CS3300 - Compiler Design

Basic Blocks and CFG

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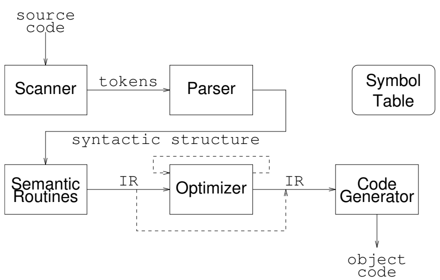
Challenges in the back end

- The input to the backend (What?).
- The target program – instruction set, constraints, relocatable or not (adv/disadv?), machine code or assembly?
- Instruction selection (undecidable): maps groups of IR instructions to one or more machine instructions. Why not say each IR instruction maps to one more more machine level instructions?
  - Easy, if we don't care about the efficiency.
  - Choices may be involved (add / inc); may involve understanding of the context in which the instruction appears.
- Register Allocation (NP-complete): Intermediate code has temporaries. Need to translate them to registers (fastest storage).
  - Finite number of registers.
  - If cannot allocate on registers, store in the memory – will be expensive.
  - Sub problems: Register allocation, register assignment, spill location, coalescing. All NP-complete.
- Evaluation order: Order of evaluation of instructions may impact the code efficiency (e.g., distance between load and use).

Compiler analysis



- Code optimization requires that the compiler has a global "understanding" of how programs use the available resources.
- It has to understand how the control flows (control-flow analysis) in the program and how the data is manipulated (data-flow analysis)
- Control-flow analysis: flow of control within each procedure.
- Data-flow analysis: understanding how the data is manipulated in the program.

Basic blocks

A graph representation of intermediate code.

Basic block properties

- The flow of control can only enter the basic block through the first instruction in the block.
- No jumps into the middle of the block.
- Control leaves the block without halting / branching (except may be the last instruction of the block).

The basic blocks become the nodes of a flow graph, whose edges indicate which blocks can follow which other blocks.

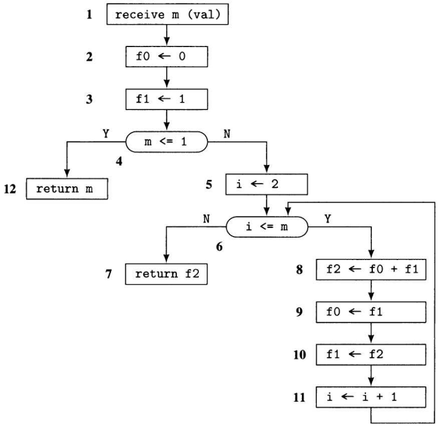
Example

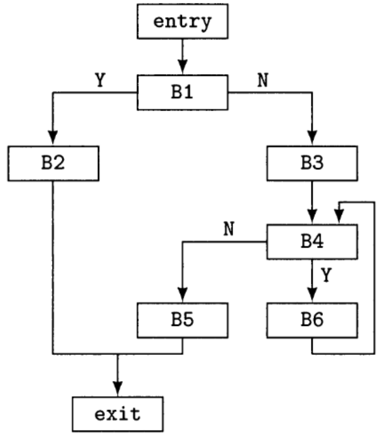
```
unsigned int fib(m)
   unsigned int m;
{  unsigned int f0 = 0, f1 = 1, f2, i;
   if (m <= 1) {
      return m;
   }
   else {
      for (i = 2; i <= m; i++) {
         f2 = f0 + f1;
         f0 = f1;
         f1 = f2;
      }
      return f2;
   }
}
```

```
1        receive m (val)
2        f0 ← 0
3        f1 ← 1
4        if m <= 1 goto L3
5        i ← 2
6    L1: if i <= m goto L2
7        return f2
8    L2: f2 ← f0 + f1
9        f0 ← f1
10       f1 ← f2
11       i ← i + 1
12       goto L1
13   L3: return m
```

- `receive` specifies the reception of a parameter. Why do we want to have an explicit receive instruction?To specify the parameter name and the parameter-passing discipline (by-value, by-result, value-result, reference); also gives a definition point.unknown and undefined
- What is the control structure? Obvious?

Example - flow chart and control-flow





- The high-level abstractions might be lost in the IR.
- Control-flow analysis can expose control structures not obvious in the high level code. Possible?Loops constructed from `if` and `goto`

Deep dive - Basic block

Basic block definition

- A basic block is a maximal sequence of instructions that can be entered only at the first of them
- The basic block can be exited only from the last of the instructions of the basic block.
- Implication:First instruction can be a) first instruction of a routine,b) target of a branch, c) instruction following a branch or a return.
- First instruction is called the leader of the BB.

How to construct the basic block?

- Identify all the leaders in the program.
- For each leader: include in its basic block all the instructions from the leader to the next leader (next leader not included) or the end of the routine, in sequence.

What about function calls?

- In most cases it is not considered as a branch+return. Why?
- Problem with setjmp() and longjmp()? [self-study]

Example 2

```
for i=1 ... 10 do
   for j=1 ... 10 do
      a[i,j] = 0.0;

for i=1 ... 10 do
      a[i,i] = 1.0;
```

```
1)  i = 1
2)  j = 1
3)  t1 = 10 * i
4)  t2 = t1 + j
5)  t3 = 8 * t2
6)  t4 = t3 - 88
7)  a[t4] = 0.0
8)  j = j + 1
9)  if j <= 10 goto (3)
10) i = i + 1
11) if i <= 10 goto (2)
12) i = 1
13) t5 = i - 1
14) t6 = 88 * t5
15) a[t6] = 1.0
16) i = i + 1
17) if i <= 10 goto (13)
```

Next use information

- Goal: when the value of a variable will be <u>used</u> next.

```
L1: x = ...
...
L2: y = x
```

  Statement `L2` uses the value of `x` computed (<u>defined</u>) at `L1`.

  We also say `x` is live at `L2`.
- For each three-address statement $x = y + z$, what is the next use of x, y, and z?

Compute next-use information

- We want to compute next use information within a basic block.
- Many uses : For example: knowing that a variable (assigned a register) is not used any further, helps reassign the register to some other variable. Any other?

Algorithm to compute next use information

Input: A basic block B of three-address statements. We assume that the symbol table initially shows all non-temporary variables in B as being live on exit.
Output: At each statement `L : x = y op z` in B, we attach to L the liveness and next-use information of `x, y,` and `z`.
begin
  List lst = Starting at last statement in B and list of instructions obtained by scan backwards to the beginning of B;
  foreach <u>statement `L: x = y op z` $\in lst$</u> **do**
    Attach to statement `L` the information currently found in the symbol table regarding the next use and liveness of `x, y`, and `z`;
    In the symbol table, set `x` to "not live" and "no next use.";
    In the symbol table, set `y` and `z` to "live" and the next uses of `y` and `z` to `L` ;
  end
end
Q: Can we interchange last two steps?

CFG - Control flow graph

Definition:

- A rooted directed graph $G = (N, E)$, where N is given by the set of basic blocks + two special BBs: `entry` and `exit`.
- And edge connects two basic blocks b_1 and b_2 if control can pass from b_1 to b_2.
- An edge(s) from `entry` node to the initial basic block(s?)
- From each final basic blocks (with no successors) to `exit` BB.

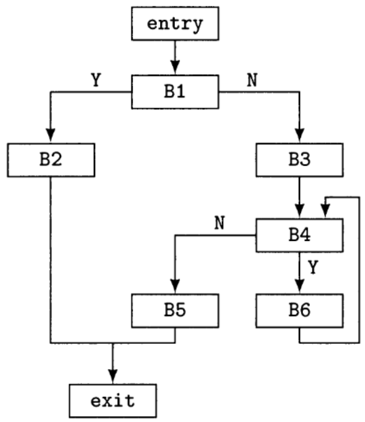
CFG continued

- successor and predecessor – defined in a natural way.
- A basic block is called branch node - if it has more than one successor.
- join node – has more than one predecessor.
- For each basic block b:

$$Succ(b) = \{n \in N | \exists e \in E \text{ such that } e = b \to n\}$$
$$Pred(b) = \{n \in N | \exists e \in E \text{ such that } e = n \to b\}$$

- A region is a strongly connected subgraph of a flow-graph.

Basic blocks - what do we get?



- entry and exit are added for reasons to be explained later.
- We can identify loops by using dominators
  - a node A in the flowgraph dominates a node B if every path from entry node to B includes A.
  - This relations is antisymmetric, reflexive, and transitive.
- back edge: An edge in the flow graph, whose head dominates its tail (example - edge from B6 to B4.
- A loop consists of all nodes dominated by its entry node (head of the back edge) and having exactly one back edge in it.

Dominators and Postdominators

- Goal: To determine loops in the flowgraph.

Dominance relation:

- Node d dominates node i (written $d\ dom\ i$), if every possible execution path from entry to i includes d.
- This relations is antisymmetric ($a\ dom\ b$, $b\ dom\ a \Rightarrow a = b$), reflexive ($a\ dom\ a$), and transitive (if $a\ dom\ b$ and $b\ dom\ c$, then $a\ dom\ c$.
- We write $dom(a)$ to denote the dominators of a.

Immediate dominance:

- A subrelation of dominance.
- For $a \neq_\beta$, we say $a\ idom\ b$ iff $a\ dom\ b$ and there does not exist a node c such that $c \neq a$ and $c \neq b$, for which $a\ dom\ c$ and $c\ dom\ b$.
- We write $idom(a)$ to denote the immediate dominator of a – note it is unique.

Strict dominance:

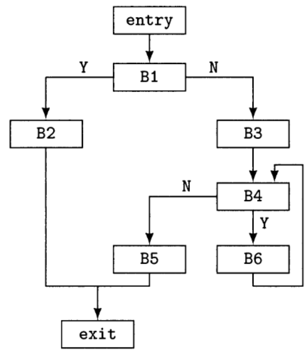
- $d\ sdom\ i$, if d dominates i and $d \neq i$.

Post dominance:

- $p\ pdom\ i$, if every possible execution path from i to exit includes p.
- Opposite of dominance ($i\ domp$), in the reversed CFG (edges reversed, entry and exit exchanged).

Computing all the dominators

```
procedure Dom_Comp(N,Pred,r) returns Node ⟶ set of Node
   N: in set of Node
   Pred: in Node ⟶ set of Node
   r: in Node
begin
   D, T: set of Node
   n, p: Node
   change := true: boolean
   Domin: Node ⟶ set of Node
   Domin(r) := {r}
   for each n ∈ N - {r} do
      Domin(n) := N
   od
   repeat
      change := false
*     for each n ∈ N - {r} do
         T := N
         for each p ∈ Pred(n) do
            T ∩= Domin(p)
         od
         D := {n} ∪ T
         if D ≠ Domin(n) then
            change := true
            Domin(n) := D
         fi
      od
   until !change
   return Domin
end   || Dom_Comp
```

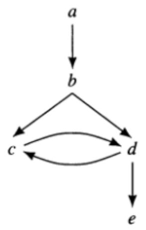


Compute the dominators.

i	Domin(i)
entry	{entry}
B1	{entry,B1}
B2	{entry,B1,B2}
B3	{entry,B1,B3}
B4	{entry,B1,B3,B4}
B5	{entry,B1,B3,B4,B5}
B6	{entry,B1,B3,B4,B6}
exit	{entry,B1,exit}

Identifying loops

- Back edge: an edge in the flowgraph, whose head dominates its tail.(Counter example)



Has a loop, but no back edge – hence not a natural loop.

- Given a back edge $m \to n$, the natural loop of $m \to n$ is
  1. the subgraph consisting of the set of nodes containing n and all the nodes from which m can be reached in the flowgraph without passing through n, and
  2. the edge set connecting all the nodes in its node set.
  3. Node n is called the loop header.

Algorithm to compute natural loops

```
procedure Nat_Loop(m,n,Pred) returns set of Node
   m, n: in Node
   Pred: in Node ⟶ set of Node
begin
   Loop: set of Node
   Stack: sequence of Node
   p, q: Node
   Stack := []
   Loop := {m,n}
   if m ≠ n then
      Stack ⊕= [m]
   fi
   while Stack ≠ [] do
      || add predecessors of m that are not predecessors of n
      || to the set of nodes in the loop; since n dominates m,
      || this only adds nodes in the loop
      p := Stack↓-1
      Stack ⊖= -1
      for each q ∈ Pred(p) do
         if q ∉ Loop then
            Loop ∪= {q}
            Stack ⊕= [q]
         fi
      od
   od
   return Loop
end   || Nat_Loop
```


Approaches to Control flow Analysis

Two main approaches to control-flow analysis of single routines.

- Both start by determining the basic blocks that make up the routine.
- Construct the control-flowgraph.

First approach:

- Use dominators to discover loops; to be used in later optimizations.
- Sufficient for many optimizations (ones that do iterative data-flow analysis, or ones that work on individual loops only).

Second approach (interval analysis):

- Analyzes the overall structure of the routine.
- Decomposes the routine into nested regions - called intervals.
- The resulting nesting structure is called a control tree.
- A sophisticated variety of interval analysis is called structural analysis.