Control Flow Graphs

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Optimizations

- Code transformations to improve program
  - Mainly: improve execution time
  - Also: reduce program size
- Can be done at high level or low level
  - E.g., constant folding
- Optimizations must be safe
  - Execution of transformed code must yield same results as the original code for all possible executions

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Optimization Safety

- Safety of code transformations usually requires certain information that may not be explicit in the code
- Example: dead code elimination

  (1) x = y + 1;
  (2) y = 2 * z;
  (3) x = y + z;
  (4) z = 1;
  (5) z = x;

- What statements are dead and can be removed?

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Optimization Safety

- Safety of code transformations usually requires certain information which may not explicit in the code
- Example: dead code elimination

  (1) x = y + 1;
  (2) y = 2 * z;
  (3) x = y + z;
  (4) z = 1;
  (5) z = x;

- Need to know whether values assigned to x at (1) is never used later (i.e., x is dead at statement (1))
  - Obvious for this simple example (with no control flow)
  - Not obvious for complex flow of control

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Dead Variable Example

- Add control flow to example:

```
x = y + 1;
y = 2 * z;
if (d)  x = y+z;
z = 1;
z = x;
```

- Is ‘x = y+1’ dead code? Is ‘z = 1’ dead code?

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Dead Variable Example

- Add control flow to example:

```
x = y + 1;
y = 2 * z;
if (d)  x = y+z;
z = 1;
z = x;
```

- Statement x = y+1 is not dead code!
- On some executions, value is used later

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Dead Variable Example

- Add more control flow:

```
while (c) {
        x = y + 1;
        y = 2 * z;
        if (d)  x = y+z;
        z = 1;
}
z = x;
```

- Is ‘x = y+1’ dead code? Is ‘z = 1’ dead code?

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Dead Variable Example

- Add more control flow:

```
while (c) {
        x = y + 1;
        y = 2 * z;
        if (d)  x = y+z;
        z = 1;
}
z = x;
```

- Statement ‘x = y+1’ not dead (as before)
- Statement ‘z = 1’ not dead either!
- On some executions, value from ‘z=1’ is used later

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Low-level Code

- Harder to eliminate dead code in low-level code:

```
label L1
fjump c L2
x = y + 1;
y = 2 * z;
fjump d L3
x = y+z;
label L3
z = 1;
jump L1
label L2
z = x;
```

Are these statements dead?

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Low-level Code

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fjump c L2
x = y + 1;
y = 2 * z;
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x = y+z;
label L3
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jump L1
label L2
z = x;
```

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Optimizations and Control Flow

- Application of optimizations requires information
  - Dead code elimination: need to know if variables are dead when assigned values
- Required information:
  - Not explicit in the program
  - Must compute it statically (at compile-time)
  - Must characterize <u>all</u> dynamic (run-time) executions
- Control flow makes it hard to extract information
  - Branches and loops in the program
  - Different executions = different branches taken, different number of loop iterations executed

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Control Flow Graphs

- Control Flow Graph (CFG) = graph representation of computation and control flow in the program
  - framework for static analysis of program control-flow
- Nodes are basic blocks = straight-line, single-entry code, no branching except at end of sequence
- Edges represent possible flow of control from the end of one block to the beginning of the other
  - There may be multiple incoming/outgoing edges for each block

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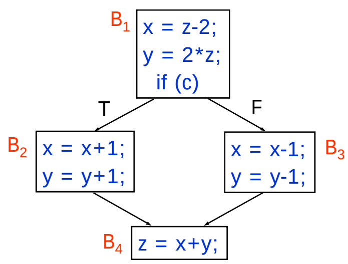
CFG Example

Program

```
x = z-2 ;
y = 2*z;
if (c)  {
    x = x+1;
    y = y+1;
}
else {
    x = x-1;
    y = y-1;
}
z = x+y;
```

Control Flow Graph



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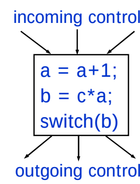
Basic Blocks

- Basic block = sequence of consecutive statements such that:
  - Control enters only at beginning of sequence
  - Control leaves only at end of sequence



- No branching in or out in the middle of basic blocks

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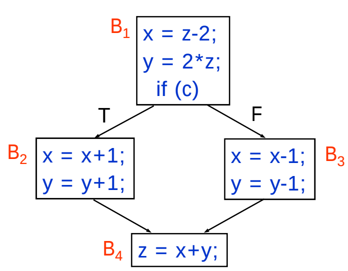
Computation and Control Flow

- Basic Blocks = Nodes in the graph = computation in the program
- Edges in the graph = control flow in the program

Control Flow Graph



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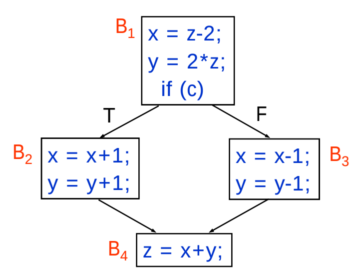
Multiple Program Executions

- CFG models all program executions
- Possible execution = path in the graph
- Multiple paths = multiple possible program executions

Control Flow Graph



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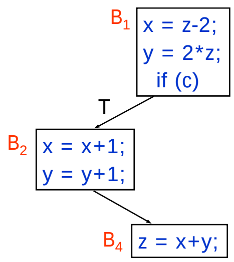
Execution 1

- CFG models all program executions
- Possible execution = path in the graph
- Execution 1:
  - c is true
  - Program executes basic blocks B_1, B_2, B_4

Control Flow Graph



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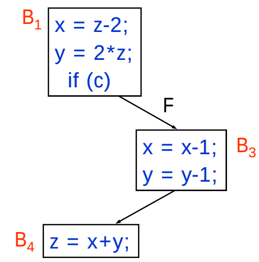
Execution 2

- CFG models all program executions
- Possible execution = path in the graph
- Execution 2:
  - c is false
  - Program executes basic blocks B_1, B_3, B_4

Control Flow Graph



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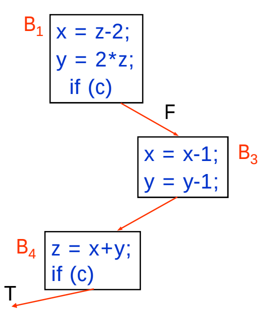
Infeasible Executions

- CFG models all program executions, and then some
- Possible execution = path in the graph
- Execution 2:
  - c is false and true (?!)
  - Program executes basic blocks B_1, B_3, B_4
  - and the T successor of B_4

Control Flow Graph



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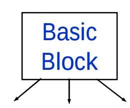
Edges Going Out

- Multiple outgoing edges
- Basic block executed next may be one of the successor basic blocks
- Each outgoing edge = outgoing flow of control in some execution of the program



outgoing edges

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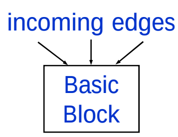
Edges Coming In

- Multiple incoming edges
- Control may come from any of the predecessor basic blocks
- Each incoming edge = incoming flow of control in some execution of the program



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Building the CFG

- Can construct CFG for either high-level IR or the low-level IR of the program
- Build CFG for high-level IR
  – Construct CFG for each high-level IR node
- Build CFG for low-level IR
  – Analyze jump and label statements

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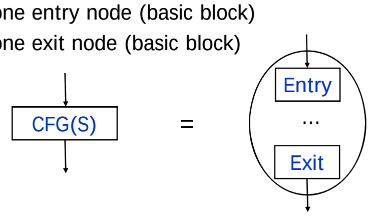
CFG for High-level IR

- CFG(S) = flow graph of high-level statement S
- CFG(S) is single-entry, single-exit graph:
  – one entry node (basic block)
  – one exit node (basic block)



- Recursively define CFG(S)

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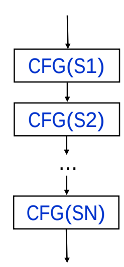
CFG for Block Statement

- CFG(S1; S2; …; SN) =



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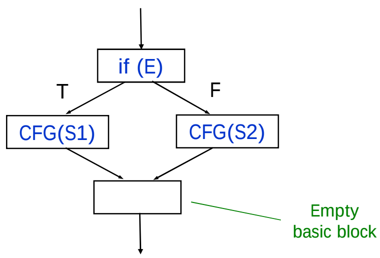
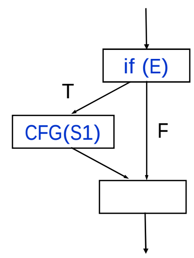
CFG for If-then-else Statement

- CFG (if (E) S1 else S2)



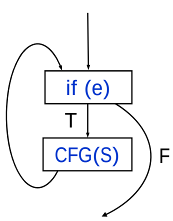
CFG for If-then Statement

- CFG(if (E) S)



CFG for While Statement

- CFG for: while (e) S



Recursive CFG Construction

- Nested statements: recursively construct CFG while traversing IR nodes
- Example:

```
while (c) {
        x = y + 1;
        y = 2 * z;
        if (d)  x = y+z;
        z = 1;
}
z = x;
```

Recursive CFG Construction

- Nested statements: recursively construct CFG while traversing IR nodes

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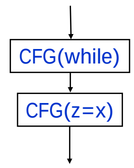

Recursive CFG Construction

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}
z = x;
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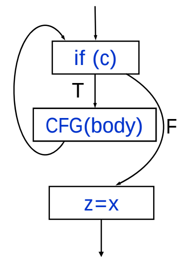

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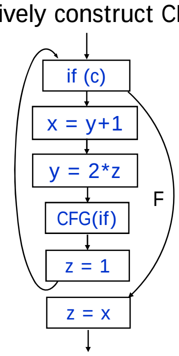

Recursive CFG Construction

- Simple algorithm to build CFG
- Generated CFG
  - Each basic block has a single statement
  - There are empty basic blocks

- Small basic blocks = inefficient
  - Small blocks = many nodes in CFG
  - Compiler uses CFG to perform optimization
  - Many nodes in CFG = compiler optimizations will be time- and space-consuming

Efficient CFG Construction

- Basic blocks in CFG:
  - As few as possible
  - As large as possible
- There should be no pair of basic blocks (B1,B2) such that:
  - B2 is a successor of B1
  - B1 has one outgoing edge
  - B2 has one incoming edge
- There should be no empty basic blocks

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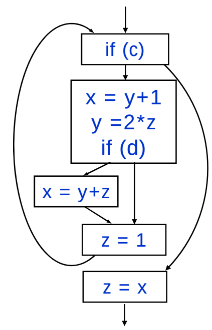
Example

- Efficient CFG:

```
while (c) {
        x = y + 1;
        y = 2 * z;
        if (d)  x = y+z;
        z = 1;
}
z = x;
```



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CFG for Low-level IR

- Identify pre-basic blocks as sequences of:
  - Non-branching instructions
  - Non-label instructions
- No branches (jump) instructions = control doesn't flow out of basic blocks
- No labels instructions = control doesn't flow into blocks

```
label L1
fjump c L2
x = y + 1;
y = 2 * z;
fjump d L3
x = y+z;
label L3

z = 1;
jump L1
label L2
z = x;
```

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CFG for Low-level IR

- Basic block start:
  - At label instructions
  - After jump instructions
- Basic blocks end:
  - At jump instructions
  - Before label instructions

```
label L1
fjump c L2
```
```
x = y + 1;
y = 2 * z;
fjump d L3
```
```
x = y+z;
```
```
label L3
z = 1;
jump L1
```
```
label L2
z = x;
```

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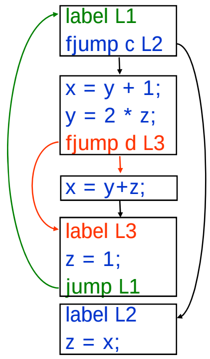
CFG for Low-level IR

- Conditional jump:
  2 successors
- Unconditional jump:
  1 successor



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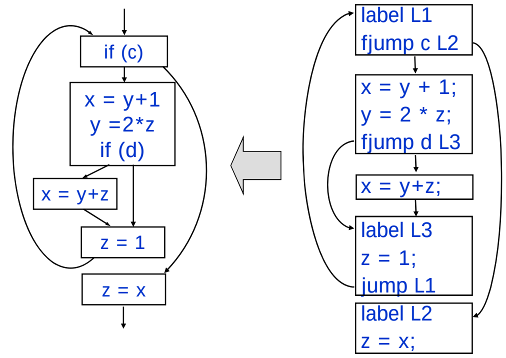
CFG for Low-level IR



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