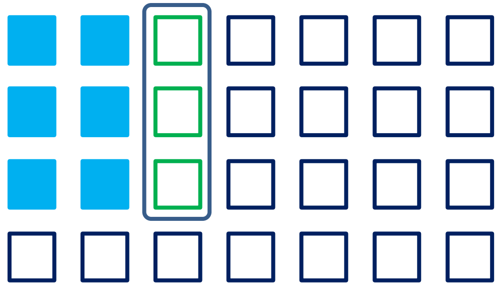
```
for i in 0..rowA {
    for j in 0..colB {
        for k in 0..colA {
            R[i][j] = R[i][j] + A[i][k]*B[k][j];
        }
    }
}
```



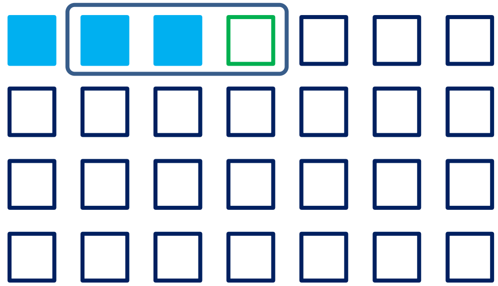
- 假设：
  - 已经算完R[0][0]..R[0][j]
  - B[][0]..B[][j]已经在cache中
- 先算R[0][j+1]还是R[1][0]?

循环交换

```
for i in 1..m-2 {
    for j in 0..n-1 {
        R[i][j] = A[i-1][j] + A[i][j] + A[i+1][j];
    }
}
```



```
for j in 0..n-1 {
    for i in 1..m-2 {
        R[i][j] = A[i-1][j] + A[i][j] + A[i+1][j];
    }
}
```



循环合并和拆分

```
for i in 0..n-1 {
    R1[i] = A[i] + B[i];
}
for i in 0..n-1 {
    R2[i] = A[i] + B[i];
}
```

合并

fusion

```
for i in 0..n-1 {
    R1[i] = A[i] + B[i];
    R2[i] = A[i] + B[i];
}
```

```
for i in 0..n-1 {
    R1[i] = A[i] + B[i];
    R2[i] = C[i] + D[i];
}
```

拆分

distribution

```
for i in 0..n-1 {
    R1[i] = A[i] + B[i];
}
for i in 0..n-1 {
    R2[i] = C[i] + D[i];
}
```

可能对寄存器分配有利：减少冲突关系

四、过程间优化

函数优化策略

常用优化技术（内联）

partial evaluation (program specialization)

compile-time execution

参数均未知

部分参数已知

全部参数已知

```
fn foo(n:int, r:int) -> int {
    if (n == 0) {
        ret r;
    } else {
        ret factorial(n-1, n*r);
    }
}

fn foo(x:int) -> int {
    foo(x, x+1);
    foo(x, 1);
    foo(0, 0);
}
```

内联

- 优点：
  - 避免函数调用规约带来的运行时开销
  - 便于代码优化，如partial evaluation
- 缺点：
  - 代码复制可能会增大代码体积
  - 函数体太大不利于寄存器分配
- 给定bugget上限，选取最优的内联函数组合
  - 转化为背包问题（Knapsack problem）

$$\max \sum_{i=1}^{n} v_i x_i \qquad s.t. \sum_{i=1}^{n} w_i x_i \le thres \text{ and } x_i \in \{0,1\}$$

尾递归函数

- return前的最后一条语句调用自己

```
fn factorial(n:int) -> int {
  if (n == 0) {
    ret 1;
  }
  else {
    ret n * factorial(n-1);
  }
}
```

```
fn factorial(n:int, r:int) -> int {
  if (n == 0) {
    ret r;
  }
  else {
    ret factorial(n-1, n*r);
  }
}
```

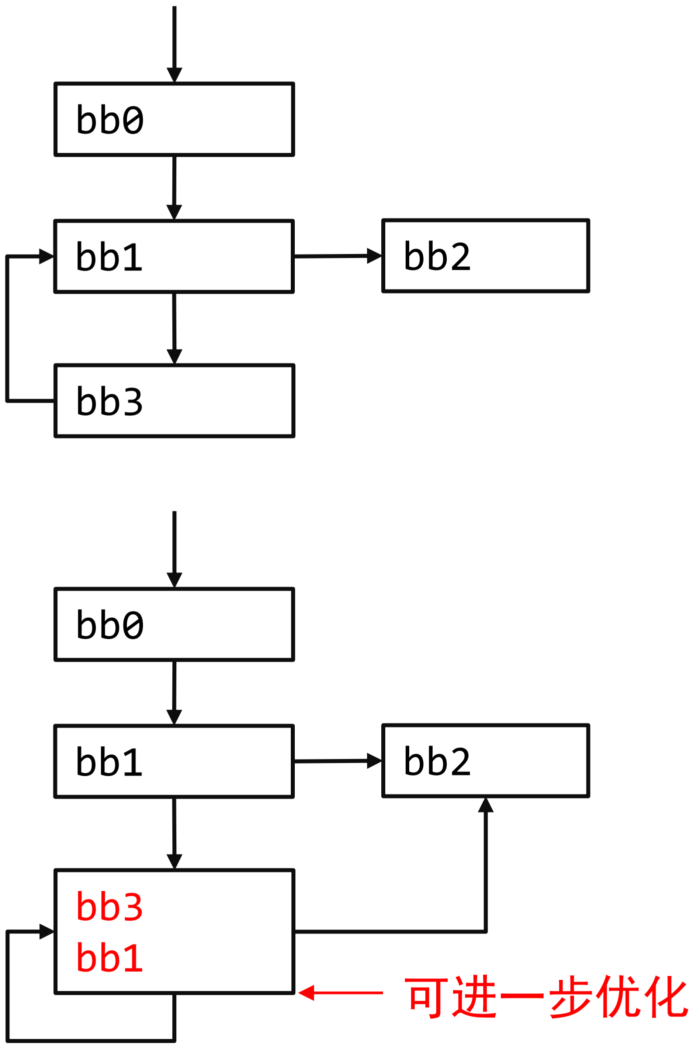
```
fn i32 factorial(%n0:i32, %r0:i32) {
%bb0:
  %n = alloca i32
  %r = alloca i32
  store i32 %n0, %n
  store i32 %r0, %r
  br label %bb1
%bb1
  %n1 = load i32, i32* %n
  %r0 = icmp eq i32 %n1, 0;
  br i1 %r0 label %bb2, label %bb3
%bb2:
  %r1 = load i32, i32* %r
  ret i32 %r1;
%bb3:
  %n2 = load i32, i32* %n
  %r2 = load i32, i32* %r
  %t0 = sub i32 %n2, 1;
  %t1 = mul i32 %n2, %r2;
  %t2 = call i32 factorial(%t0, %t1);
  ret %t2;
}
```

尾递归消除

```
fn i32 factorial(%n0:i32, %r0:i32) {
%bb0:
  %n = alloca i32
  %r = alloca i32
  store i32 %n0, %n
  store i32 %r0, %r
  br label %bb1
%bb1
  %n1 = load i32, i32* %n
  %r0 = icmp eq i32 %n1, 0;
  br i1 %r0 label %bb2, label %bb3
%bb2:
  %r1 = load i32, i32* %r
  ret i32 %r1;
%bb3:
  %n2 = load i32, i32* %n
  %r2 = load i32, i32* %r
  %t0 = sub i32 %n2, 1;
  %t1 = mul i32 %n2, %r2;
  %t2 = call i32 factorial(%t0, %t1);
  ret %t2;
}
```

```
fn i32 factorial(%n0:i32, %r0:i32) {
%bb0:
  %n = alloca i32
  %r = alloca i32
  store i32 %n0, %n
  store i32 %r0, %r
  br label %bb1
%bb1
  %n1 = load i32, i32* %n
  %r0 = icmp eq i32 %n1, 0;
  br i1 %r0 label %bb2, label %bb3
%bb2:
  %r1 = load i32, i32* %r
  ret i32 %r1;
%bb3:
  %n2 = load i32, i32* %n
  %r2 = load i32, i32* %r
  %t0 = sub i32 %n2, 1;
  %t1 = mul i32 %n2, %r2;
  store i32 %t0, %n
  store i32 %t1, %r
  br %bb1
}
```

尾递归优化




```
fn i32 factorial(%n0:i32, %r0:i32) {
%bb0:
  %n = alloca i32
  %r = alloca i32
  store i32 %n0, %n
  store i32 %r0, %r
  br label %bb1
%bb1
  %n1 = load i32, i32* %n
  %r0 = icmp eq i32 %n1, 0;
  br i1 %r0 label %bb2, label %bb3
%bb2:
  %r1 = load i32, i32* %r
  ret i32 %r1;
%bb3:
  %n2 = load i32, i32* %n
  %r2 = load i32, i32* %r
  %t0 = sub i32 %n2, 1;
  %t1 = mul i32 %n2, %r2;
  store i32 %t0, %n
  store i32 %t0, %r
  %n3 = load i32, i32* %n
  %r2 = icmp eq i32 %n3, 0;
  br i1 %r0 label %bb2, label %bb3
}
```

Sibling Call优化

- Caller和callee函数签名相同并且是tail call
- 栈帧结构复用（汇编代码优化）

```
fn foo(a:int) -> int{
  if (a < 0) {
    return a;
  }
  let b:int = a - 1;
  ret bar(b);
}

fn bar(b:int) -> int{
  let c:int = b - 1;
  ret c;
}
```