COS320: Compiling Techniques

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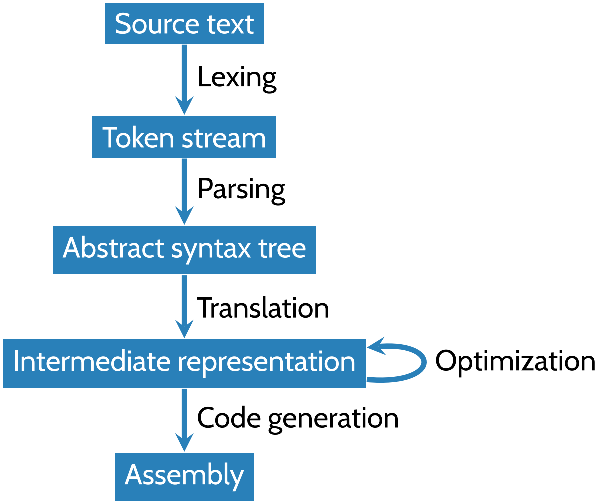
February 8, 2024

- Reminder: HW1 due **Monday** Feb 12
- Bonus OCaml office hours 4pm Friday Feb 9, in CS 003

Compiler phases (simplified)



Source text

Lexing

Token stream

Parsing

Abstract syntax tree

Translation

Intermediate representation

Optimization

Code generation

Assembly

Last time: let-based IR

Each instruction has at most three operands (“three-address code”)

```
  <instr> :=let <uid> = <operand> <op> <operand>;      Instructions
          | load <uid> = <var>;
          | store <var> = <operand>;
          | return <operand>;
<operand> :=<uid> | <integer>                          Operands
     <op> :=+ | *                                      Operations
```

Control Flow

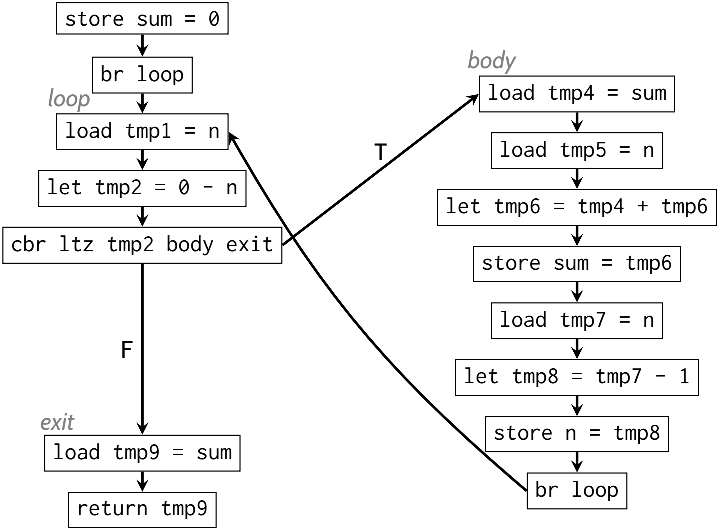
Concrete syntax

```
      <instr> :=let <uid> = <operand> <op> <operand>;              Instructions
                | load <uid> = <var>;
                | store <var> = <operand>;
    <operand> :=<uid> | <integer>                                  Operands
         <op> :=+ | *                                              Operations

 <terminator> ::=br <label>                                        Branch
                | cbr <cc> <operand> <label> <label>    Conditional branch
                | return <operand>                                 Return
         <cc> ::=EqZ | LeZ | LtZ
      <block> ::=<instr><block> | <terminator>
    <program> ::=<program><label>: <block> | <block>
```

Control Flow Graphs (CFG)

```
int sum_upto(int n) {
  int sum = 0;
  while (n > 0) {
    sum += n;
    n--;
  }
  return sum;
}
```



```
store sum = 0
br loop
```

loop

```
load tmp1 = n
let tmp2 = 0 - n
cbr ltz tmp2 body exit
```

body

```
load tmp4 = sum
load tmp5 = n
let tmp6 = tmp4 + tmp6
store sum = tmp6
load tmp7 = n
let tmp8 = tmp7 - 1
store n = tmp8
br loop
```

exit

```
load tmp9 = sum
return tmp9
```

Control Flow Graphs (CFG)

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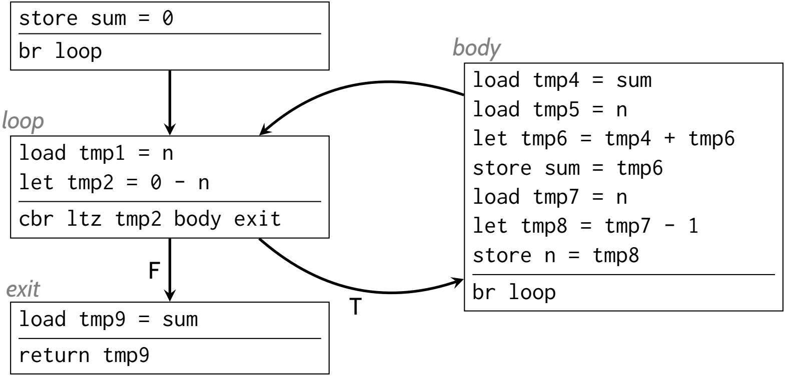
   int sum = 0;
   while (n > 0) {
      sum += n;
      n--;
   }
   return sum;
}
```



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load tmp4 = sum
load tmp5 = n
let tmp6 = tmp4 + tmp6
store sum = tmp6
load tmp7 = n
let tmp8 = tmp7 - 1
store n = tmp8
-------------
br loop
```

exit

```
load tmp9 = sum
-------------
return tmp9
```

- Control flow graphs are a graphical representation of the control flow through a procedure
- A *basic block* is a sequence of instructions that
  1. Starts with an *entry*, which is named by a label
  2. Ends with a control-flow instruction (`br`, `cbr`, or `return`)
     - the *terminator* of the basic block
  3. Contains no interior labels or control flow instructions
- A *control flow graph* (CFG) for a procedure P is a directed, rooted graph where
  - The nodes are basic blocks of P
  - There is an edge $BB_i \to BB_j$ iff BB_j may execute immediately after BB_i
  - There is a distinguished entry block where the execution of the procedure begins, which has no incoming edges

- CFG models all program executions
  - Every execution corresponds to a path in the CFG, starting at entry
    - Path = sequence of basic blocks $B_1, \ldots, B_n$ such that for each i, there is an edge from B_i to B_{i+1}
    - *Simple* path = path without repeated basic blocks
  - (But not vice-versa!)

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  - (But not vice-versa!)
- Graph structure used extensively in optimization (data flow analysis, loop recognition, ...)
- Simple application: dead code elimination
  1. Depth-first traversal of the CFG
  2. Any *unvisited node* is removed

Why basic blocks?

- Control flow graphs may be defined at the instruction-level rather than basic-block level
- However, there are good reasons for using basic blocks
  - More compact
  - Some optimization passes (“local” optimizations) operate @ basic block level
    - E.g., the implementation of redundant load elimination in `let3.ml`

Constructing a CFG

- “Forwards“ algorithm:
  - Traverse statements in IR from top to bottom
    - Find *leaders*: first statement & first statement following a label
    - Basic block = leader up to (but not including) next leader
- Alternately, traverse IR from bottom to top, starting a new basic blocks for each terminator and finishing at label (`build_cfg` in `let3.ml`)
  - (Assumes every label has a corresponding terminator. Does not assume every terminator has a corresponding label–implicitly eliminated dead code)
- Can also construct CFG directly from AST

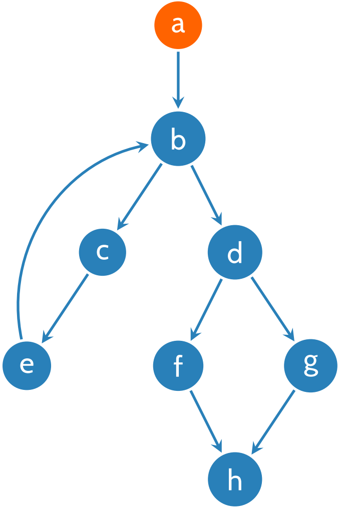
Generating code from a CFG

- Simple strategy: terminator always compiles to return / jump / conditional jump
    - "Fall-through" semantics of assembly blocks is never used

Generating code from a CFG

- Simple strategy: terminator always compiles to return / jump / conditional jump
  - "Fall-through" semantics of assembly blocks is never used
- More efficient strategy: elide jumps by ordering blocks appropriately
  - A *covering set of traces* is a set of traces such that
    - Each trace is a simple path (loop free)
    - Each basic block belongs to a trace
  - Any covering set of traces corresponds to a (partial) ordering of blocks, which may elide *some* jumps.

Generating a covering set of traces



Basic algorithm: depth-first traversal of the CFG

- If at least one successor is *unvisited*, elide jump and place the successor next in sequence
- If all successors are visited, terminate branch

(see `codegen_cfg_trace` in `let3.ml`)

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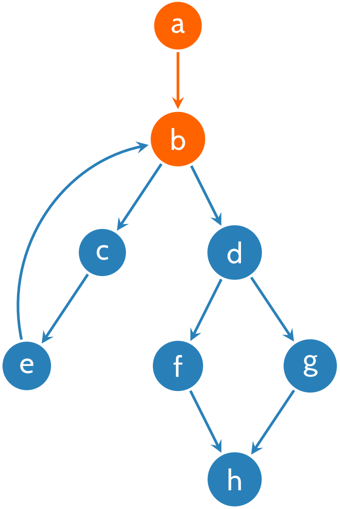

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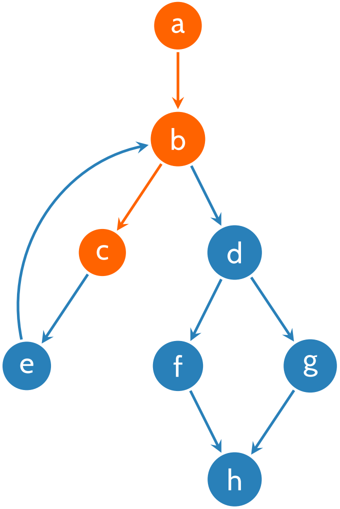

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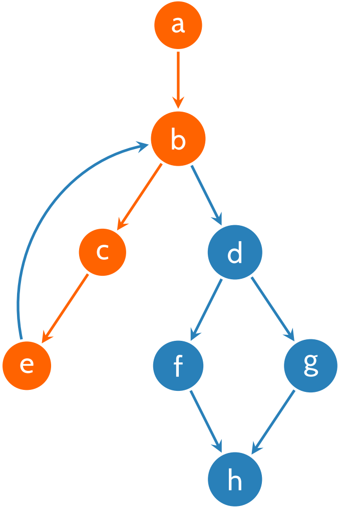

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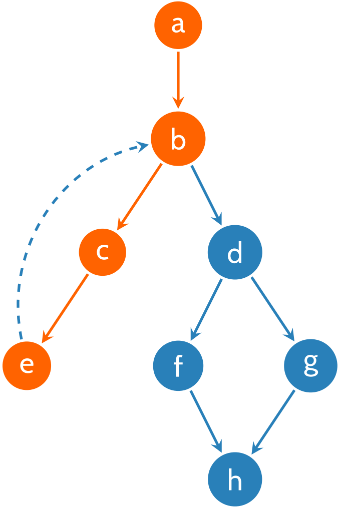

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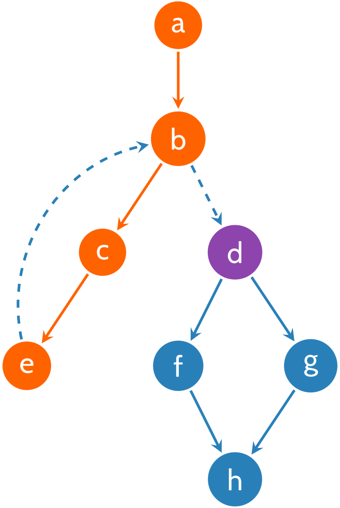

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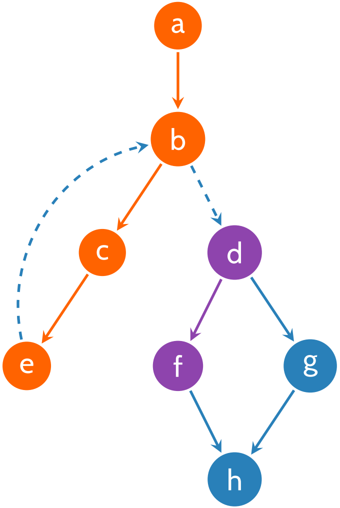

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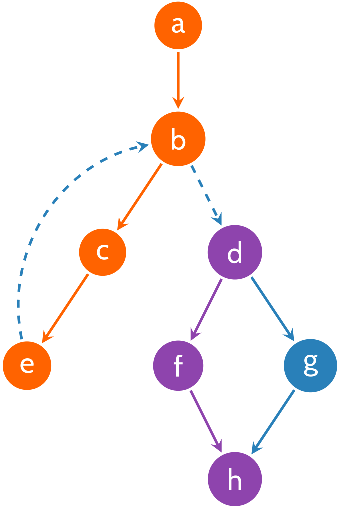

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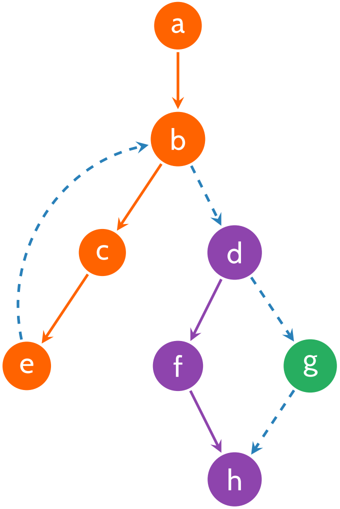

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