五、目标代码生成
(17. 寄存器分配)

魏恒峰

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Register Allocation

The *Register Allocation problem* consists in mapping a program P_v, that can use an unbounded number of virtual registers, to a program P_p that contains a finite (possibly small) number of physical registers. Each target architecture has a different number of physical registers. If the number of physical registers is not enough to accommodate all the virtual registers, some of them will have to be mapped into memory. These virtuals are called *spilled virtuals*.

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- Target-independent code generation algorithms
  - Instruction Selection
    - Introduction to SelectionDAGs
    - SelectionDAG Instruction Selection Process
    - Initial SelectionDAG Construction
    - SelectionDAG LegalizeTypes Phase
    - SelectionDAG Legalize Phase
    - SelectionDAG Optimization Phase: the DAG Combiner
    - SelectionDAG Select Phase
    - SelectionDAG Scheduling and Formation Phase
    - Future directions for the SelectionDAG
  - SSA-based Machine Code Optimizations
  - Live Intervals
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    - Live Intervals Analysis
  - Register Allocation
    - How registers are represented in LLVM
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  - Prolog/Epilog Code Insertion
  - Compact Unwind
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  - Code Emission
    - Emitting function stack size information
  - VLIW Packetizer
    - Mapping from instructions to functional units
    - How the packetization tables are generated and used

https://www.llvm.org/docs/CodeGenerator.html#register-allocator

Built in register allocators

The LLVM infrastructure provides the application developer with three different register allocators:

- *Fast* — This register allocator is the default for debug builds. It allocates registers on a basic block level, attempting to keep values in registers and reusing registers as appropriate.
- *Basic* — This is an incremental approach to register allocation. Live ranges are assigned to registers one at a time in an order that is driven by heuristics. Since code can be rewritten on-the-fly during allocation, this framework allows interesting allocators to be developed as extensions. It is not itself a production register allocator but is a potentially useful stand-alone mode for triaging bugs and as a performance baseline.
- *Greedy — The default allocator.* This is a highly tuned implementation of the *Basic* allocator that incorporates global live range splitting. This allocator works hard to minimize the cost of spill code.
- *PBQP* — A Partitioned Boolean Quadratic Programming (PBQP) based register allocator. This allocator works by constructing a PBQP problem representing the register allocation problem under consideration, solving this using a PBQP solver, and mapping the solution back to a register assignment.

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以非 SSA 形式的中间代码为例

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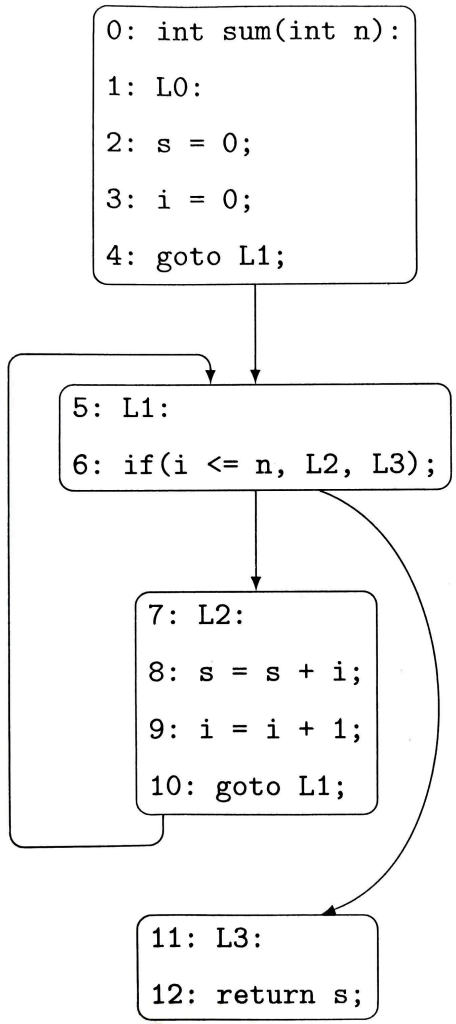

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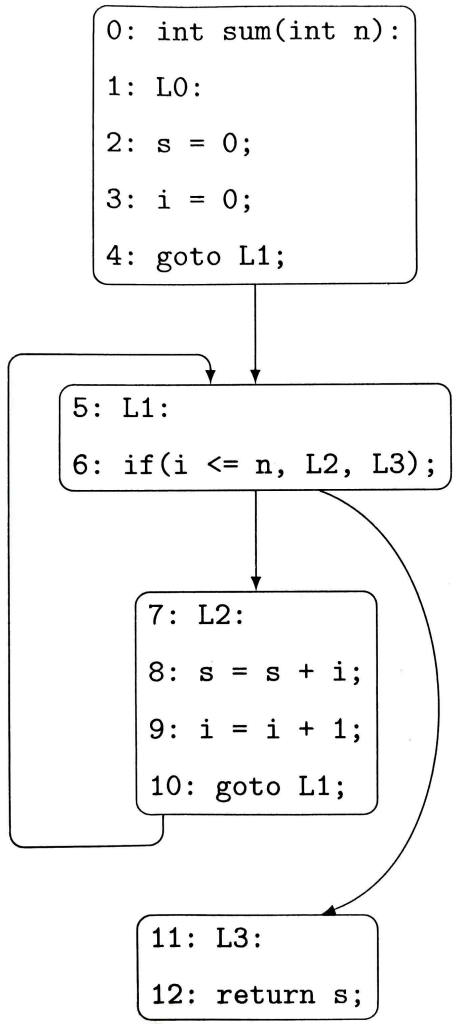

问题 2: 在第 3 行后, 有哪些变量是活跃的?

Definition (活跃 (Live))

对于给定的变量 x, 考虑从其一个定义点 p 到使用点 q 的路径 l。

对于该路径 l 上的任意点 r, 如果 r 和 q 之间没有对变量 x 的其它定义, 则称 x 在程序点 r 上是活跃的。

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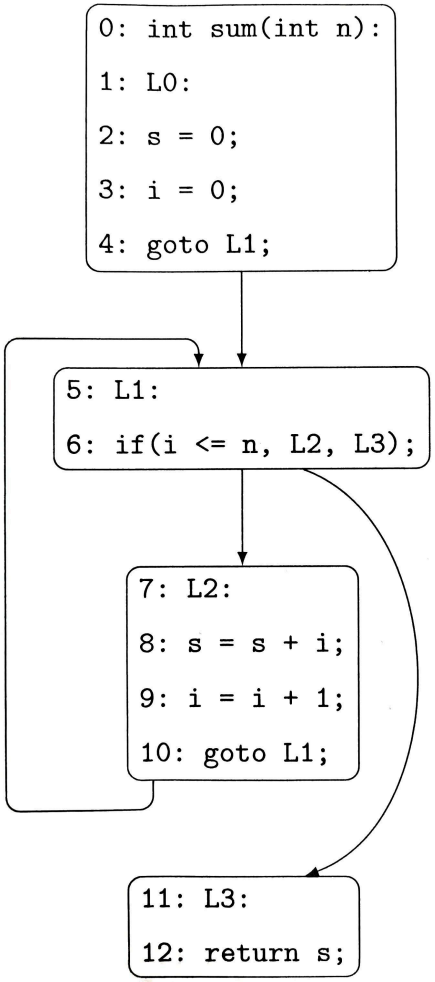
Definition (活跃分析 (Liveness Analysis))

分析变量的活跃点的程序分析被称为 *活跃分析*。

LiveIn(s) : s 执行前的活跃变量集合



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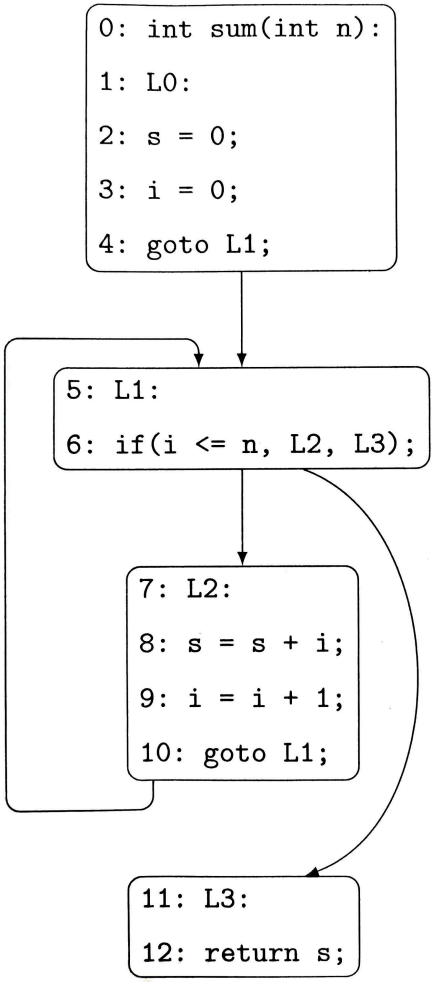

$$\textsc{LiveOut}(s) = \bigcup_{p \in succ(s)} \textsc{LiveIn}(p)$$

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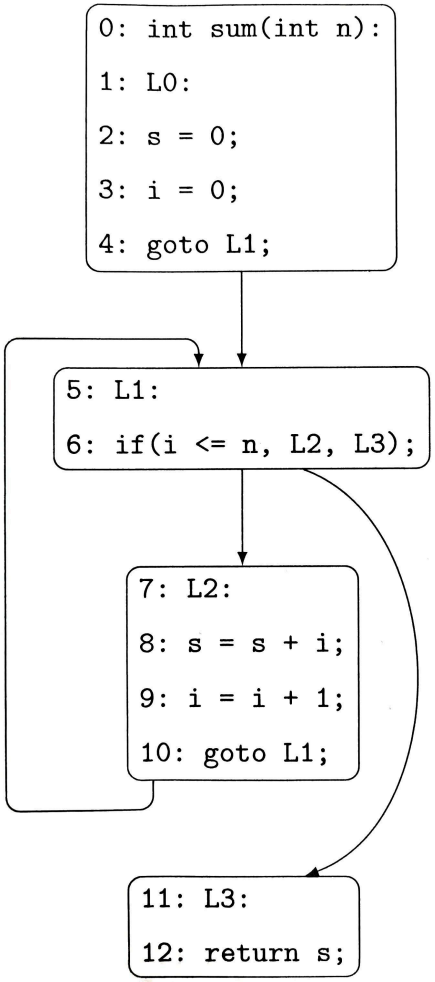

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如何求解这个“数据流”方程组?

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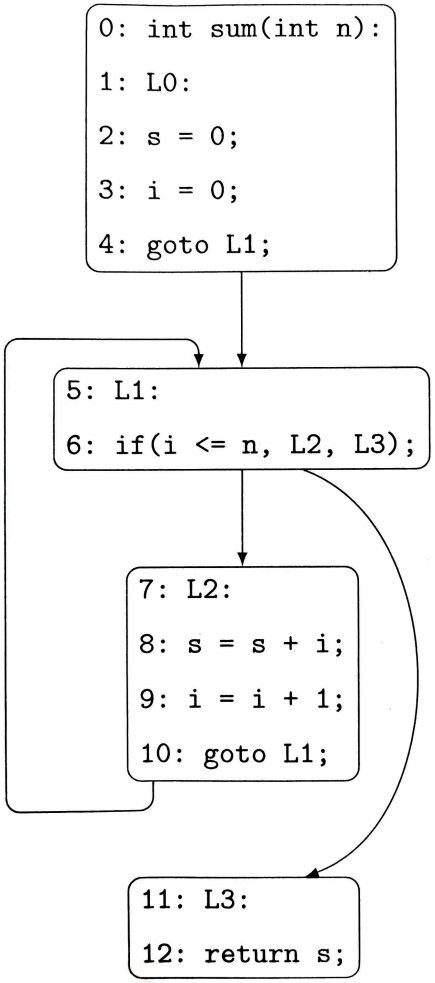
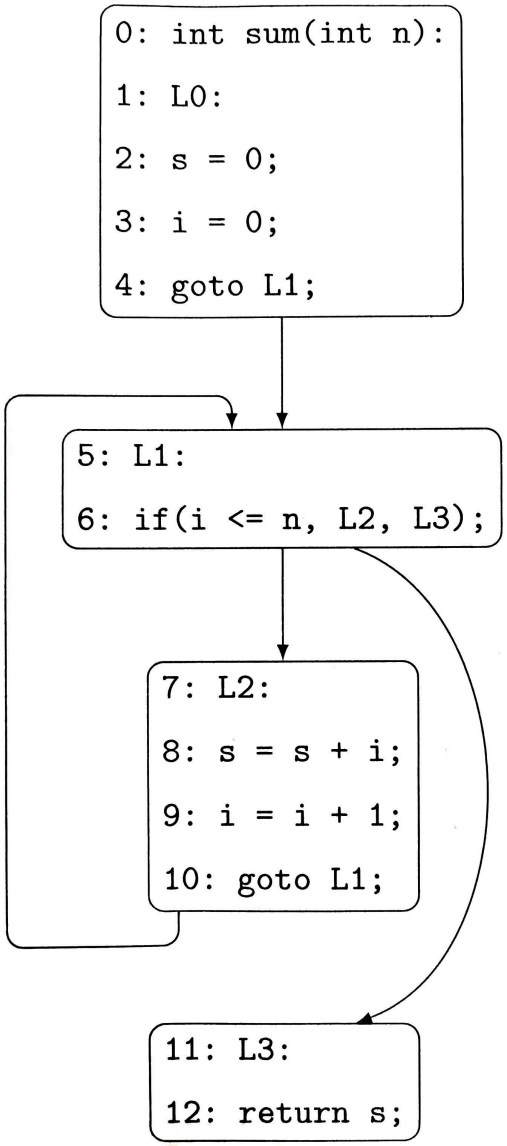
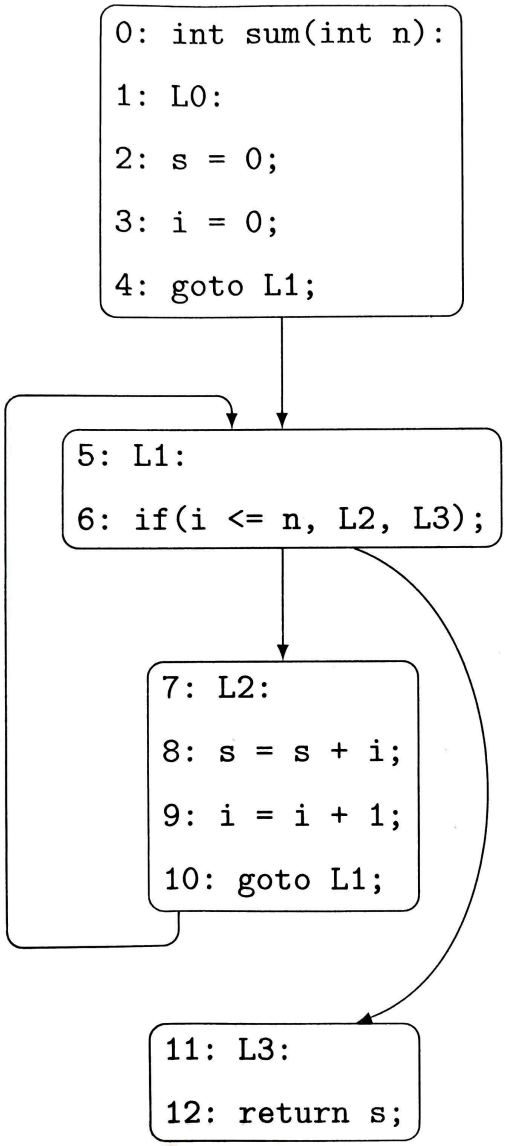



```
1  void liveness(program p){
2    for(each statement s in p){
3      liveIn[s] = ϕ;
4      liveOut[s] = ϕ;
5    }
6    while(liveIn or liveOut set still changing){
7      for(each statement s in p){
8        liveOut[s] = ⋃_i liveIn(p_i); // p_i are successor of s
9        liveIn[s] = (liveOut[s] - def(s)) ⋃ use(s);
10     }
11   }
12 }
```

不动点算法



语句	use	def	out/in 初始值	out	in	out	in
2	∅	s	∅	n,s	n	…	…
3	∅	i	∅	i,n,s	n,s	…	…
6	i,n	∅	∅	i,s	i,n,s	…	…
8	i,s	s	∅	i	i,s	…	…
9	i	i	∅	∅	i	…	…
12	s	∅	∅	∅	s	…	…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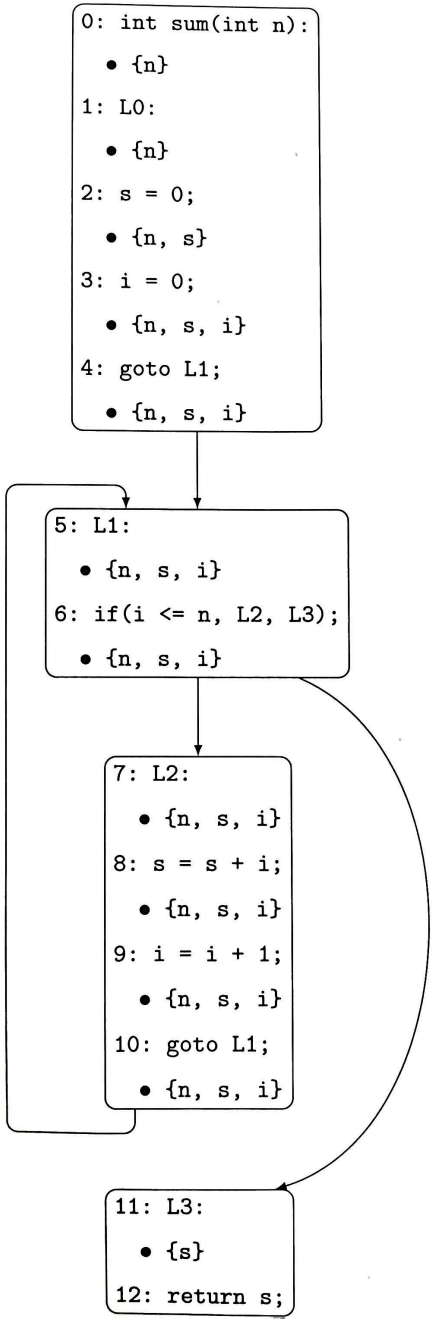
0: int sum(int n):
• {n}
1: L0:
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2: s = 0;
• {n, s}
3: i = 0;
• {n, s, i}
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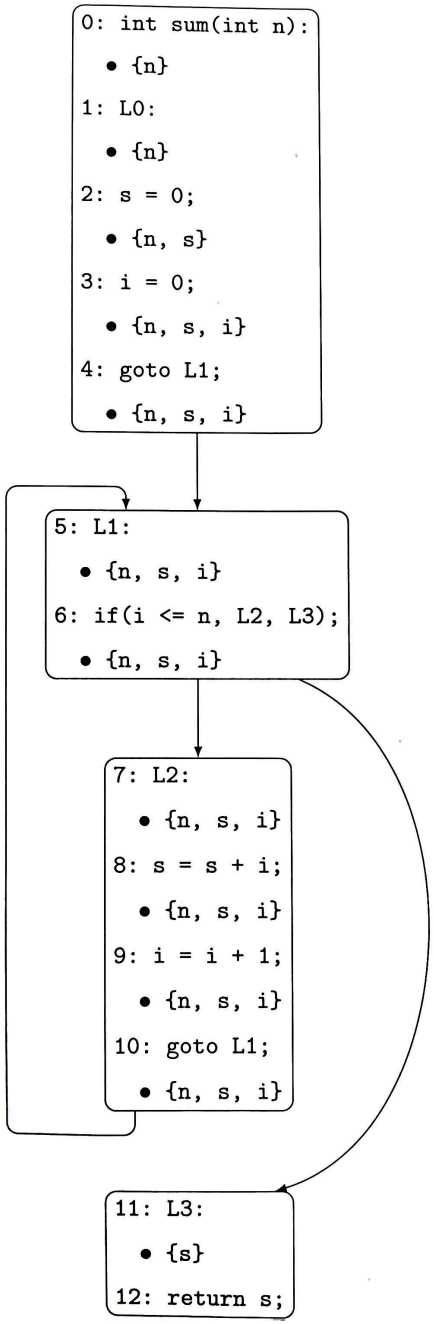

s.index：语句 s 的行号

```
14  // Input: a list of basic blocks, which have been linearized
15  // for any variable x in the program, update the lower and upper bound
16  // of variable x in the map "interval"
17  void calculate_intervals(block blocks[]){
18    for(each variable x in this program)
19      for(each statement s in blocks)
20        if(x ∈ liveOut(s)){ // x is live at statement s
21          if(s.index < interval[x].l)
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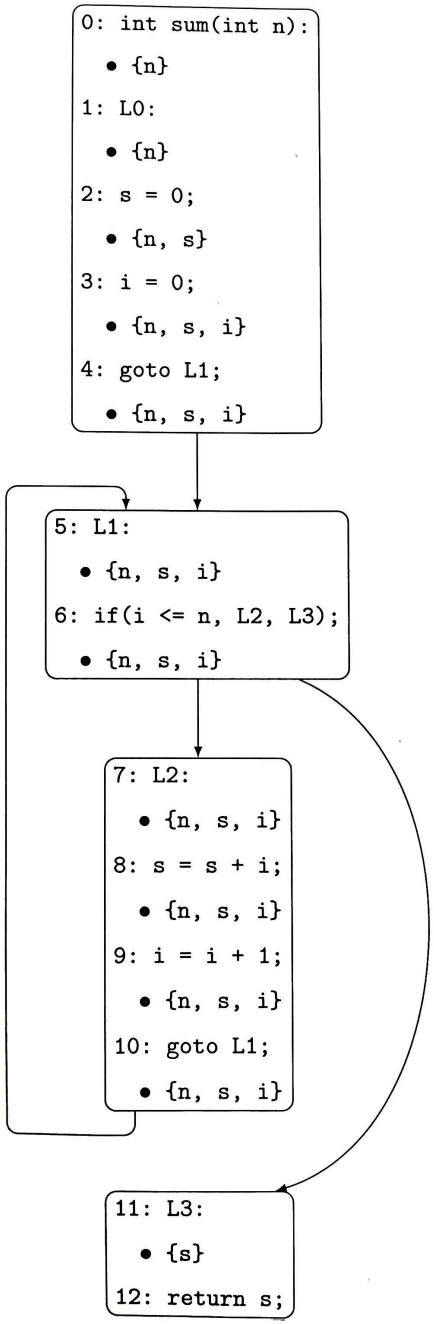

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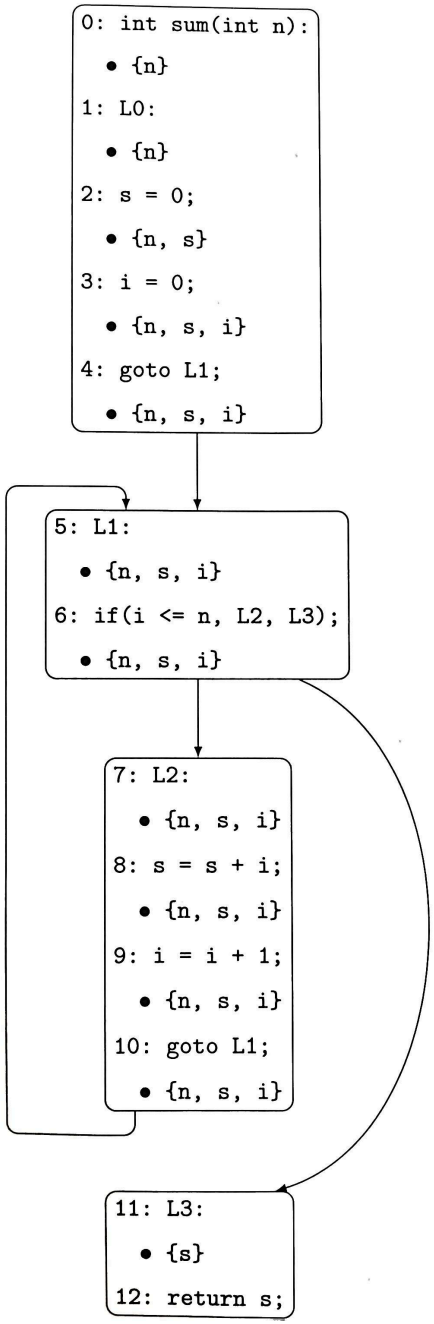

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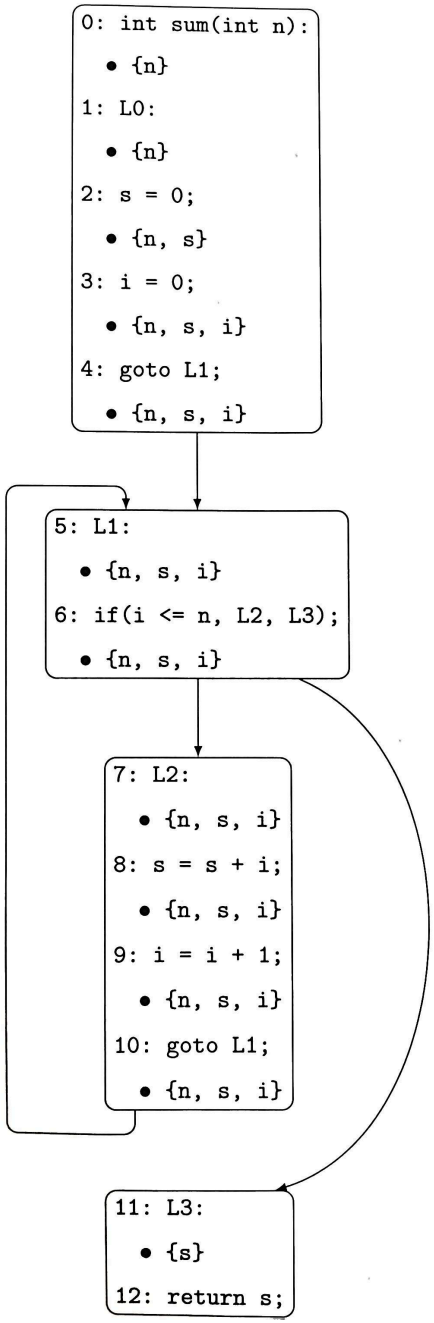

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线性扫描分配算法 @ TOPLAS1999

Linear Scan Register Allocation

MASSIMILIANO POLETTO
Laboratory for Computer Science, MIT
and
VIVEK SARKAR
IBM Thomas J. Watson Research Center

三大关键操作: **占用、释放、溢出**

$x_1 : [2, 16]$

$x_2 : [2, 20]$

$x_3 : [7, 8]$

$x_4 : [9, 10]$

$x_5 : [11, 12]$

$x_6 : [15, 19]$

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$|R| = 3 \quad (R_1, R_2, R_3)$

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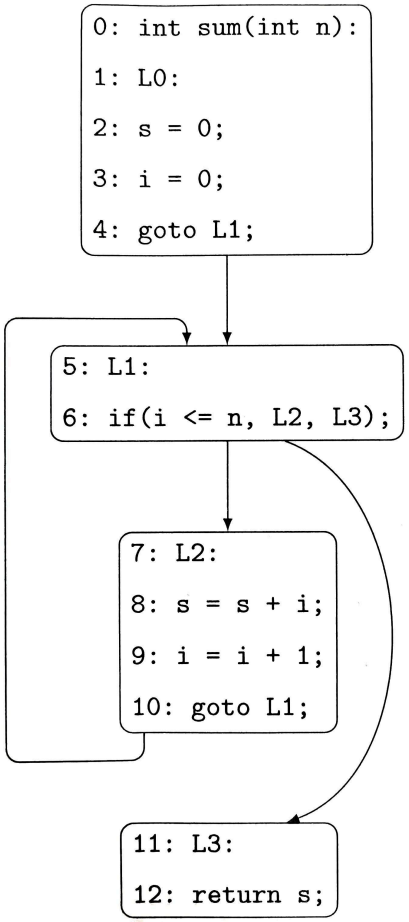
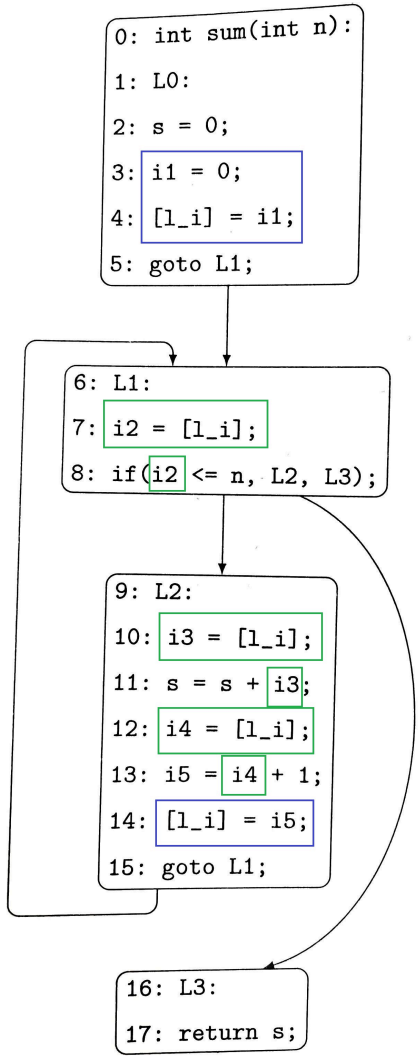
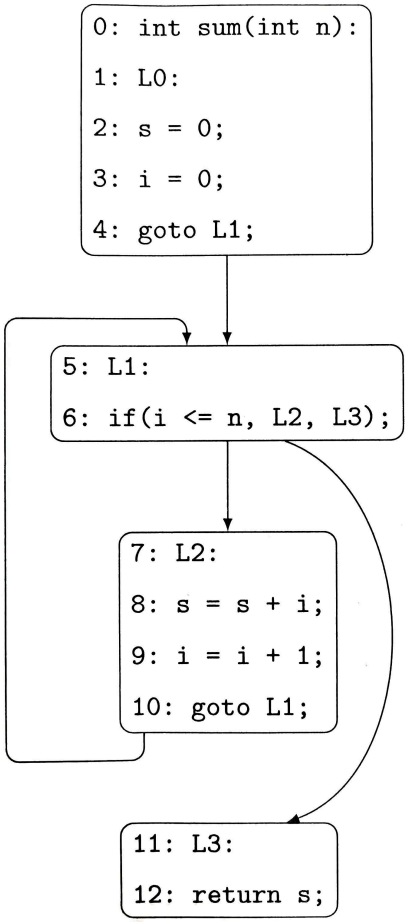
$|R| = 2 \quad (R_1, R_2)$

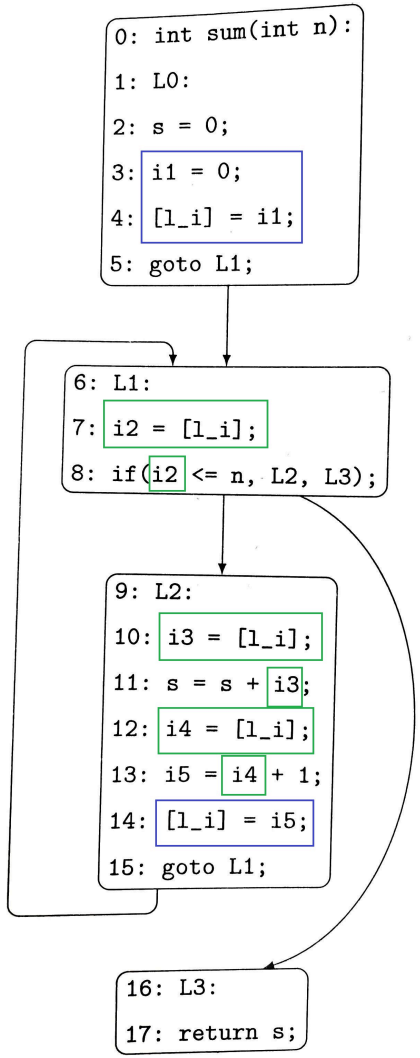




溢出变量 i: 使用 store/load 存/取内存

缺点：引入了新的临时变量，需要进行迭代





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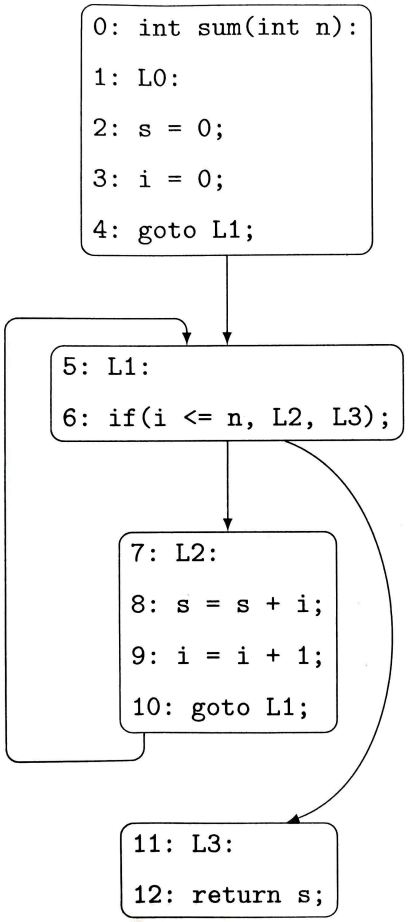
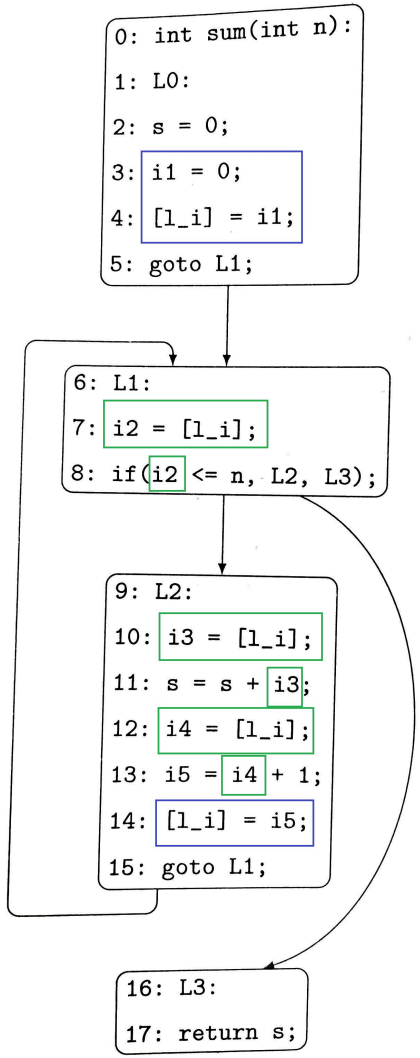
(稍感欣慰的是，新临时变量的活跃区间都很短)





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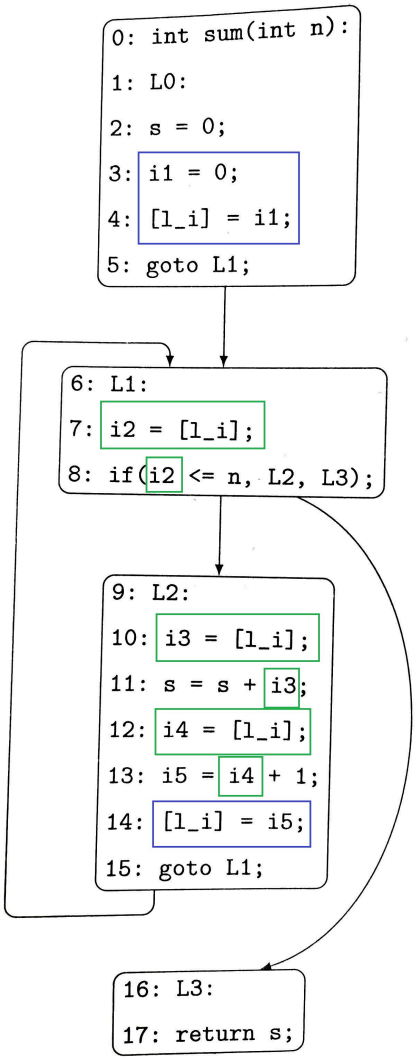

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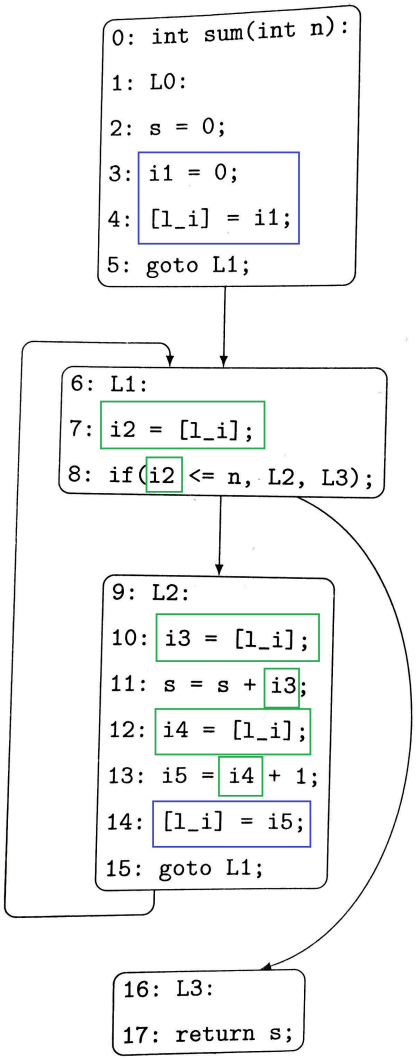

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使用某寄存器前将其保存到内存中

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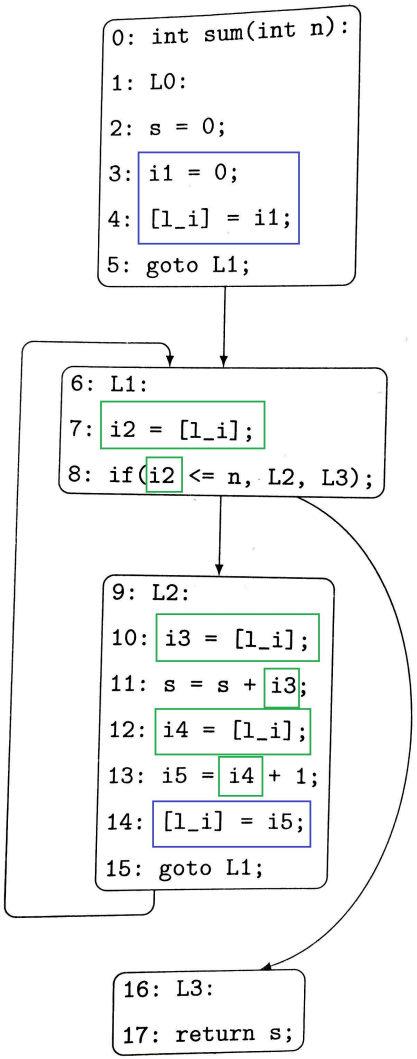

但是，物理寄存器本来就不够用

使用某寄存器前将其保存到内存中

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addi sp, sp, -4
store x2, sp, 0
```

使用 x2 作为临时寄存器

```
load x2, sp, 0
addi sp, sp, 4
```

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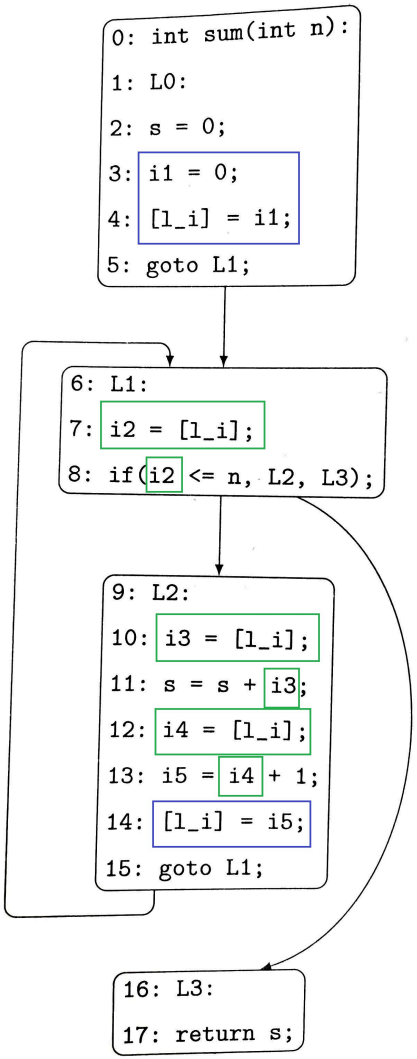

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load x2, sp, 0
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```

缺点：可能带来大量内存操作

解决方案二: 预留若干物理寄存器, 作为溢出处理时所需的临时寄存器

$$\cdots = x$$

$$\cdots$$

$$x = \cdots$$

$$r_i = \cdots$$

$$[l_x] = r_i$$

$$\cdots$$

$$r_i = [l_x]$$

$$\cdots = r_i$$

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预留多少 (K) 个物理寄存器?

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K 为程序中所有语句 def 集合或 use 集合的最大元素个数

解决方案二: 预留若干物理寄存器, 作为溢出处理时所需的临时寄存器

$$\cdots = x \qquad r_i = \cdots$$

$$\cdots \qquad [l_x] = r_i$$

$$x = \cdots \qquad \cdots$$

$$r_i = [l_x]$$

$$\cdots = r_i$$

预留多少 (K) 个物理寄存器?

K 为程序中所有语句 def 集合或 use 集合的最大元素个数

(对于 RISC-V 典型程序, $K = 2$)

解决方案二: 预留若干物理寄存器, 作为溢出处理时所需的临时寄存器

$$y = \tau(x_1, x_2, \cdots, x_K)$$

假设 $x_1, \cdots, x_K, y$ 均发生溢出

$$r_1 = [l_{x_1}]$$

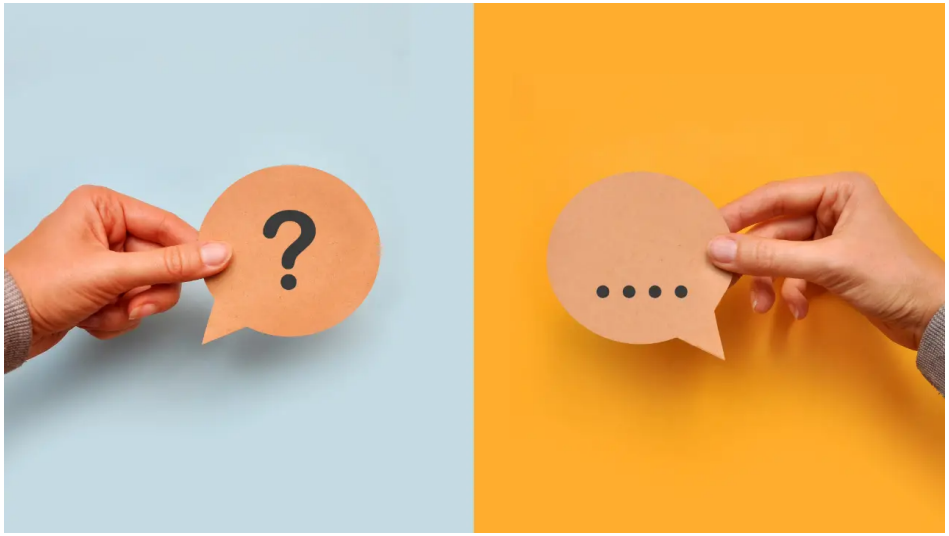
$$\cdots$$

$$r_K = [l_{x_K}]$$

$$r_1 = \tau(r_1, \cdots, r_K)$$

$$[l_y] = r_1$$

还有两个重要问题要解决



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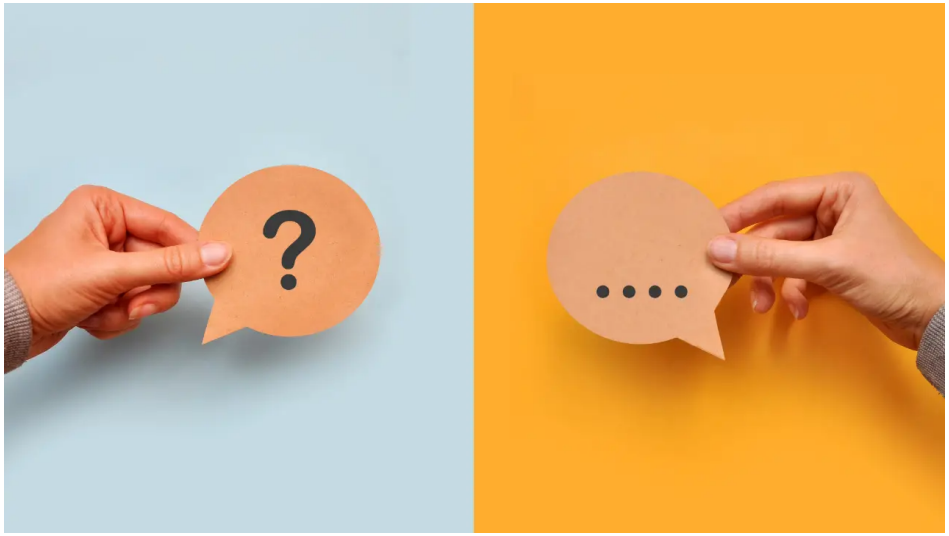
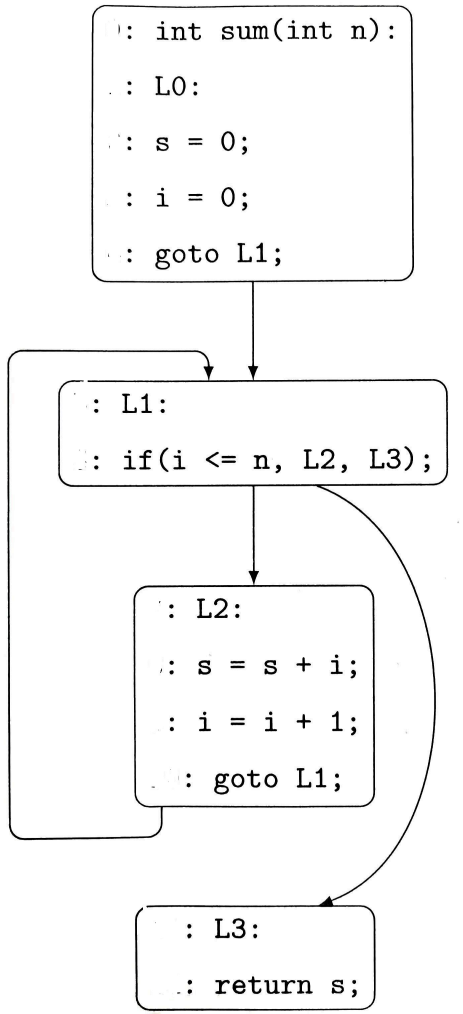


代码编号问题 (index)　　ϕ-指令消除问题

```
int sum(int n):
  L0:
    s = 0;
    i = 0;
    goto L1;
  L1:
    if(i<=n, L2, L3);
  L2:
    s = s + i;
    i = i + 1;
    goto L1;
  L3:
    return s;
}
```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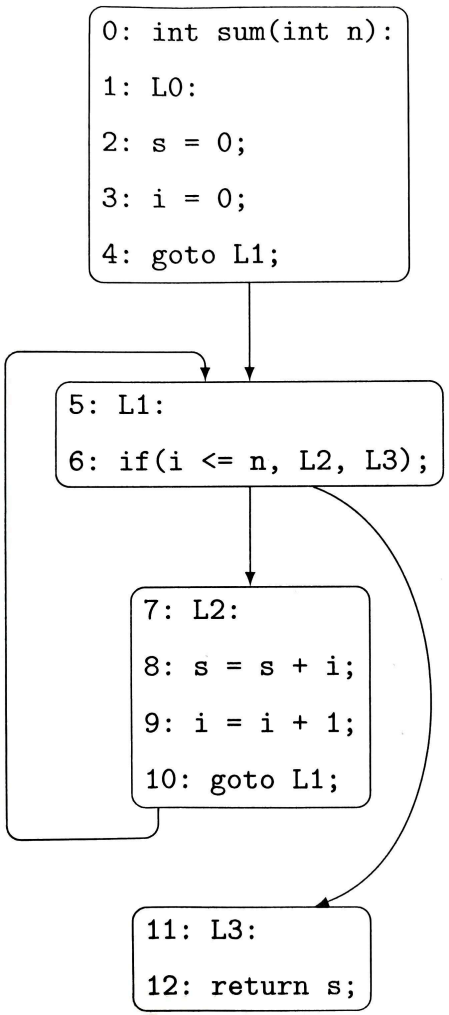
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8: s = s + i;
9: i = i + 1;
10: goto L1;
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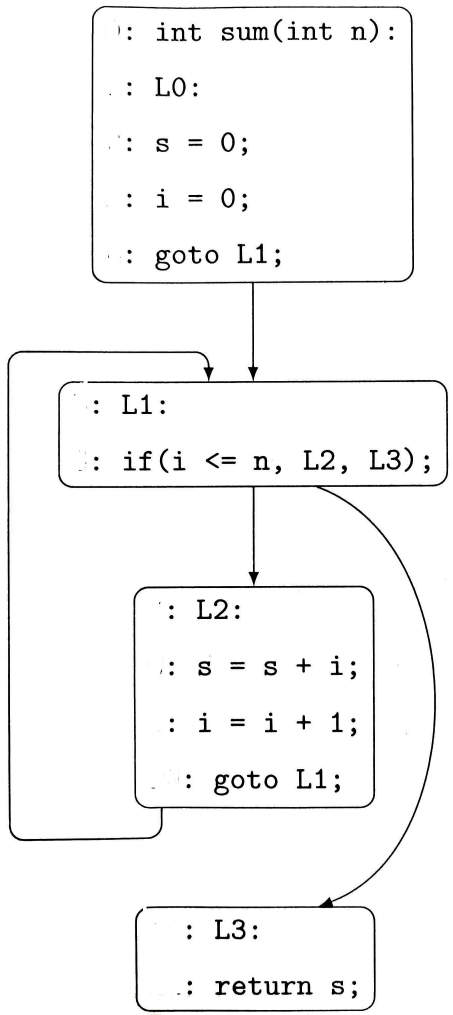
12: return s;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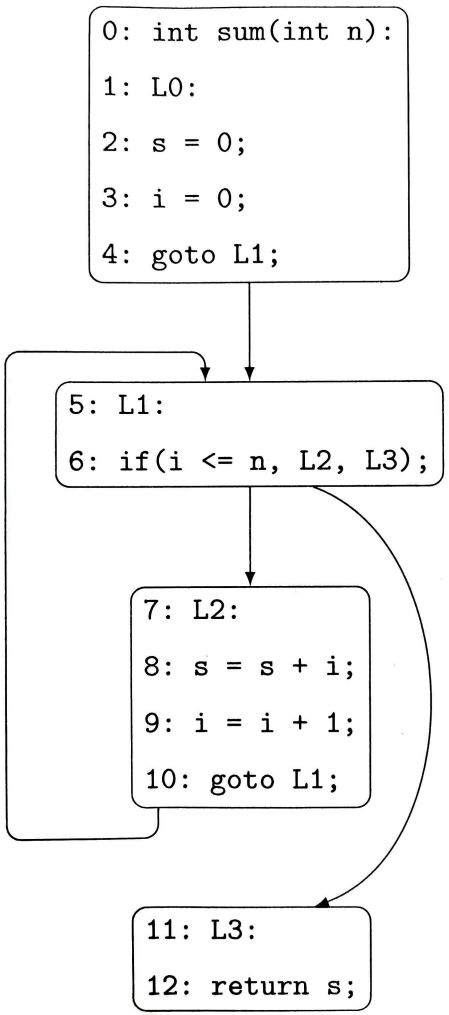
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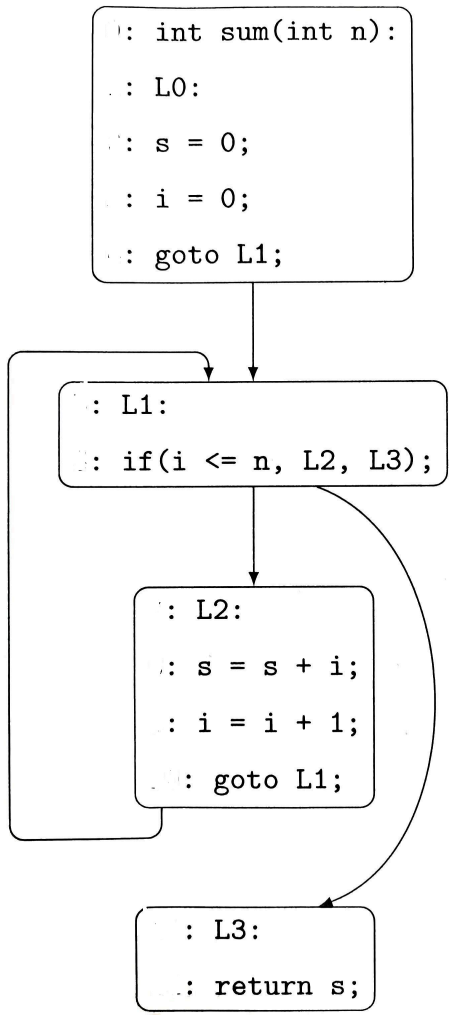
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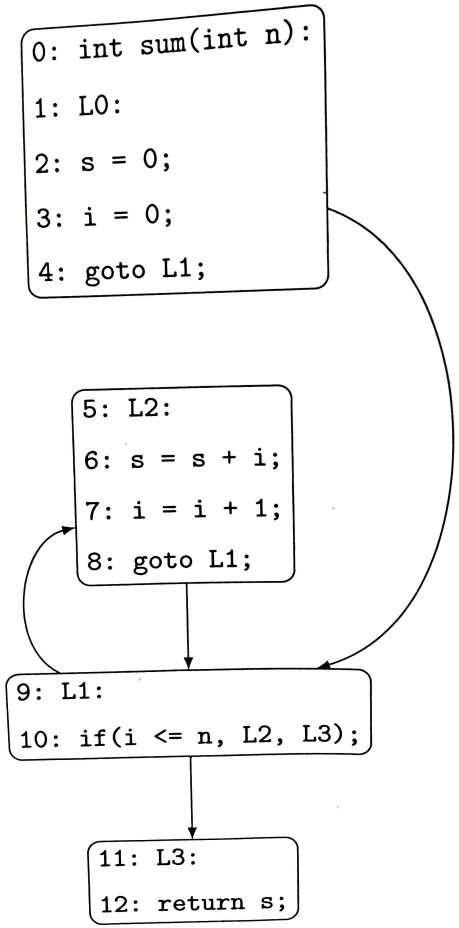
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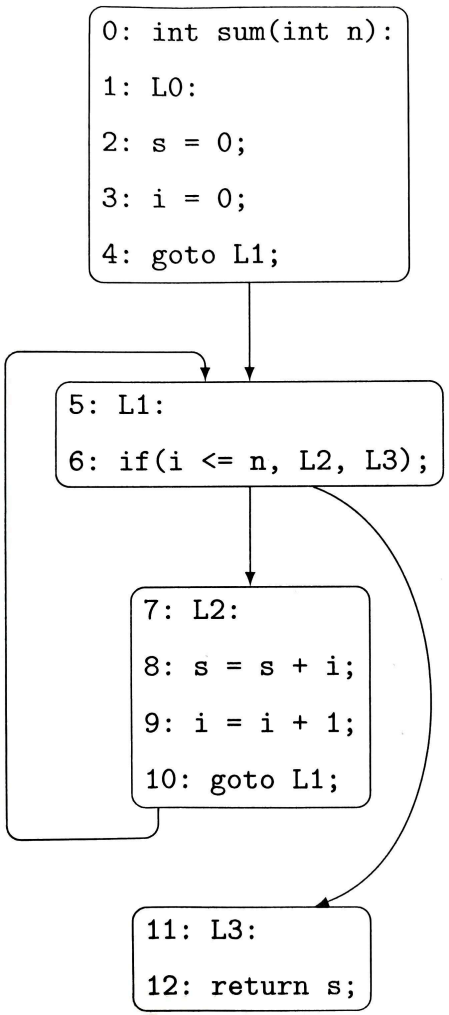
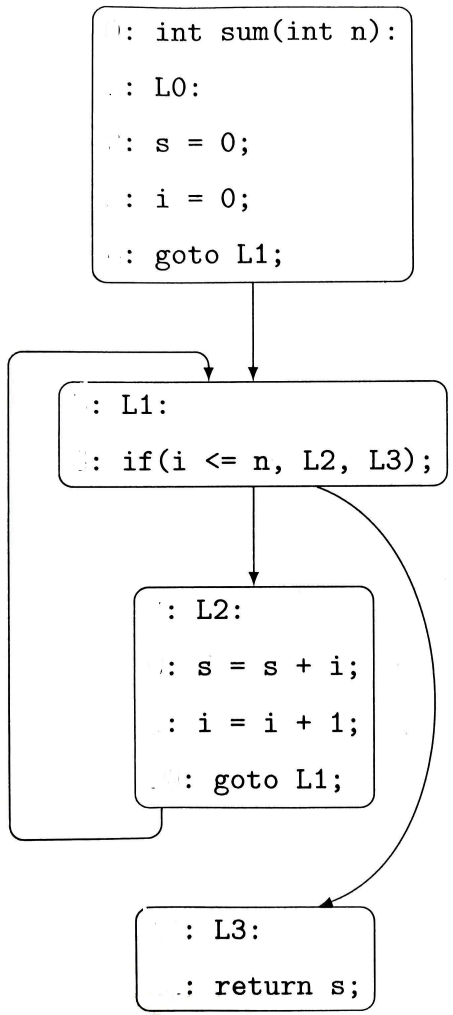
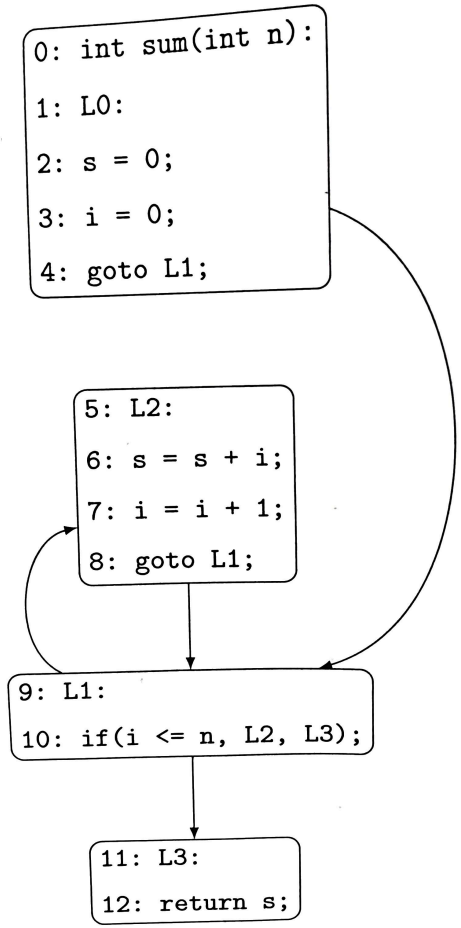
影响“活跃变量”分析结果吗?







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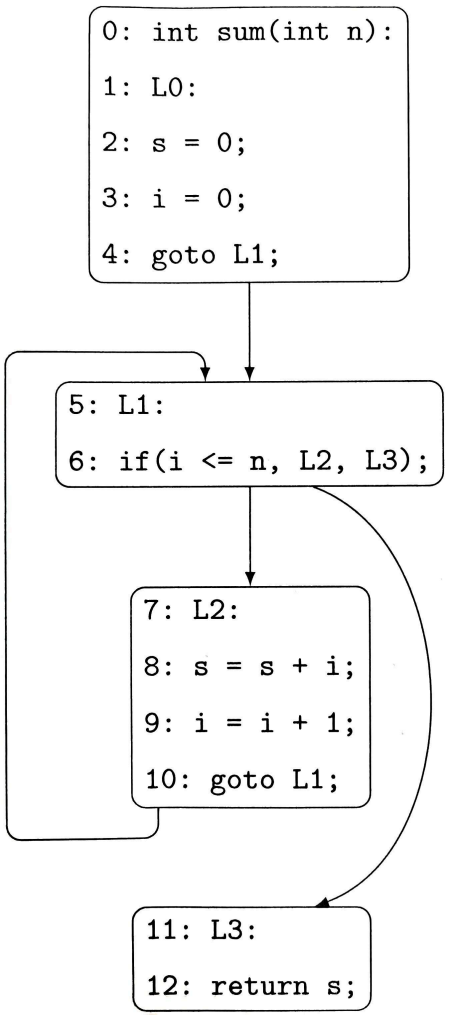

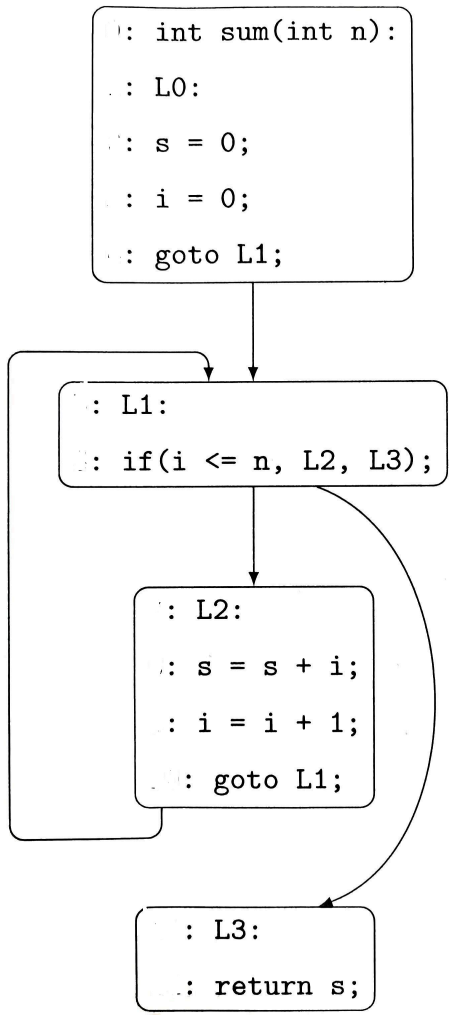

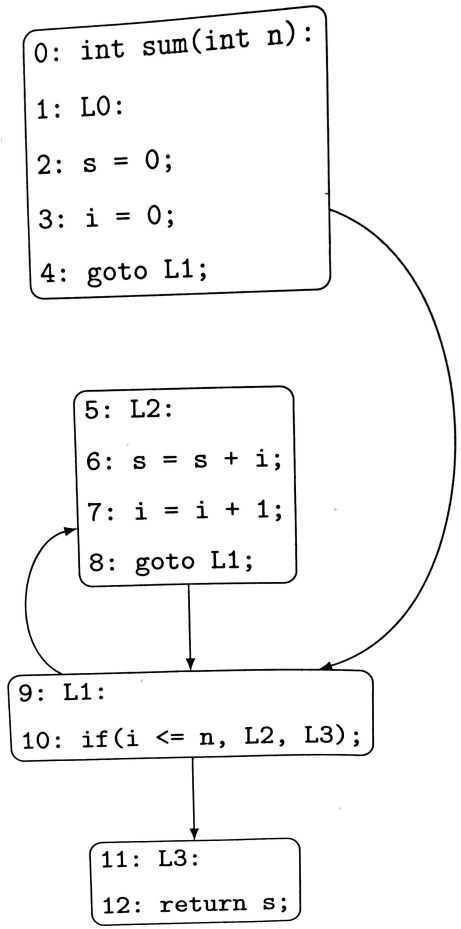

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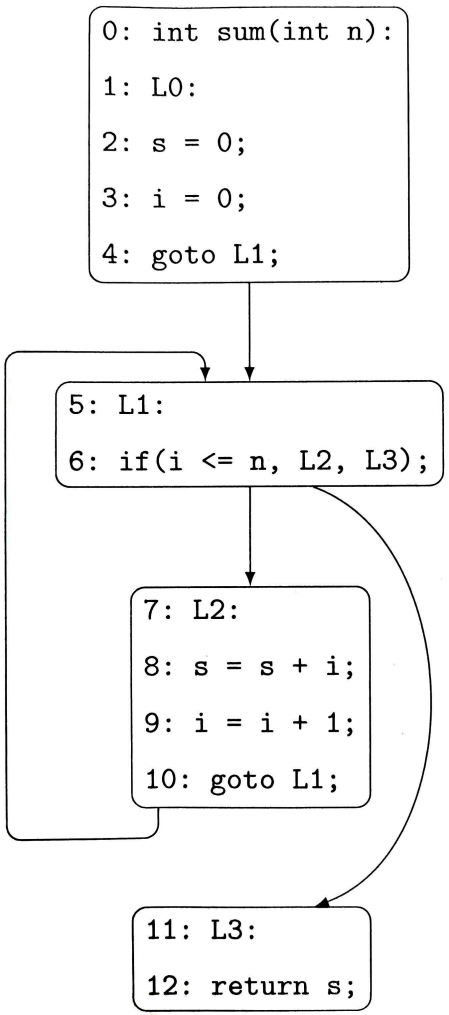
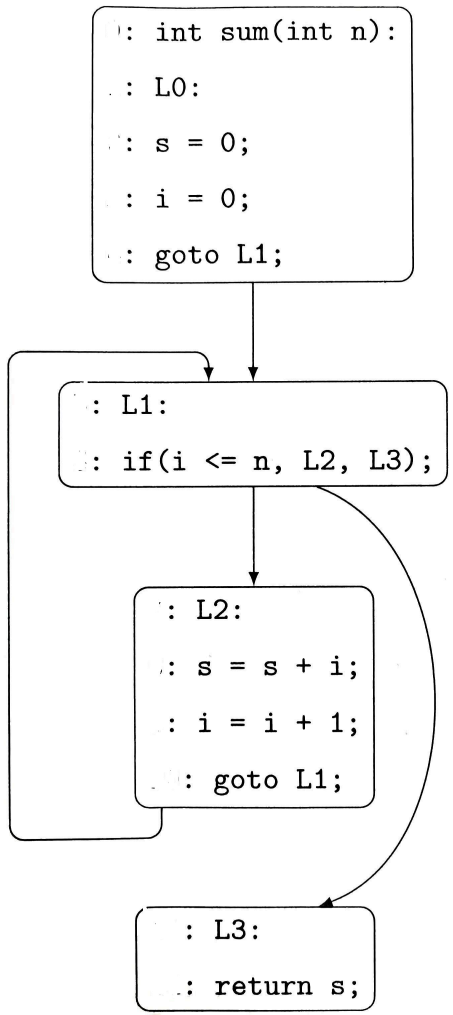
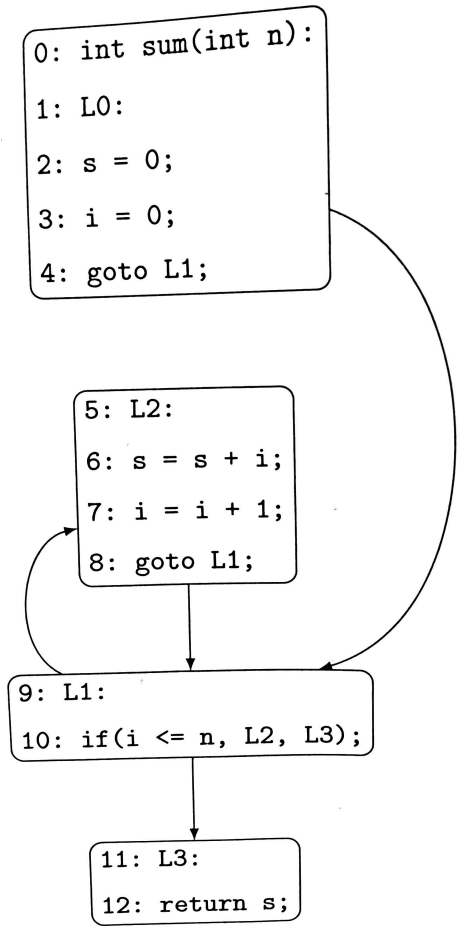
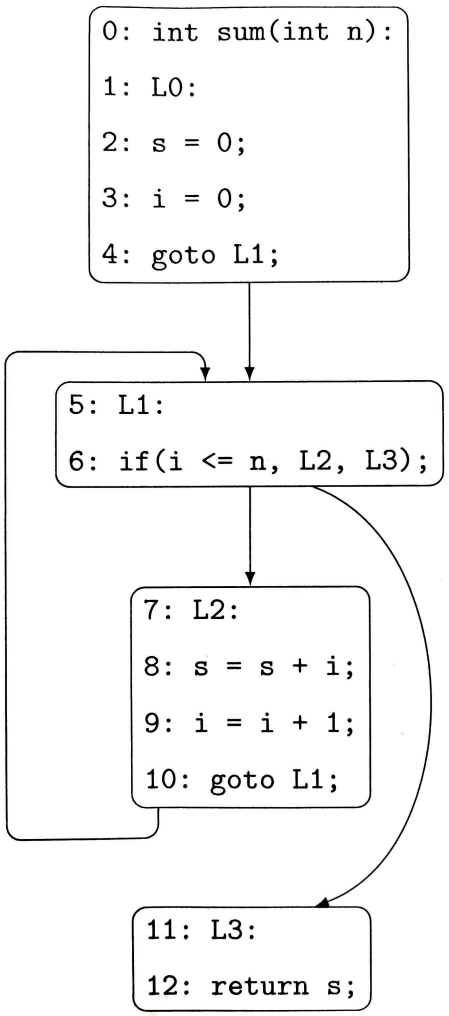


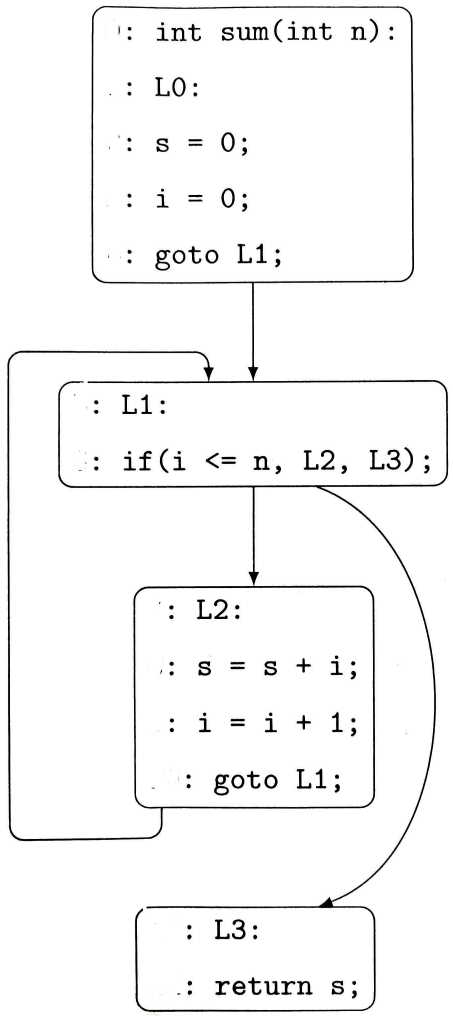


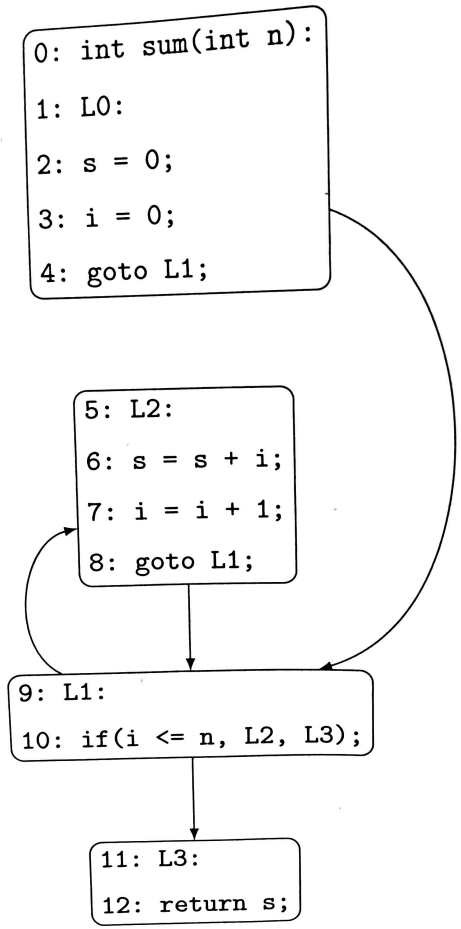


影响“活跃区间”分析结果吗?

影响“活跃变量”分析结果吗? (不影响)







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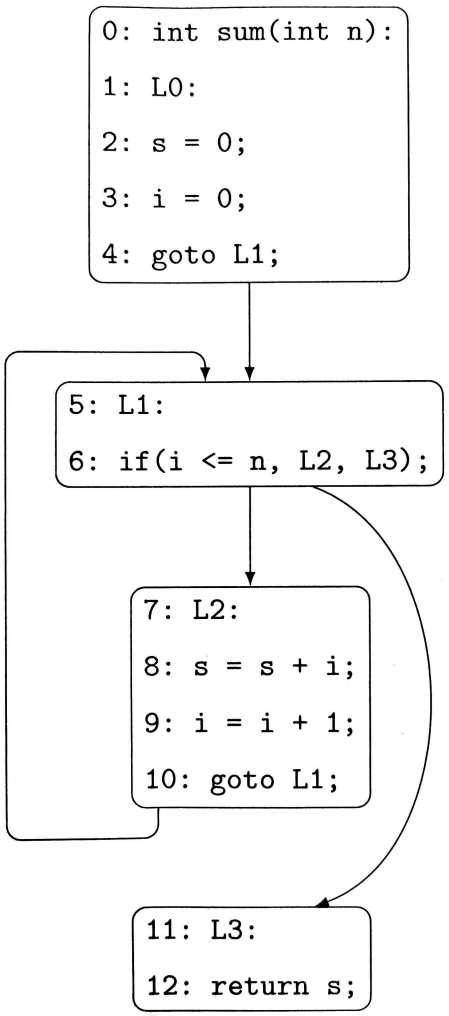
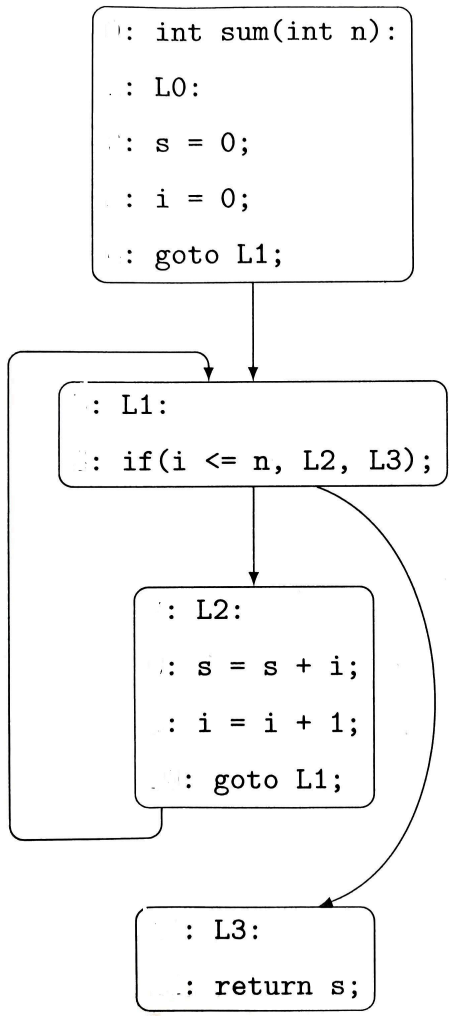
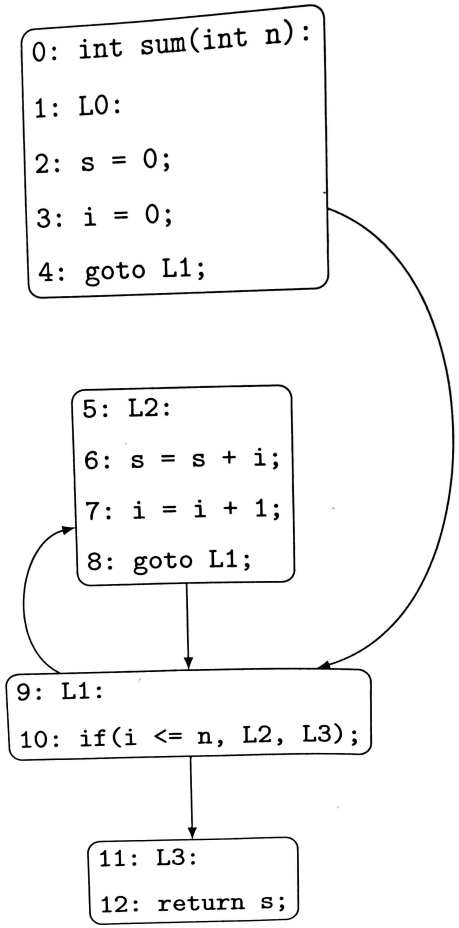


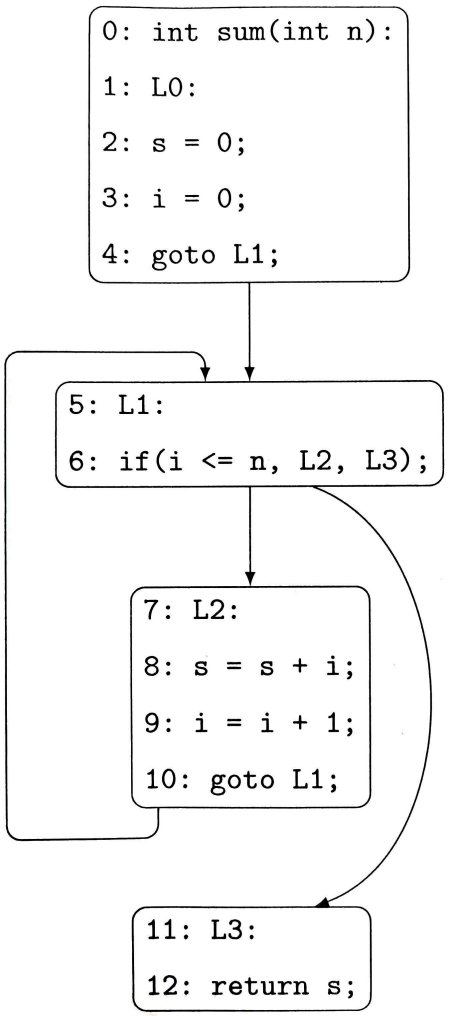


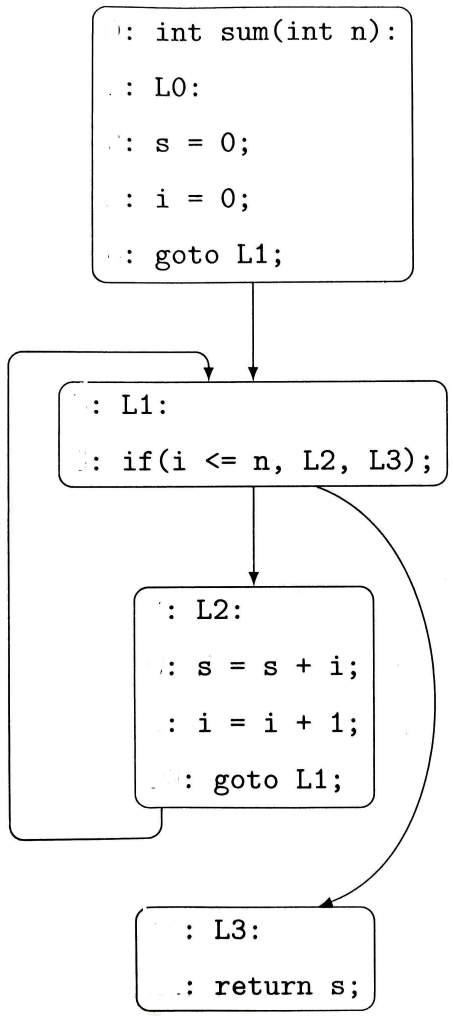


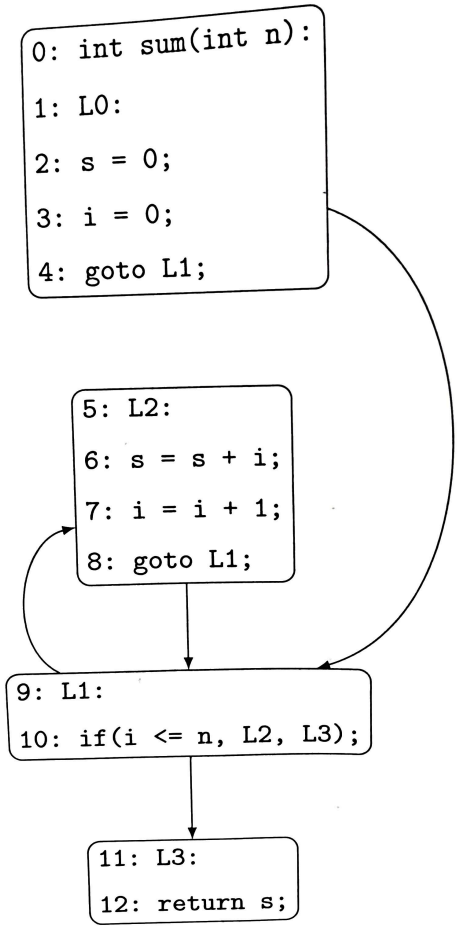
影响“活跃区间”分析结果吗? (影响)

影响“线性扫描算法”正确性吗?

影响“活跃变量”分析结果吗? (不影响)



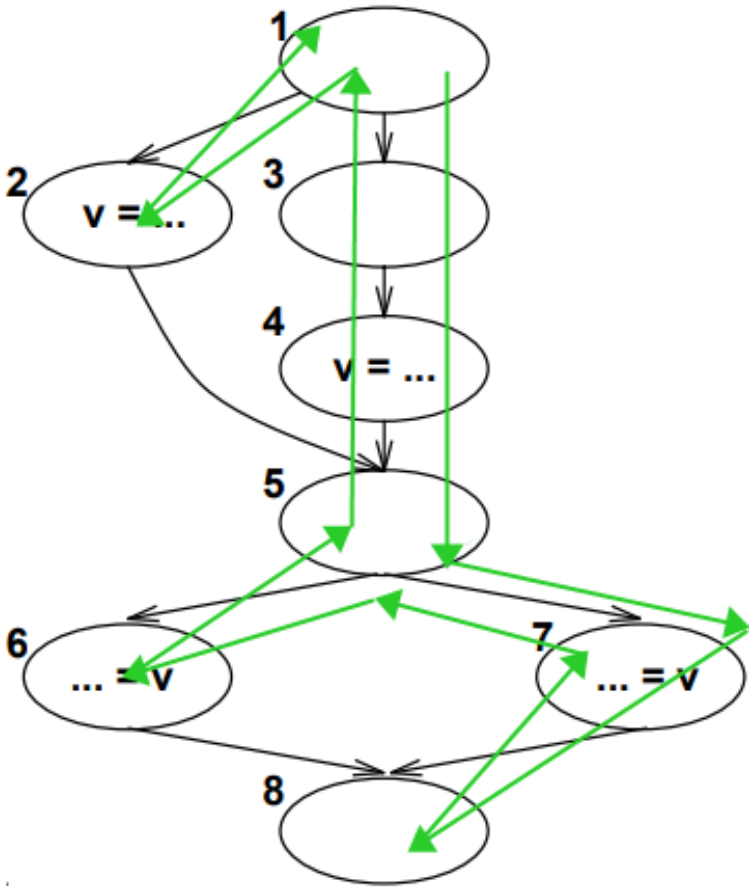




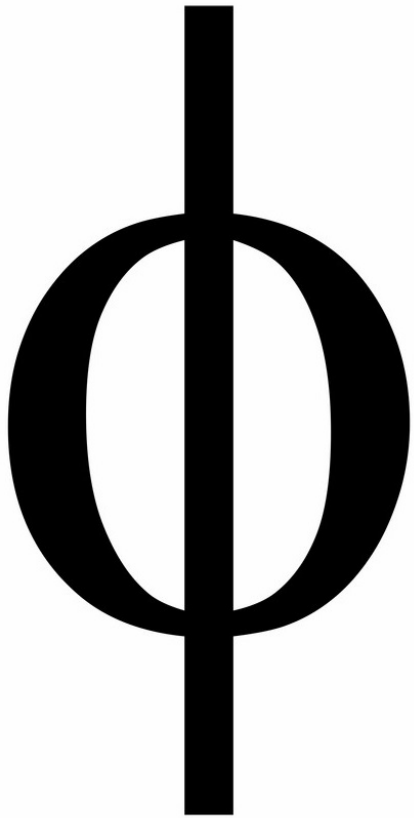
影响“活跃区间”分析结果吗? (影响)

影响“线性扫描算法”正确性吗? (不影响)

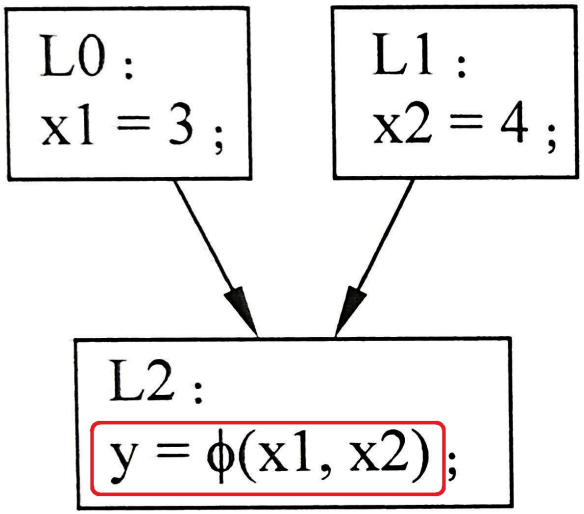
常用编号策略: 深度优先搜索顺序

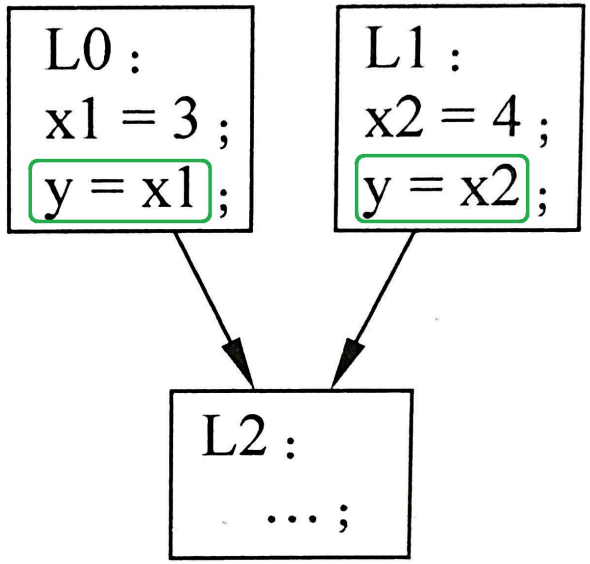


逆后序遍历序 (reverse post-order traversal ordering)



基本思想: 将“拷贝”操作上推到前驱基本块的末尾





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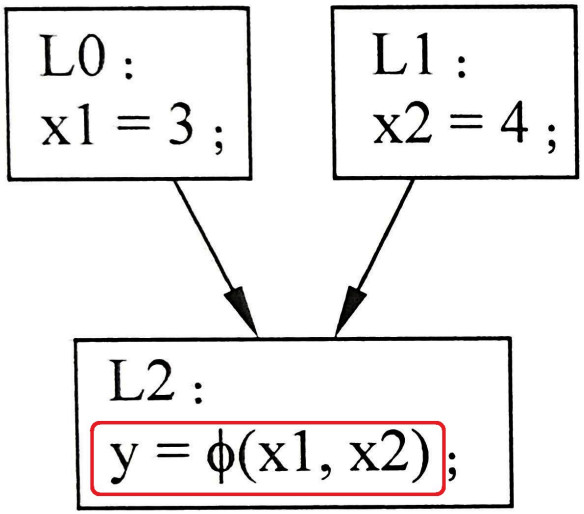
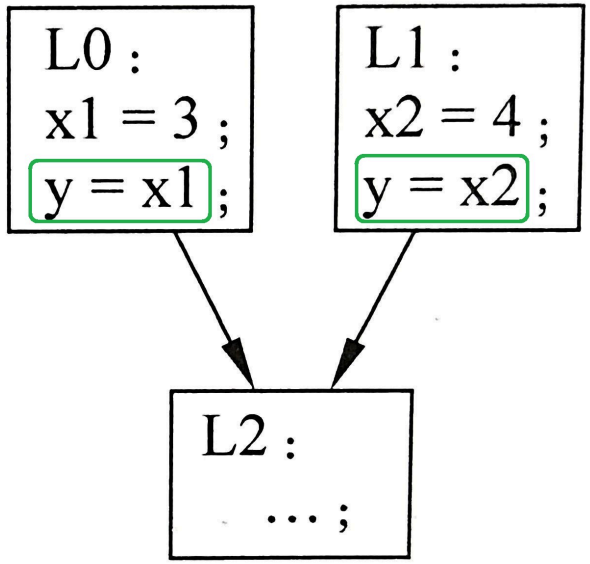
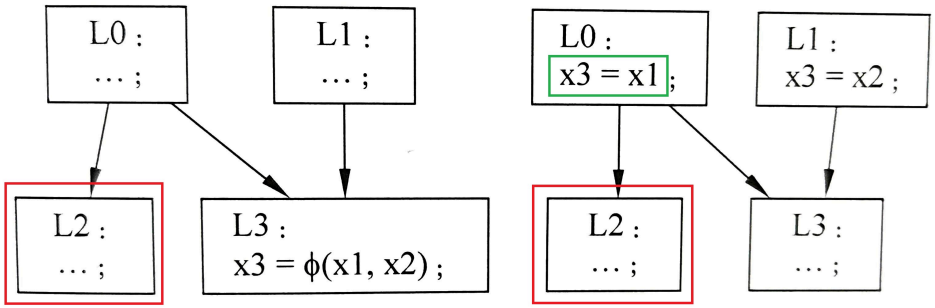


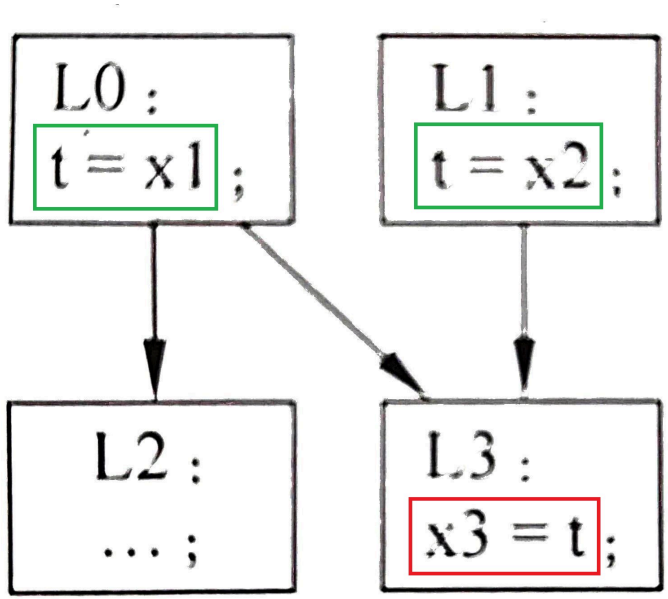


注意“循环”情况

问题一：备份丢失 (lost-copy) 问题

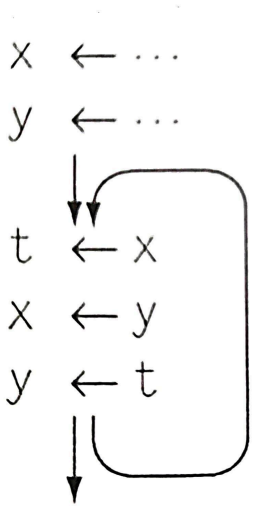


“关键路径”导致的备份丢失问题



引入临时变量消除备份丢失

问题二: 交换 (swap) 问题



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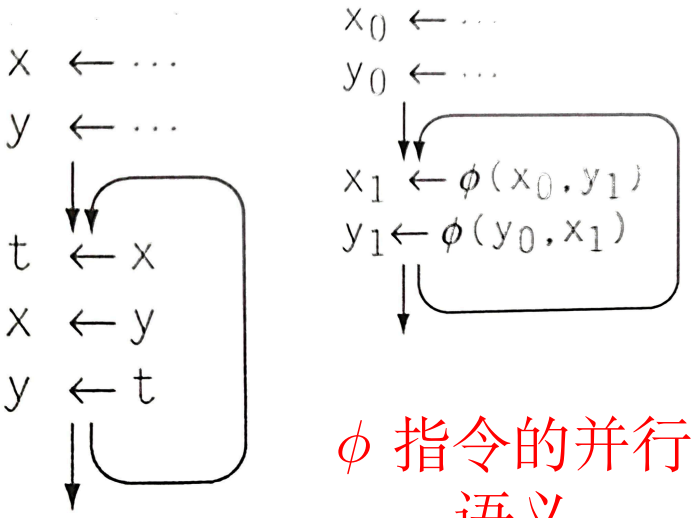
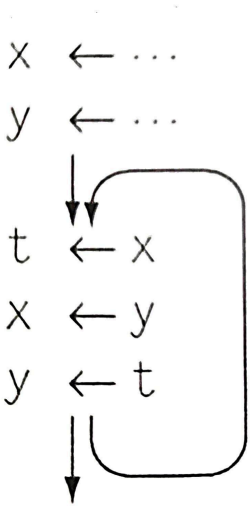
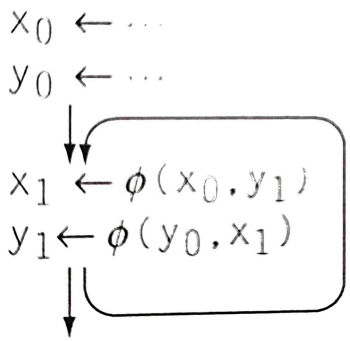


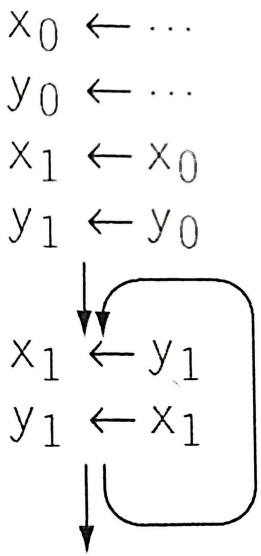
ϕ 指令的并行语义

问题二: 交换 (swap) 问题



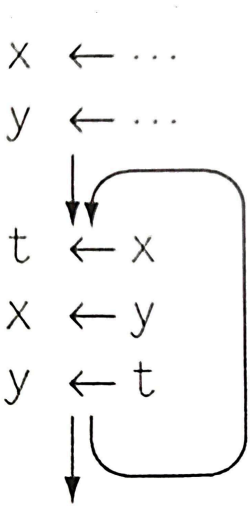


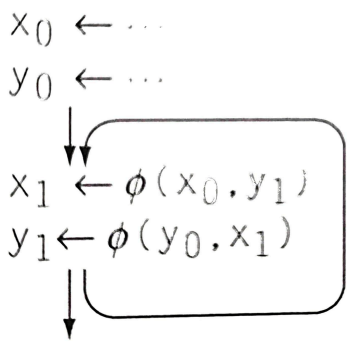
ϕ 指令的并行语义



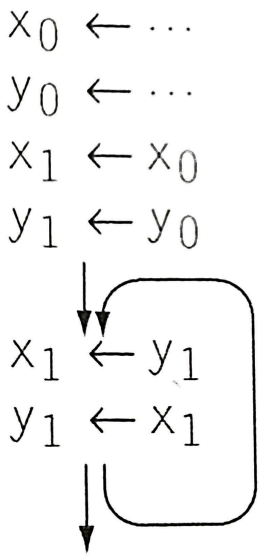
交换问题

问题二: 交换 (swap) 问题





ϕ 指令的并行语义



交换问题

$t_x \leftarrow x_0$

$t_y \leftarrow y_0$

引入临时变量

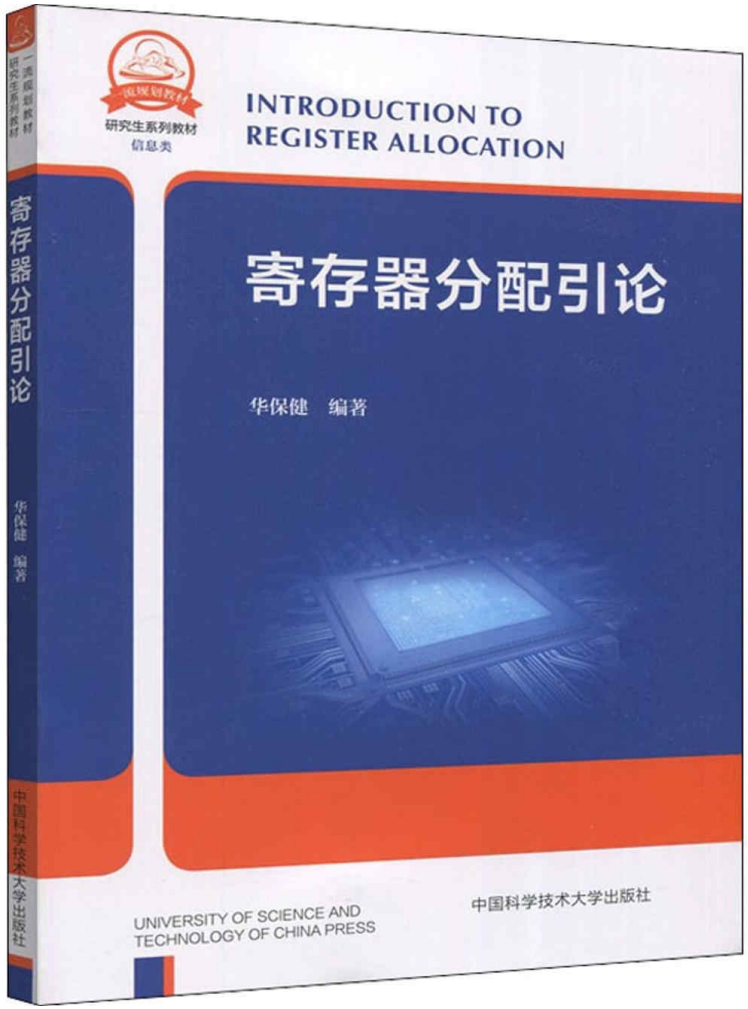
$x_1 \leftarrow t_x$

$y_1 \leftarrow t_y$

$\cdots$

$t_x \leftarrow y_1$

$t_y \leftarrow x_1$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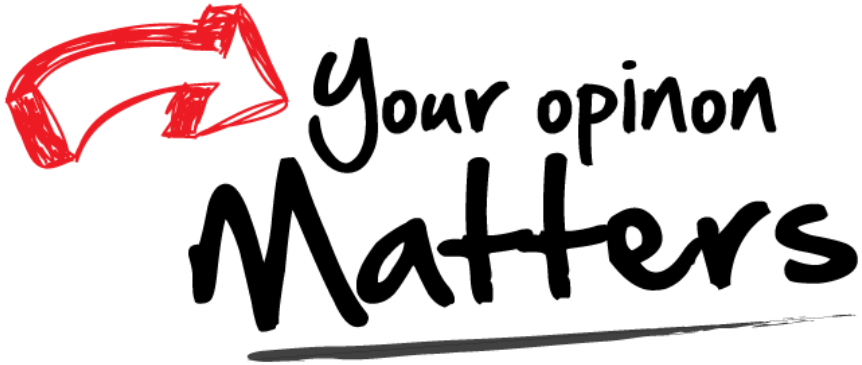
Thank
You!



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