Control Flow Analysis

PLT (Fall 2018)

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Representing Control Flow

High-level representation

–Control flow is implicit in an AST

Low-level representation:

–Use a **Control-flow graph (CFG)**

–Nodes represent statements (low-level linear IR)

–Edges represent explicit flow of control

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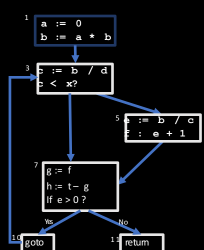
What Is Control-Flow Analysis?

```
1        a := 0
2        b := a * b
3  L1:  c := b/d
4        if c < x goto L2
5        e := b / c
6        f := e + 1
7  L2:  g := f
8        h := t - g
9        if e > 0 goto L3
10 goto L1
11 L3:  return
```



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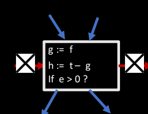
Basic Blocks

- A **basic block** is a sequence of straight line code that can be entered only at the beginning and exited only at the end



Building basic blocks

– Identify **leaders**

–The first instruction in a procedure, or

–The target of any branch, or

–An instruction immediately following a branch (implicit target)

– Gobble all subsequent instructions until the next leader

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Basic Block Example

```
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Leaders?

– {1, 3, 5, 7, 10, 11}

Blocks?

– {1, 2}
– {3, 4}
– {5, 6}
– {7, 8, 9}
– {10}
– {11}

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Building a CFG From Basic Block

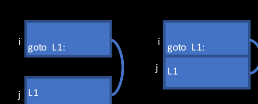
Construction

–Each CFG node represents a basic block

–There is an edge from node i to j if

–Last statement of block i branches to the first statement of j, or

–Block i does **not** end with an unconditional branch and is immediately followed in program order by block j (fall through)



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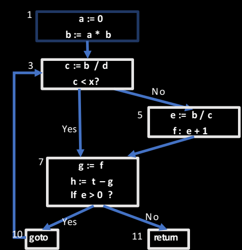

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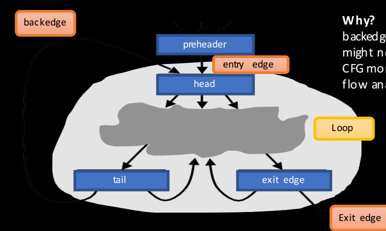
Looping



Why?
backedges indicate that we might need to traverse the CFG more than once for data flow analysis

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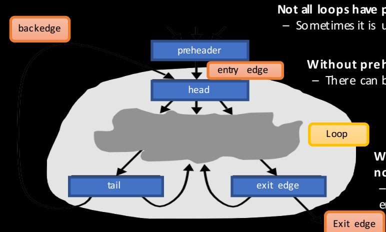
Looping



Not all loops have preheaders
- Sometimes it is useful to create them

Without preheader node
- There can be multiple entry edges

With single preheader node
- There is only one entry edge

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Looping Terminology

Loop:	Strongly connected component of CFG
Loop entry edge:	Source not in loop & target in loop
Loop exit edge:	Source in loop & target not in loop
Loop header node:	Target of loop entry edge

Natural loop: Loop with only a single loop header

Back edge:	Target is loop header & source is in the loop
Loop tail node:	Source of back edge

Looping Terminology

Loop preheader node: Single node that's source of the loop entry edge
Nested loop: Loop whose header is inside another loop

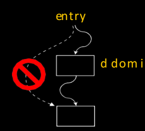
Reducible flow graph: CFG whose loops are all natural loops

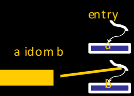
Identifying Loops

- **Why is it important?**
  - –Most execution time spent in loops, so optimizing loops will often give most benefit
- **Many approaches**
  - –Interval analysis
    - –Exploit the natural hierarchical structure of programs
    - –Decompose the program into nested regions called intervals
  - –Structural analysis: a generalization of interval analysis
  - –Identify **dominators** to discover loops

Dominators

- d **dom** i if all paths from entry to node i include d
- Strict Dominator (d sdom i)
  - If d dom i, but d != i
- Immediate dominator (a idom b)
  - a sdom b and there does not exist any node c such that a != c, c != b, a dom c, c dom b
- Post dominator (p pdom i)
  - If every possible path from i to exit includes p





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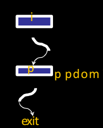
Dominators

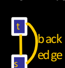
- **Post dominators (p pdom i)**

if every possible path from i to exit includes p (p dom i in the flow graph whose arcs are reversed and entry and exit are interchanged)



Identifying Natural Loops and Dominators

- Back Edge
  - A **back edge** of a natural loop is one whose target of the back edge dominates its source
- Natural Loop
  - The **natural loop** of a back edge (m→n), where n dominates m, is the set of nodes x such that n dominates x and there is a path from x to m not containing n



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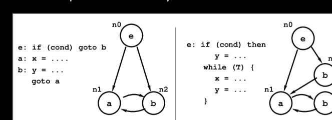
Reducibility

- A CFG is **reducible** (well-structured) if we can partition its edges into two disjoint sets, the **forward edges** and the **back** edges, such that
  - The forward edges form an acyclic graph in which every node can be reached from the entry node
  - The back edges consist only of edges whose targets dominate their sources
  - Non-natural loops ⇔ irreducibility



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Reducibility

- **Structured control-flow constructs give rise to reducible CFGs**
- **Value of reducibility:**
  - Dominance useful in identifying loops
  - Simplifies code transformations (every loop has a single header)
  - Permits interval analysis

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Handling Irreducible CFG's

- Node splitting
  - Can turn irreducible CFGs into reducible CFGs

General idea
- Reduce graph (iteratively remove self edges, merge nodes with single pred)
- More than one node ⇒ irreducible
  - Split any multi-parent node and start over

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Why go through all this trouble?

- We can work on the binary code
- Most modern languages still provide a **goto** statement
- Languages typically provide multiple types of loops. This analysis lets us treat them all uniformly
- We may want a compiler with multiple front ends for multiple languages; rather than translating each language to a CFG, translate each language to a canonical IR and then to a CFG

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