编译原理

8. Basic Blocks and Traces

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课程内容

1. Introduction
2. Lexical Analysis
3. Parsing
4. Abstract Syntax
5. Semantic Analysis
6. Activation Record
7. Translating into Intermediate Code
8. **Basic Blocks and Traces**
9. Instruction Selection
10. Liveness Analysis
11. Register Allocation
13. Garbage Collection
14. Object-oriented Languages
18. Loop Optimizations

Outline

1. Canonical Form
2. Step I: Canonical Trees
3. Step II & III: Taming Conditional Branches

1. Canonical Form

Motivation

- The trees generated by semantic analysis phase must be translated into assembly or machine language
- The operators of the *Tree* language are chosen carefully to match the capabilities of most machines
- However,
  - Some aspects of the *Tree* language do not correspond exactly with machine languages
  - Some aspects of the *Tree* language interfere with compile-time optimization analyses

Mismatches: Trees vs. Machine Code

1. CJUMP can jump to two labels

- Real machines' conditional jump instructions fall through to the next instruction if the condition is false (e.g., JZ, JNZ)

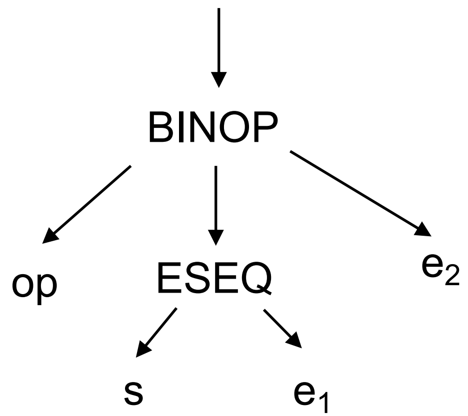
```
CJUMP(e, t, f)
...
LABEL(t)
if-true code
LABEL(f)
```

```
    evaluate e
    JZ  f
    if-true code
f:
```

- 真正的汇编指令里有conditional jump, 在条件成立会跳转; 条件不成立的情况下就**执行自己的后一条指令**
- 而在IR tree里无论成立还是不成立，都需要跳转

Mismatches: Trees vs. Machine Code

1. **CJUMP can jump to two labels (but machine code "falls through")**
2. **ESEQ nodes within expressions are inconvenient**
   – Different orders of evaluating subtrees yield different results.
   – But it is useful to be able to evaluate the subexpressions of an expression in any order.



如果计算s的时候有side-effect，那就会导致谁先做谁后做结果不一样(为什么)

Evaluate e2 first?

回顾: 关于ESEQ的理解

- **ESEQ(s, e)**：The statement s is evaluated for side effects, then e is evaluated for a result.
  - 假设s是statement a=5, e是expression a+5
  - Statement (如a=5)不返回值,但是有副作用
  - ESEQ(a=5, a + 5)最终的结果是10
- 关于副作用(Side effects) (重要)
  - **Side-effects** means **updating** the contents of a **memory cell** or a **temporary register**

Mismatches: Trees vs. Machine Code

1. **CJUMP can jump to two labels (but machine code "falls through")**
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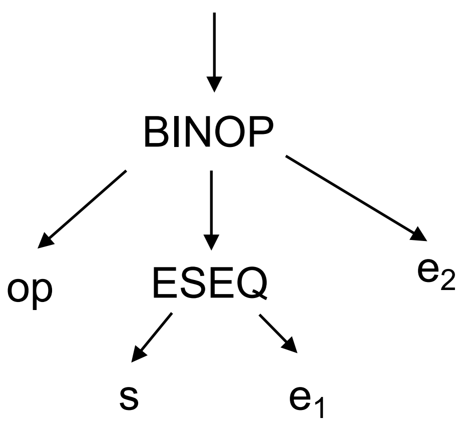


如果计算s的时候有side-effect，那就会导致谁先做谁后做结果不一样

- 考虑**BINOP(PLUS, TEMP a,**
  ESEQ(MOVE(TEMP a, u), v))
- **MOVE**有副作用: 修改了临时变量/虚拟寄存器a的值！
- 也就是说, ESEQ(s, e1)可能改变了e2!

Evaluate e2 first or not?

Mismatches: Trees vs. Machine Code (Cont.)

1. **CJUMP can jump to two labels (but machine code "falls through")**
2. **ESEQ nodes within expressions are inconvenient**
3. **CALL nodes within expressions also depend on order (have side effects)**
   - When trying to put arguments into a fixed set of formal-parameter registers
   - e.g., CALL(f, [e1, CALL(g, [e2, …])])

Idea: Transform the **IR to a canonical form** to eliminate the above cases!

Why Canonical Form?

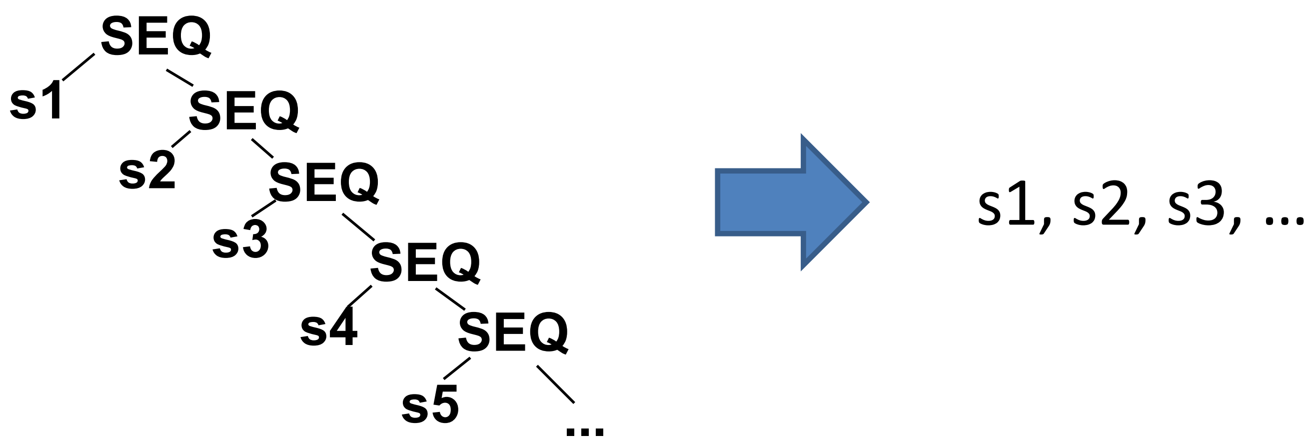
- Intermediate code has general tree form
  - Easy to generate from AST,
  - But hard to translate directly to assembly

- Assembly code is **a sequence of statements!**

- Characteristics of **canonical form**
  - All statements brought up to top level of tree
  - Can generate assembly directly

Example: Canonical Form

- In canonical form, all SEQ nodes go down right chain:



- A function is just one big SEQ containing all statements: SEQ(s1,s2,s3,s4,s5,…)
- Can translate to assembly more directly!

Transforming to Canonical Form

- To make instruction selection easier, we transform the IR tree in three stages:

  1. A tree is rewritten into a list of canonical trees without SEQ or ESEQ nodes

  2. This list is grouped into a set of basic blocks, which contain no internal jumps or labels

  3. The basic blocks are ordered into a set of traces in which every CJUMP is immediately followed by its false label

2. To Canonical Trees (Linerization)

- **eliminate ESEQs**
- move CALLs to top level
- eliminate SEQs

What are Canonical Trees

- **Canonical Trees** are defined as having these properties:
  1. **No SEQ or ESEQ**
  2. **The parent of each CALL is either EXP(…) or MOVE(TEMP t, …)**

- **Property 1:**
  – Each canonical tree only contains one statement node, i.e., the root node. Other nodes are all expression nodes.

Canonical Trees

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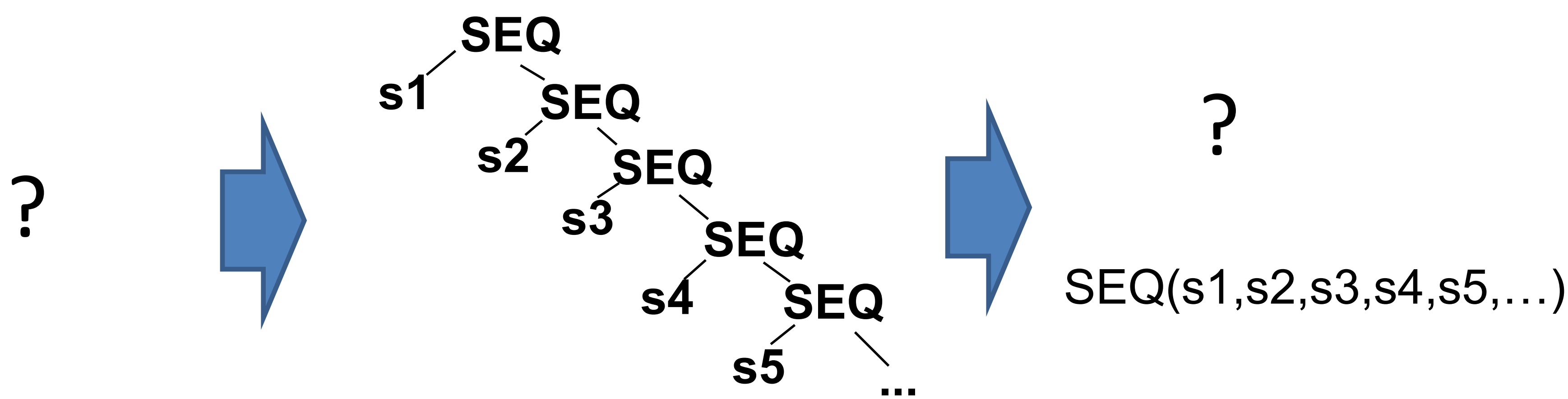
  1. **No SEQ or ESEQ**
  2. **The parent of each CALL is either EXP(…) or MOVE(TEMP t, …)**

- **Property 1:**
  - Each canonical tree only contains one statement node, i.e., the root node. Other nodes are all expression nodes.
- **Property 1 and property 2:**
  - The parent of a CALL node must be the root node of a canonical tree and must be EXP(..) or MOVE(TEMP t, ..).
  - There can only be one CALL node in a canonical tree, because EXP(…) and MOVE(TEMP t, ...) can only contains one CALL.

Stage I: To *Canonical Trees*

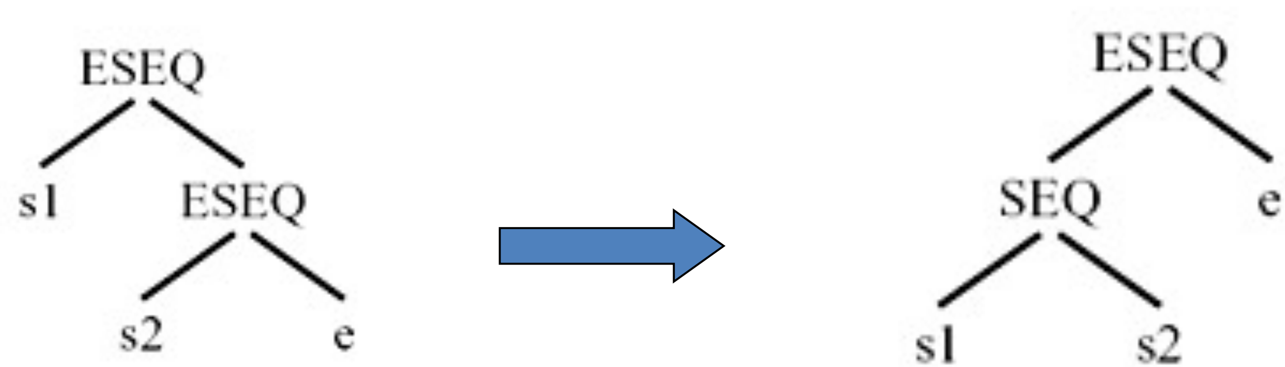
- To perform stage-one transformation, we need to:
  1. **eliminate ESEQ**
  2. **move CALLs to top level**
  3. **eliminate SEQs (turn into linear lists)**



把statements全部移上去，最后就会
和汇编比较接近(statement序列!)

Linearization Rules for ESEQ

- How can the ESEQ nodes be eliminated?
  - **Lift them higher and higher in the tree, until they can become SEQ nodes.**

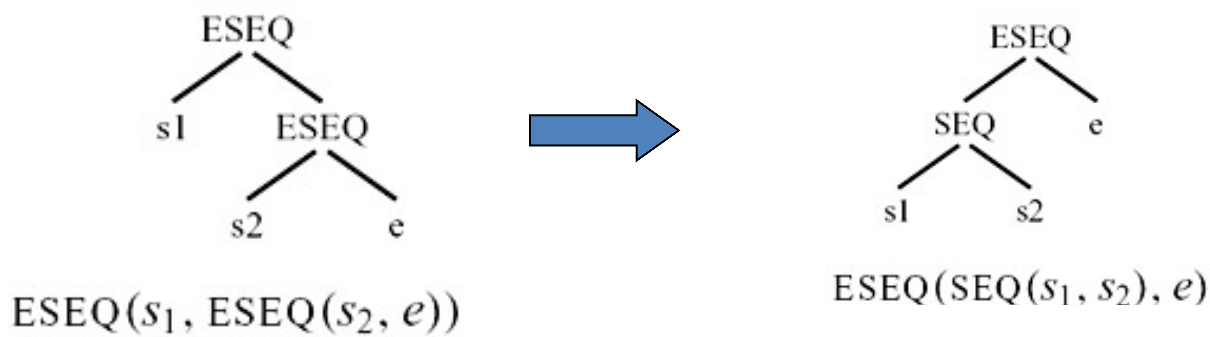


$\mathrm{ESEQ}(s_1, \mathrm{ESEQ}(s_2, e))$ $\qquad$ $\mathrm{ESEQ}(\mathrm{SEQ}(s_1, s_2), e)$

ESEQ(s1, ESEQ(s2,e)) => ESEQ(SEQ(s1,s2),e)

Linearization Rules for ESEQ Cont.

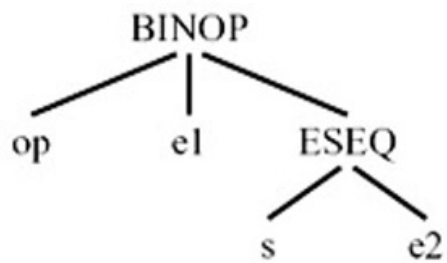
- **ESEQ(s1, ESEQ(s2, e))**$\Rightarrow$ ESEQ(SEQ(s1,s2), e))



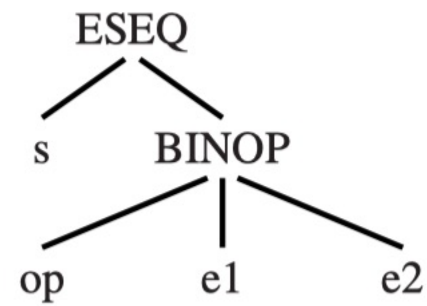
- BINOP(op, ESEQ(S, e1,), e2) $\Rightarrow$ ESEQ(s, BINOP(op, e1, e2))
- MEM(ESEQ(s,e1)) $\Rightarrow$ ESEQ(s, MEM(e1))
- JUMP(ESEQ(s, e1)) $\Rightarrow$ SEQ(s, JUMP(e1))
- CJUMP(op, ESEQ(s, e1), e2, l1,l2) $\Rightarrow$ SEQ(s, CJUMP(op, e1, e2, l1,l2))

Impact of Side Effects on Linearization Rules

Consider the Tree: BINOP(op, e1, ESEQ(s, e2))



Can we ?



$\mathrm{BINOP}(op, e_1, \mathrm{ESEQ}(s, e_2))$ $\qquad$ $\mathrm{ESEQ}(s, \mathrm{BINOP}(op, e_1, e_2))$

Can we interchange the order of s and e1??

- **Problem**: s may have side effects that affect value of e1!
- **Solution**: use a temporary to store value of e1

Suppose:
s = MOVE(MEM(x), y)
e1 =MEM(x)

Side Effects and Commutativity

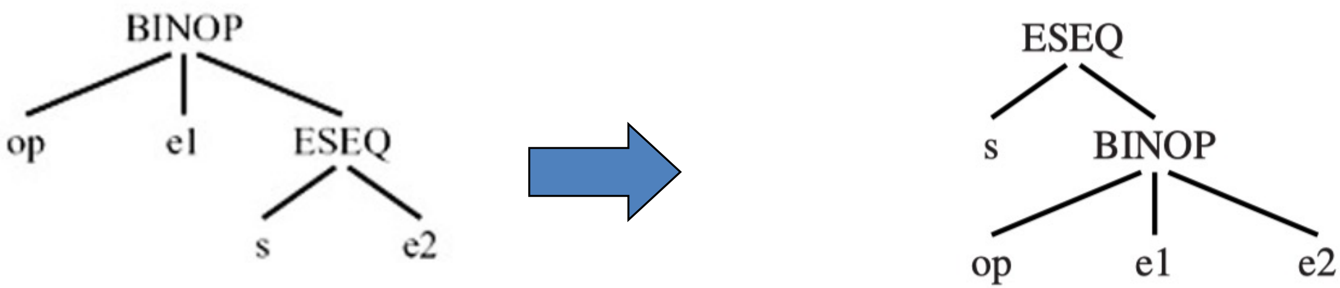
- **Commutativity**: statement **s** and expression **e** can commute if **s** does not affect the value of **e**
  - E.g., consider MOVE (MEM(t1), e) and MEM(t2)
  - If t1 != t2, then MOVE (MEM(t1), e) and MEM(t2) commute

- What if statement **s** and expression **e** do not commute?
  - we may need **new temporary locations to store intermediate results** to get canonical trees

Effect of Commutativity on Linearization Rules

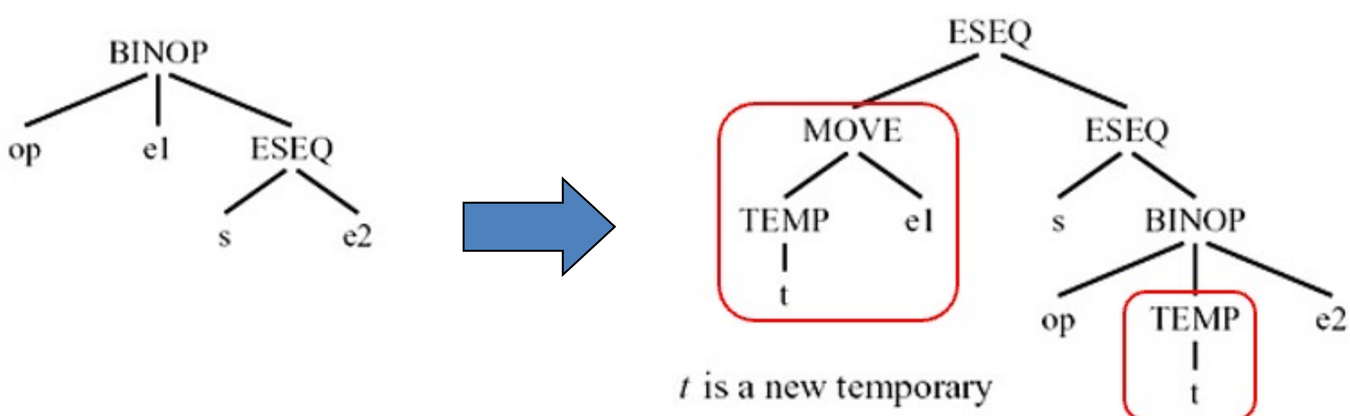
Consider BINOP(op, e1, ESEQ(s, e2))

Statement **s** and expression **e** commute



$\text{BINOP}(op, e_1, \text{ESEQ}(s, e_2))$ $\text{ESEQ}(s, \text{BINOP}(op, e_1, e_2))$

Statement **s** and expression **e** do not commute



t is a new temporary

$\text{BINOP}(op, e_1, \text{ESEQ}(s, e_2))$

$\text{ESEQ}(\text{MOVE}(\text{TEMP}\ t, e_1),$
$\quad \text{ESEQ}(s, \text{BINOP}(op, \text{TEMP}\ t, e_2)))$

Example: Effect of Commutativity on Linearization

If s, e1 commute, we have

- **BINOP(op, e1, ESEQ(s, e2))** $\Rightarrow$ ESEQ(s, BINOP(op, e1, e2))
- **CJUMP(op, e1, ESEQ(s, e2), l1,l2)** $\Rightarrow$ SEQ(s, CJUMP(op, e1, e2, l1,l2)

Else, we use the following rules (that have new temporaries)

- **BINOP(op, e1, ESEQ(s, e2))**

$\Rightarrow$ ESEQ(MOVE(TEMP t, e1),
ESEQ(s, BINOP(op, TEMP t, e2)))

- **CJUMP(op, e1, ESEQ(s, e2), l1, l2)**

$\Rightarrow$ SEQ(MOVE(TEMP t, e1),
SEQ(s, CJUMP(op, TEMP t, e2, l1,l2)))

Deciding Commutativity

Whether a statement s commutes with an expression e?

- **Problem**: commutativity is hard to known statically.
- Make a **conservative approximation**, which means
  - commute(s, e) = True if s and e definitely do commute
  - commute(s, e) = False otherwise
- E.g., a naïve strategy to estimate whether a statement commutes with an expression:
  - A constant commutes with any statement
  - An empty statement commutes with any expression.
  - **Anything else is assumed not to commute**

Deciding Commutativity (此页不要求掌握)

- Rules for BINOP and MOVE rely on the interchanging the order of a lowered statement s and an expression e
  - This can be done safely when the statement cannot alter the value of the expression

- **Two conditions that s and e cannot be interchanged**
  1. The statement could **change** the value of **a temporary variable** used by the expression
  2. The statement could **change** the value of **a memory location** used by the expression.

Deciding Commutativity (此页不要求掌握)

How to check the above two conditions?

- **Temporaries**: It is easy to determine whether the statement updates a temporary used by the expression, because temporaries have unique names.
- **Memory**: It is much harder because two memory locations can be **aliases**!
  – The statement s uses a memory location MME(e1) as a destination
  – The expression reads from the memory location MEM(e2)
  – e1 might have the save value as e2!!

More precise (still conservative) approximation: use some **alias analyses**!

“Falcon: A Fused Approach to Path-sensitive Sparse Data Dependence Analysis,” PLDI 2024.

2. To Canonical Trees (Linerization)

- eliminate ESEQs
- **move CALLs to top level**
- eliminate SEQs

Moving Calls to Top Level

- How to implement CALL expression?
  - Assign the return value to a dedicated return-value register (to reduce memory traffic)
  - For example, eax/rax on x86/x86-64

- Consider BINOP(PLUS, CALL(...), CALL(...))
  - The second call will overwrite the RV register before the PLUS can be execute

像这样的式子，树结构逻辑上也没问题，但机器实现就出问题。因为函数的返回值都是用同一个寄存器（rax）来存的，连续运算两个，有一个就丢失了，然后再op就没法做。

Move CALLS to Top Level

- **Idea**: assign each return value immediately into a fresh temporary register:

```
CALL(fun, args) ->
    ESEQ(MOVE(TEMP t, CALL(fun, args)), TEMP t)
```

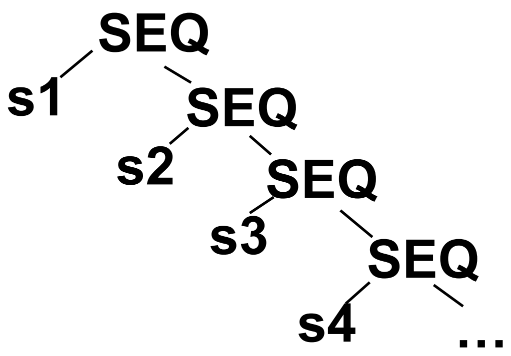
2. To Canonical Trees (Linerization)

- eliminate ESEQs
- move CALLs to top level
- **eliminate SEQs**

A Linear List of Statements

- After applying the above rules, we obtain

SEQ(SEQ(SEQ(..., sx), sy), sz)



- Next, we repeatedly apply the rule:

SEQ(SEQ(a, b), c) = SEQ(a, seq(b, c))

- And obtain a statement of the form

SEQ(s_1, SEQ(s_2, ..., SEQ(s_{n-1},s_n)...))

- We can just consider this to be a simple list of statements:

s_1, s_2, ..., s_{n-1}, s_n

(None of the s_i contain SEQ/ESEQ nodes)

3. Taming Conditional Branches

- **Basic Blocks**
- **Traces**

Taming Conditional Branches

- **Problem of CJUMP**: NO counterpart for two-way branch on most machines
- **Goal**: rearrange the trees so that CJUMP(cond, l_t, l_f) is immediately followed by LABEL(l_f)

```
CJUMP xxx α β
```

```
CJUMP xxx Label_alpha
β ...
Label_alpha:
α
```

- **Solution**: two-stages approach
  1. Form a list of canonical trees into basic blocks
  2. Order the basic blocks into traces

Solution

- We transform the tree in three stages:

1. ~~A tree is rewritten into a list of *canonical trees* without SEQ or ESEQ nodes~~
2. **This list is grouped into a set of basic blocks, which contain no internal jumps or labels**
3. The basic blocks are ordered into a set of traces in which every CJUMP is immediately followed by its false label.

Basic Blocks

$\mathsf{LABEL}(l)$
...
$\mathsf{CJUMP}(e,\ l_1,\ l_2)$

- A **basic block** is
  - A sequence of statements that is always entered at the beginning and exited at the end

- That is:
  1. The first statement is a LABEL
  2. The last statement is a JUMP or CJUMP
  3. There are no other LABELs, JUMPs, or CJUMPs I the block

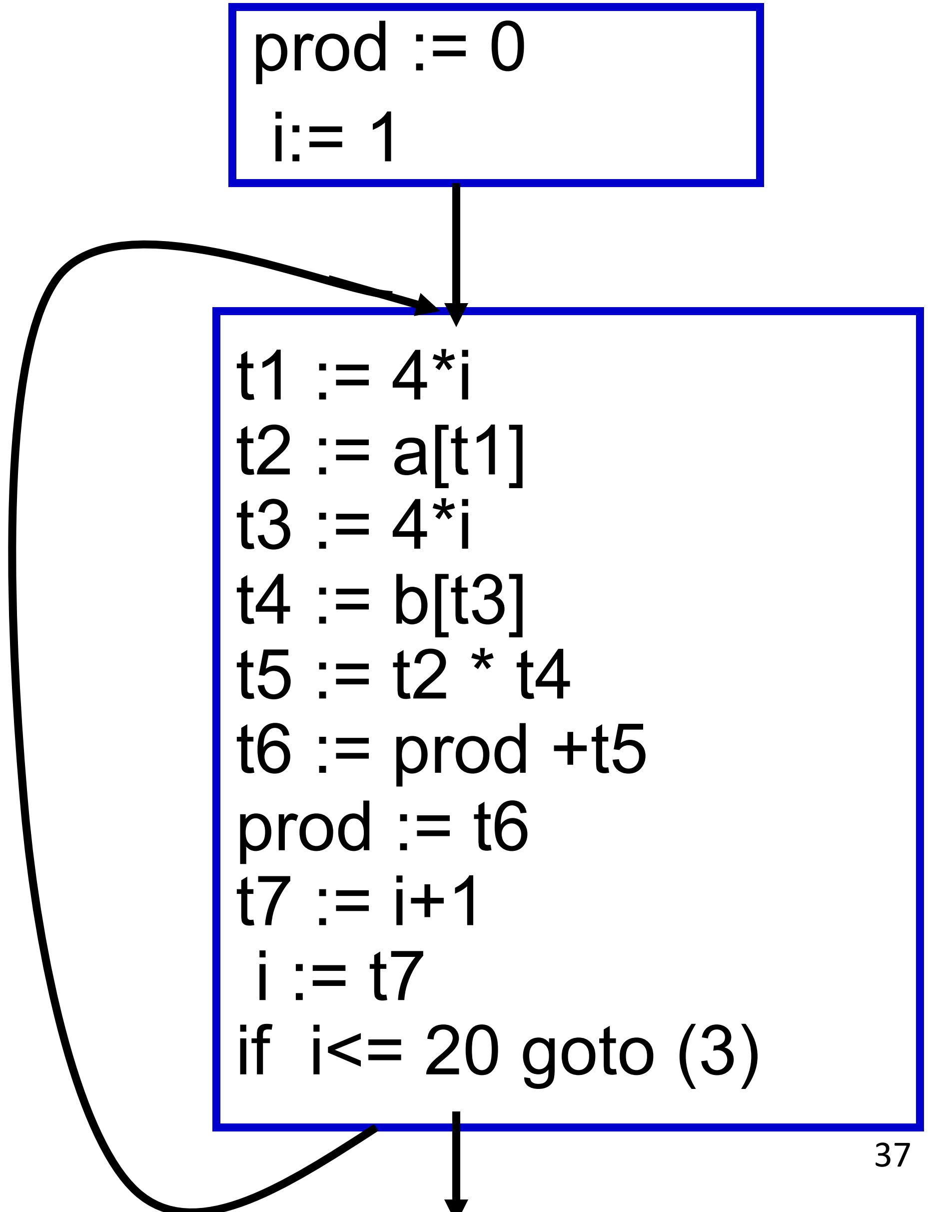
Algorithm for Basic Block Construction

Given sequence of intermediate code statements

1. Scan from beginning to end
2. When a label is found, start a new block (and end the previous block)
3. Whenever a cjump/jump is found the current block is ended (and the next block is started)
4. If this leaves a block ending without a cjump/jump, then append a jump to the next block
5. If a block has no label at the begining, invent one, and add it

Example: Basic Blocks

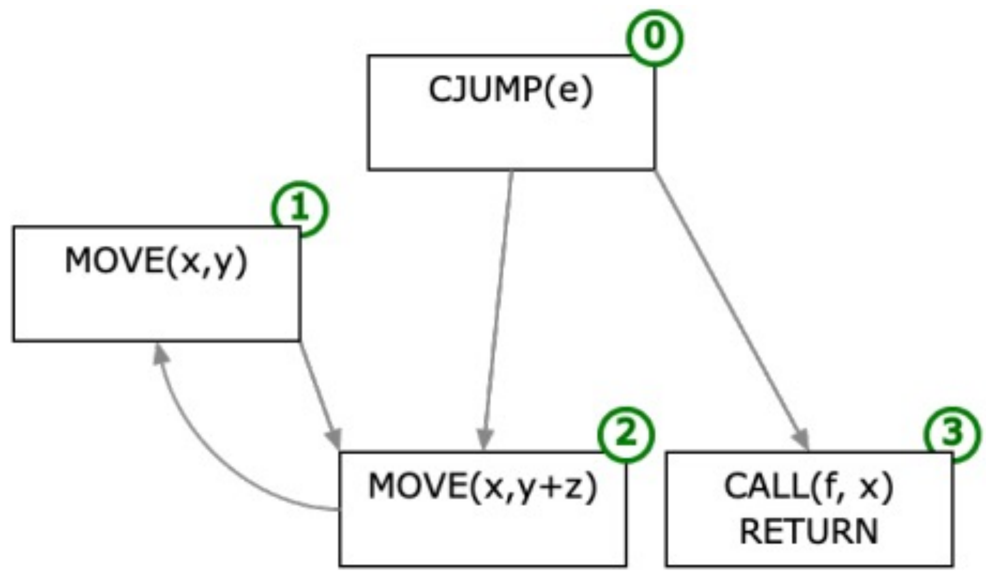
```
(1)  prod := 0
(2)  i:= 1
(3)  t1 := 4*i
(4)  t2 := a[t1]
(5)  t3 := 4*i
(6)  t4 := b[t3]
(7)  t5 := t2 * t4
(8)  t6 := prod +t5
(9)  prod := t6
(10) t7 := i+1
(11) i := t7
(12) if  i<= 20 goto (3)
```



Example: Basic Blocks

- Control flow graph (CFG): nodes are basic blocks and edges are jumps between them
  - In some contexts, the node of a CFG is a statement (to be discussed in the register allocation section)

L0:	CJUMP(e, L2, L3)
L1:	MOVE(x, y)
L2:	MOVE(x, y + z) JUMP(L1)
L3:	CALL(f, x) RETURN



3.Taming Conditional Branches

- Basic Blocks
- Traces

Solution

- How to eliminate these mismatches?
- We transform the tree in three stages:

1. ~~A tree is rewritten into a list of *canonical trees* without SEQ or ESEQ nodes~~
2. ~~This list is grouped into a set of basic blocks, which contain no internal jumps or labels~~
3. **The basic blocks are ordered into a set of traces, in which every CJUMP is immediately followed by its false label.**

Recap: Taming Conditional Branches

- **Issue of CJUMP**: NO counterpart for two-way branch on most machines
- **Problem Statement**: rearrange the trees so that CJUMP(cond, l_t, l_f) is immediately followed by LABEL(l_f)

```
CJUMP xxx α β
```

```
CJUMP xxx Label_alpha
β ...
Label_alpha:
α
```

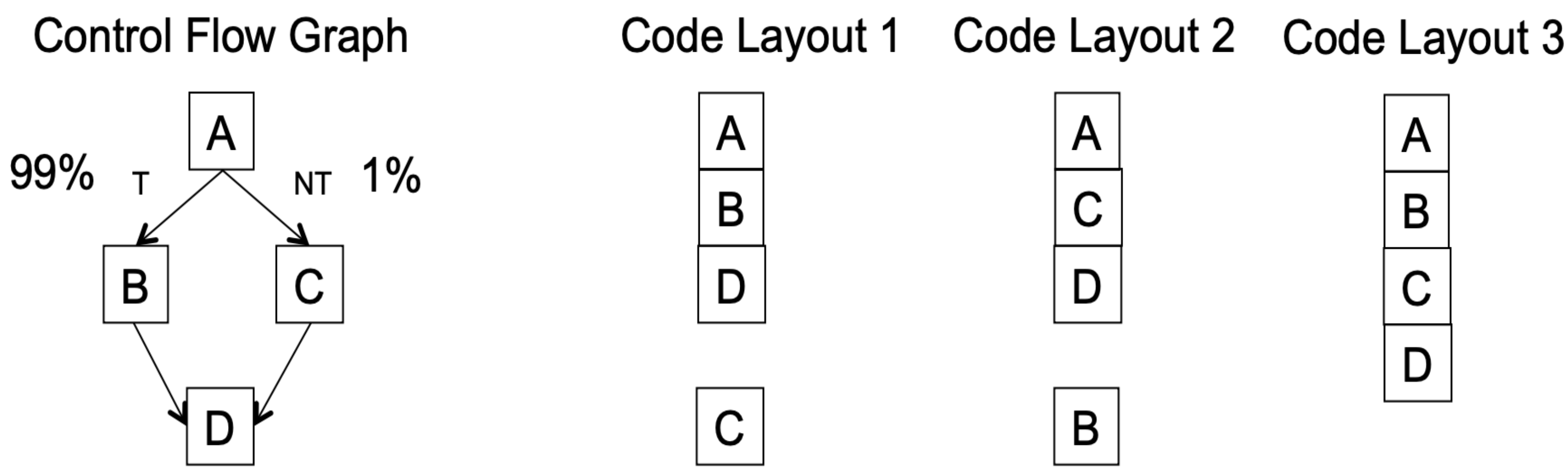
- **Solution**: two-stages approach
  1. Form a list of canonical trees into basic blocks
  2. **Reorder the basic blocks into traces**

Basic Block Reordering

- The basic blocks can be arranged in any order, and the result of executing the program will be the same
- Based on this property, we can optimize the ***nature*** and ***number*** of jumps:
  1. Choose an ordering of the blocks such that **each CJUMP is followed by its false label**
  2. Arrange that many of the unconditional JUMPs are immediately followed by their target label
     - Allow the **deletion of the unconditional jumps**, making the compiled program run a bit faster.
  3. (Other aspects: may also optimize instruction cache, etc.)

Example: Basic Block Reordering

- How to generate target code from CFG?
- The basic blocks can be arranged in any order, and the result of executing the program will be the same



- 90%, 10%: the execution frequency (from dynamic profiling)
- Code Layout 1 reduces fetch breaks, increases I-cache hit rate,…

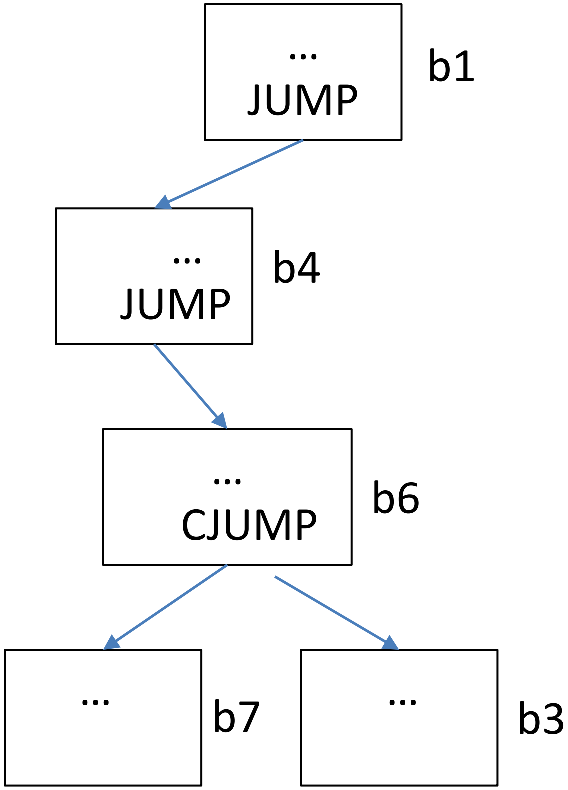
“Profile Guided Code Positioning,” PLDI 1990.

Traces for Basic Block Reording

- The usual technique for finding a good ordering of basic blocks is to construct traces
- **Trace:** A sequence of statements that could be consecutively executed during the execution
    - Alternatively, a sequence of basic blocks
- **A covering set of traces**
  - Each trace is loop free
  - Each block must be in exactly one trace

Basic Rule for Generating ONE Trace

- Suppose block $b1$ ends with a **JUMP** to $b4$, and $b4$ has a JUMP to $b6$. Then, we can make the trace ***b*1, *b*4, *b*6**.
- Suppose b6 ends with a conditional jump **CJUMP**(cond, b7, b3). We append b3 to our trace and continue with the rest of the trace after b3.
- The basic block b7 will be in some other trace.



Make sure that CJUMP(cond, l_t, l_f) is immediately followed by LABEL(l_f)!

Generating a Covering Set of Traces

Put all the blocks of the program into a **list Q**
While **Q** is not empty
    start a **new (empty) trace**, call it **T**
    remove the **head element** **b** from **Q**
    while **b** is not marked
        mark **b**; append **b** to the end of the current trace **T**;
        examine the **successors** of **b**
        if there is any unmarked successor c
            b $\leftarrow$ c
    end the current trace T

Algorithm 8.3 or Tiger Book

- Start with some block and follow a chain of jumps, marking each block and appending it to the **current trace**
- When coming to a block whose successors are all marked, the generation of **one trace is finished** → Pick an unmarked block to start the **next trace**

Generating a Covering Set of Traces

迭代式计算covering sets of traces

- **如何计算1个trace**
  - 从某个basic block开始，往后继节点遍历，标记每个被访问的basic block并将其附加到当前trace中
  - 当到达某basic block后继节点均已标记, 这个trace就算完了
- **如何计算新的trace**
  - 选择一个未标记的basic block作为下一个trace的起点
- **全局终止条件**
  - 不断迭代、直到所有的basic blocks都被标记了

Example: Generating a Covering Set of Traces

- **Basic algorithm**: depth-first traversal of the CFG
  - 从某个basic block开始，往后继节点遍历，标记每个被访问的basic block并将其附加到当前trace中
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Covering set of traces

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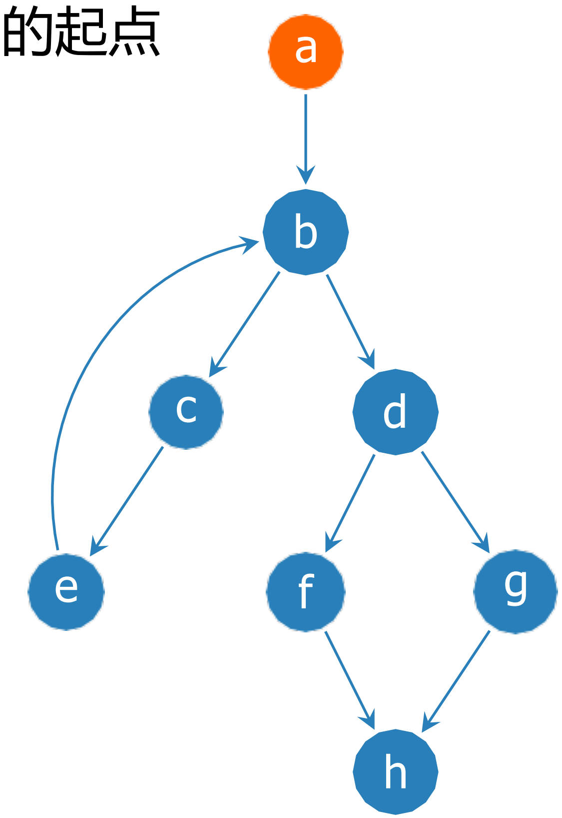

Example: Generating a Covering Set of Traces

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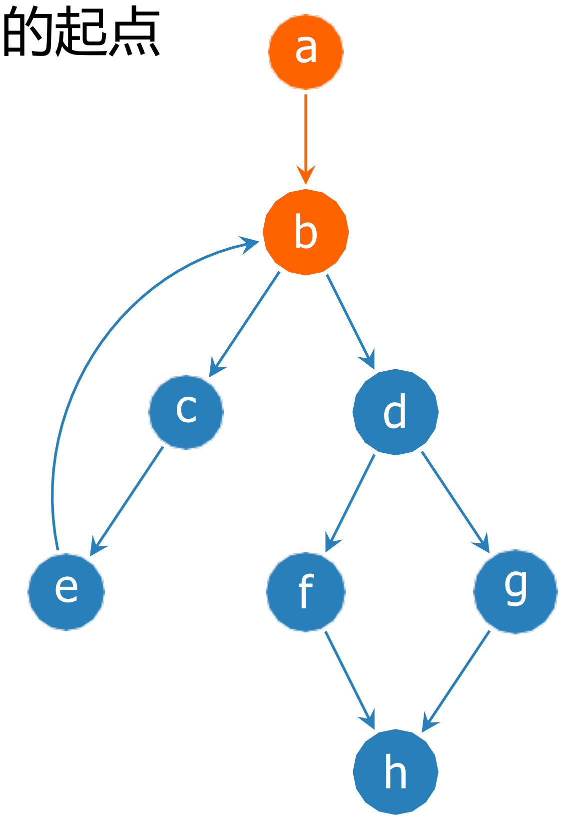

Covering set of traces

- ?

Example: Generating a Covering Set of Traces

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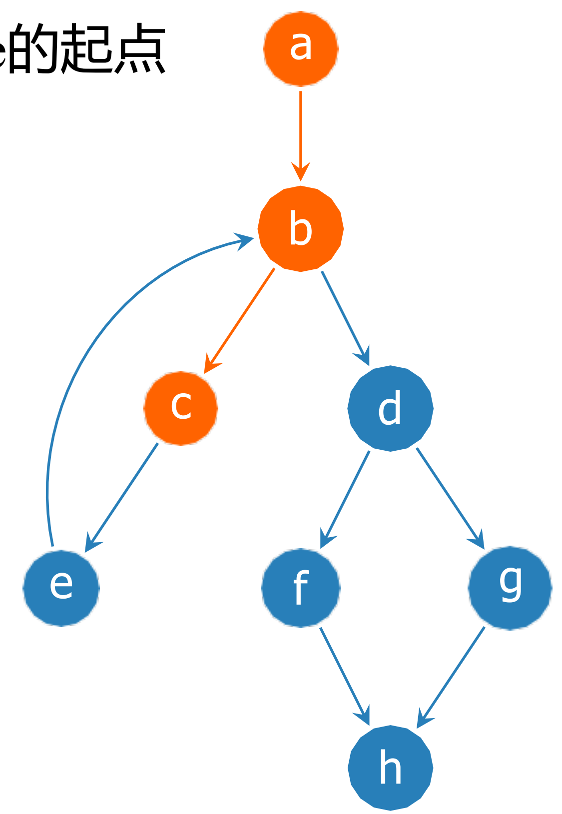

Covering set of traces

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Example: Generating a Covering Set of Traces

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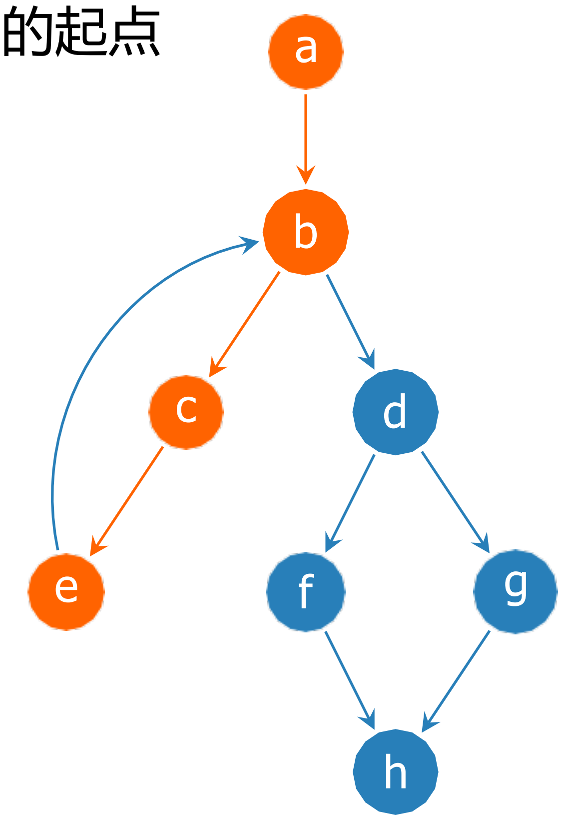

Covering set of traces
- ?

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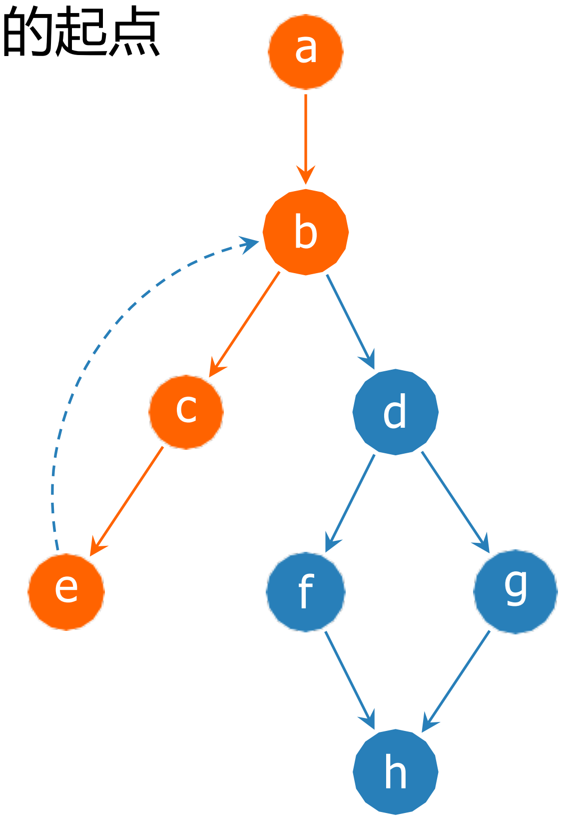

Covering set of traces

- {a, b, c, d}

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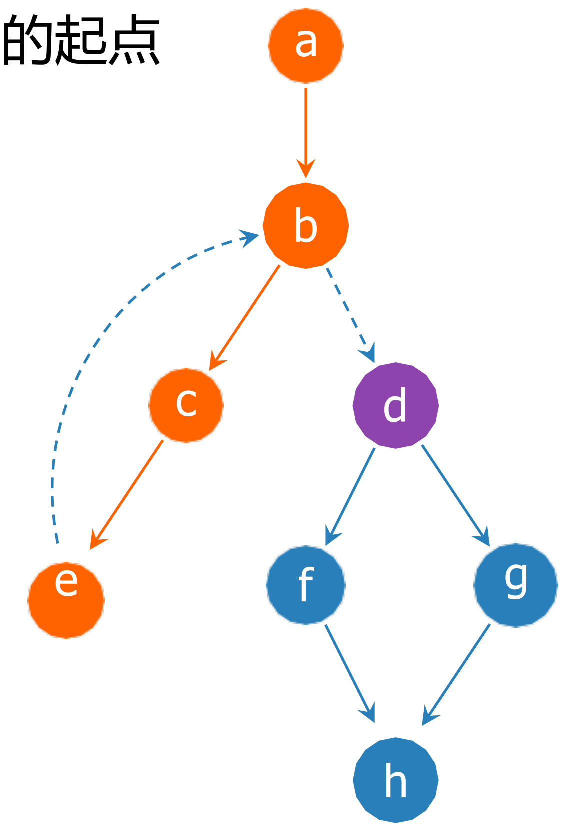

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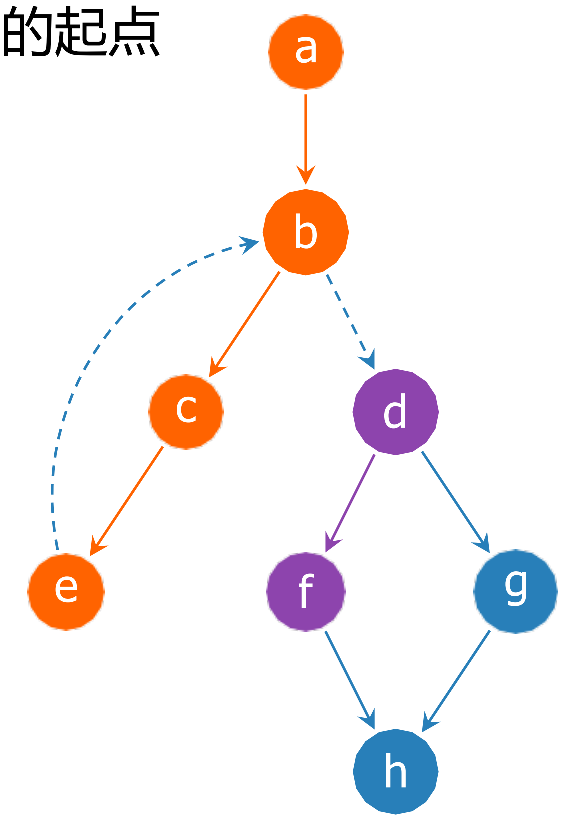

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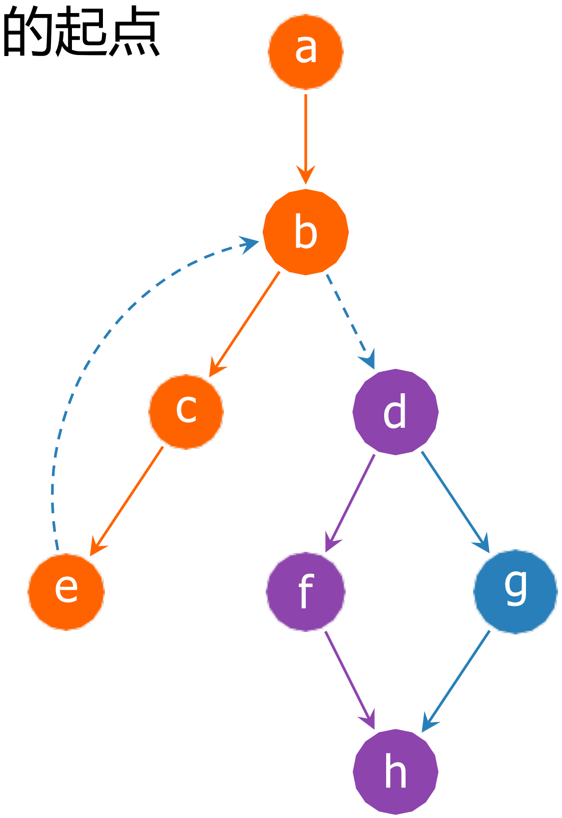

Covering set of traces

- {a, b, c, d}
- {d, f, h}

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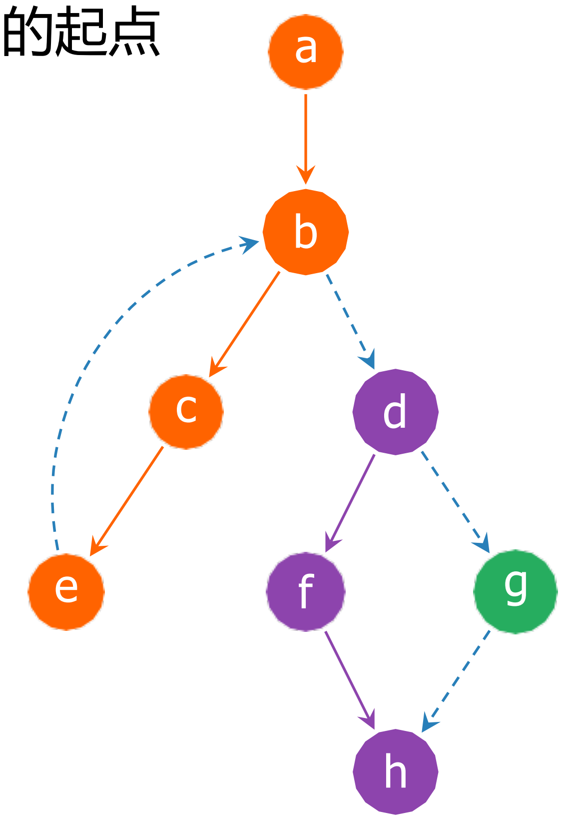
Covering set of traces

- {a, b, c, d}
- {d, f, h}
- {g}



Finishing Up (JUMP Consideration)

- We prefer CJUMP followed by its false label, since this translates to machine code conditional jump
  - **For any CJUMP followed by its true label**
    - Switch the true and false labels and negate the condition.
  - **For any CJUMP immediately followed by its false label**
    - We let alone (there will be many of these).
  - **For any CJUMP(cond, a, b, lt, lf) followed by neither label, replace with**

CJUMP(*cond, a, b, lt, lf '*)
LABEL *lf '*
JUMP(NAME *lf*)

- Remove all JUMPS followed by their targe LABLES (remove unconditional jumps)

Optimal Traces

- "Optimality" needs criteria

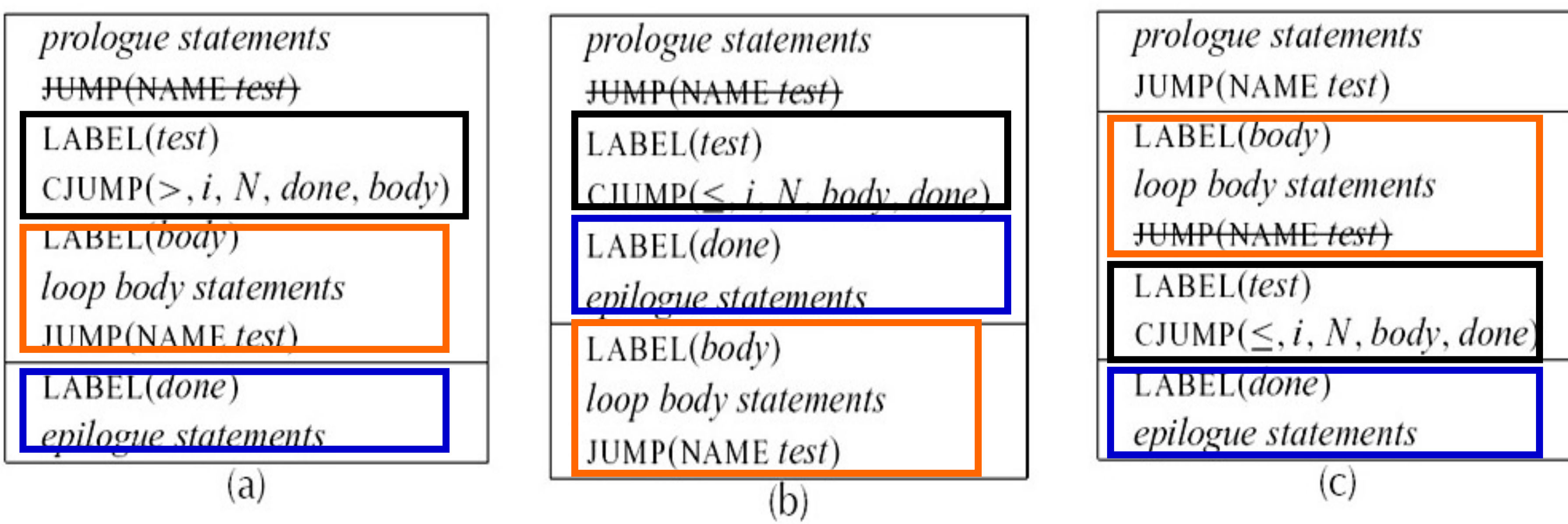
- E.g., any frequently executed sequence of instructions (such as the body of a loop) should occupy its own trace.
  - This helps to reduce the number of unconditional jumps
  - This helps with other kinds of optimizations.
    - register allocation
    - instruction scheduling
    - …

Example: Optimal Traces

(a): While循环的每个迭代有一个CJUMP和一个JUMP

(b): 使用了不同traces, 但每个迭代仍有一个CJUMP和一个JUMP

(c): 每个迭代都没有JUMP



Summary

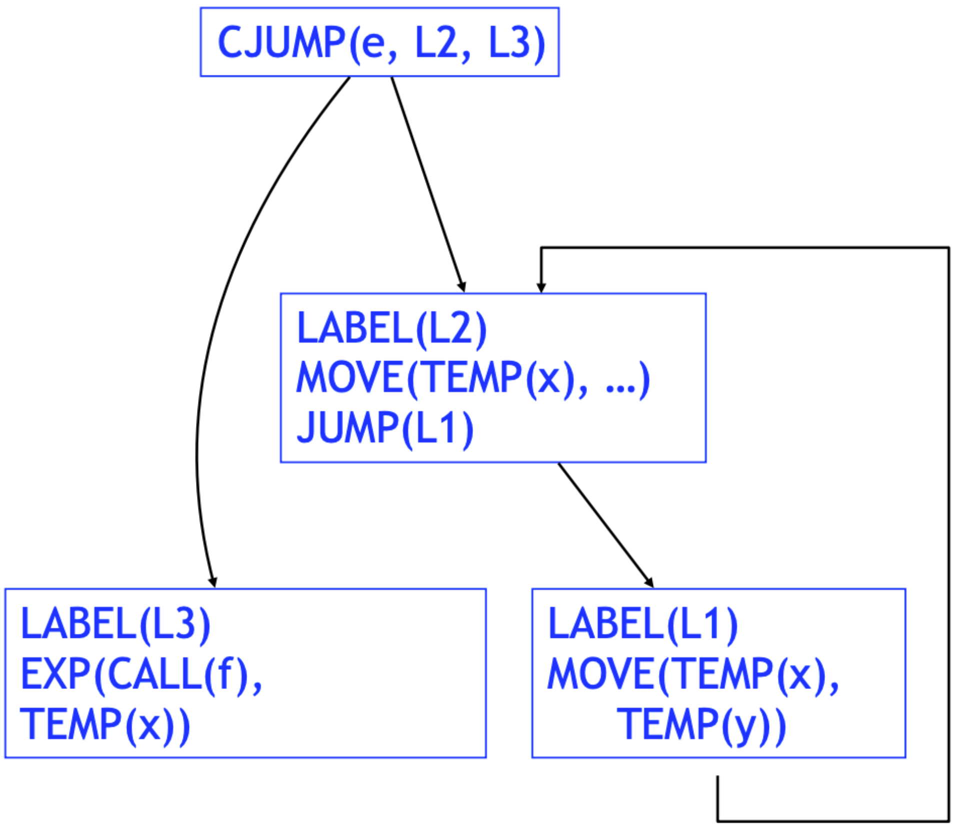
- **Problem**: mismatches between tree code and machine instructions:
  - 1. CJUMP to two labels; machine conditionals fall through on false
  - 2. ESEQ and CALL order evaluation of subtrees matters (side-effects)
  - 3. CALL as argument to another CALL causes interference between register arguments
- **Idea**: rewrite to equivalent trees without these cases
  - SEQ can only be subtree of another SEQ
  - SEQs clustered at top of tree
  - might as well turn into simple linear list of statements
- **Approach**: 3-stage transformation:
  - To linear list of canonical trees without SEQ/ESEQ
  - To basic blocks with no internal jumps or labels
  - To traces with every CJUMP immediately followed by false target

Overview of IR → Machine Code

- **Step #1** : Transform the IR trees into **a list of canonical trees**
  - a. eliminate SEQ and ESEQ nodes
  - b. the arguments of a CALL node should never be other CALL nodes
- **Step #2** : Rearrange the **canonical trees** (into **traces**) so that every CJUMP(cond,lt,lf) is immediately followed by LABEL(lf)
- **Step #3** : **Instruction Selection** --- generate the pseudo-assembly code from the canonical trees in the step #2
- **Step #4** : Perform **register allocations** on pseudo-assembly code

Thank you all for your attention

Example: Reordered Code



CJUMP(e, L2, [L3])
JUMP(L3)

LABEL(L2)
MOVE(TEMP(x), TEMP(y) +
TEMP(z))
~~JUMP(L1)~~

LABEL(L1)
MOVE(TEMP(x), TEMP(y)
JUMP(L2)

LABEL(L3)
EXP(CALL(NAME(f)), TEMP(x))

Rules for Canonical Trees Construction

ESEQ(s1, ESEQ(s2, e))	⇒	ESEQ(SEQ(s1,s2), e))
BINOP(op, ESEQ(S, e1,), e2)	⇒	ESEQ(s, BINOP(op, e1, e2))
MEM(ESEQ(s,e1))	⇒	ESEQ(s, MEM(e1))
JUMP(ESEQ(s, e1))	⇒	SEQ(s, JUMP(e1))
CJUMP(op, ESEQ(s, e1), e2, l1,l2)	⇒	SEQ(s, CJUMP(op, e1, e2, l1,l2))
BINOP(op, e1, ESEQ(s, e2))	⇒	ESEQ(MOVE(TEMP t, e1), ESEQ(s, BINOP(op, TEMP t, e2)))
CJUMP(op, e1, ESEQ(s, e2), l1, l2)	⇒	SEQ(MOVE(TEMP t, e1), SEQ(s, CJUMP(op, TEMP t, e2, l1,l2)))
MOVE(ESEQ(s, e1), e2)		SEQ(s, MOVE(e1, e2))
CALL(f , a)		ESEQ(MOVE(TEMP t, CALL(f , a)), TEMP(t))

ESEQ

- 简单说就是把ESEQ往上提，考虑ESEQ(s, e)，移动s和e表达式的时候，只要s在e前面执行，并且最后返回值是e，ESEQ的语义就保留了。
- 但问题是，移动之后，s和e之间就有了其他的表达式，这些表达式的计算如果和s有关系，那么也会被s的副作用影响，而这是不对的。
- 我们并不总是能在编译阶段判断两个表达式之间是否有影响，这意思是说，像CONST的语句，肯定无影响，但MEM就无法判断是否是同一个数据，
- 所以，对于无影响的，我们就能比较简单的交换顺序，有影响的，我们可以通过多做一次MOVE来消除影响

BINOP(op, e1, ESEQ(s, e2))=>ESEQ(MOVE(TEMP t, e1), ESEQ(s, BINOP(op, TEMP t, e2)));

也就是说，用中间变量保存可能受影响的变量