Control Flow Analysis

Last time
- Undergraduate compilers in a day ⬅

Today
- Assignment 0 due
- Control-flow analysis
  - Building basic blocks
  - Building control-flow graphs
  - Loops

Compiling Arrays

Array declaration
- Store name, size, and type in symbol table

Array allocation
- Call `malloc()` or create space on the runtime stack

Array referencing
- `A[i]` ➡ `*(&A + i * sizeof(A_elem))` ⬇

```
t1 := &A
t2 := sizeof(A_elem)
t3 := i * t2
t4 := t1 + t3
*t4
```

Compiling Procedures

Properties of procedures

- Procedures define scopes
- Procedure lifetimes are nested
- Can store information related to dynamic invocation of a procedure on a call stack (*activation record* or AR or stack frame):
  - Space for saving registers
  - Space for passing parameters and returning values
  - Space for local variables
  - Return address of calling instruction

Compiling Procedures

Runtime stack management

- Push an AR on procedure entry
- Pop an AR on procedure exit
- Why do we need a stack?

Compiling Procedures (cont)

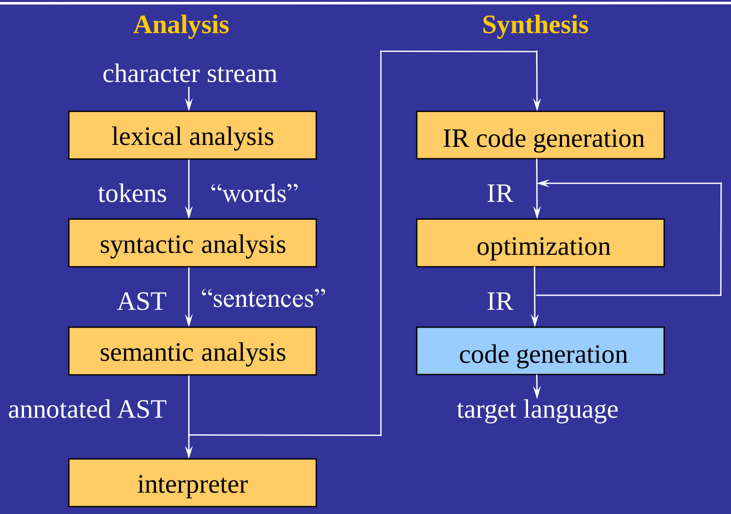
Code generation for procedures

- Emit code to manage the stack
- Are we done?

Translate procedure body

- References to local variables must be translated to refer to the current activation record
- References to non-local variables must be translated to refer to the appropriate activation record or global data space

Structure of a Typical Compiler



Code Generation

Conceptually easy

- Three address code is a generic machine language
- Instruction selection converts the low-level IR to actual machine instructions

The source of heroic effort on modern architectures

- Alias analysis
- Instruction scheduling for ILP
- Register allocation
- More later. . .

Concepts

Compilation stages

- Scanning, parsing, semantic analysis, intermediate code generation, optimization, code generation

Representations

- AST, low-level IR (RTL)

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January 28, 2015 Control Flow Analysis 9

Motivation

Q: Why is control flow analysis important?

A: Control flow is a key component of program behavior

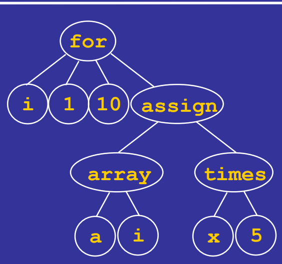
Control flow analysis
- Discovers the flow of control within a procedure
- Builds a representation of control flow (loops, etc)

January 28, 2015 Control Flow Analysis 10

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

  – Edges represent explicit flow of control

Other options

– Control dependences in program dependence graph (PDG) [Ferrante87]

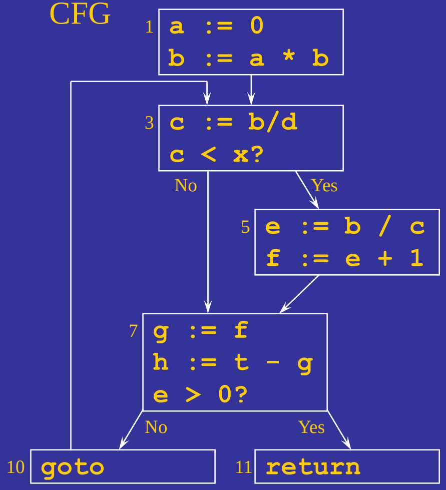
– Dependences on explicit state in value dependence graph (VDG) [Weise 94]

Example

Source code

```
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
```

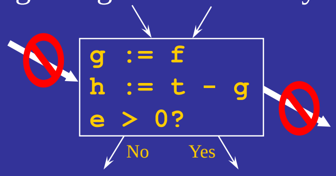
CFG



Basic Blocks

Definition

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



Why are basic blocks useful?

– Straightline code is easy to reason about

– They give rise to local optimizations

How Might We Identify Basic Blocks?

Source code

```
        a := 0
        b := a * b
L1:     c := b/d
        if c < x goto L2
        e := b / c
        f := e + 1
L2:     g := f
        h := t - g
        if e > 0 goto L3
        goto L1
L3:     return
```

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

Algorithm for Building Basic Blocks

Input: List of n instructions (instr[i] = i^{th} instruction)
Output: Set of leaders & list of basic blocks
(block[x] is block with leader x)

```
leaders = {1}                          // First instruction is a leader
for i = 1 to n                         // Find all leaders
    if instr[i] is a branch
      leaders = leaders ∪ set of potential targets of instr[i]
foreach x ∈ leaders
    block[x] = { x }
    i = x+1                            // Fill out x's basic block
    while i ≤ n and i ∉ leaders        // Gobble, gobble, gobble
      block[x] = block[x] ∪ { i }
      i = i + 1
```


Building Basic Blocks Example

```
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
```

Leaders?
{1, 3, 5, 7, 10, 11}

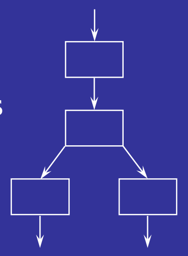
Blocks?
{1, 2}
{3, 4}
{5, 6}
{7, 8, 9}
{10}
{11}

Extended Basic Blocks

Extended basic blocks

– A maximal sequence of instructions that has no merge points in it (except perhaps in the leader)

– Single entry, multiple exits



How are these useful?

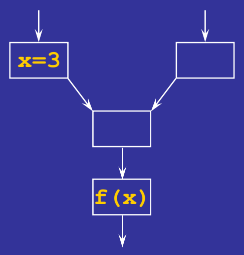
– Increases the scope of any local analysis or transformation that "flows forwards" (*e.g.*, copy propagation, register renaming, instruction scheduling)

January 28, 2015 Control Flow Analysis 17

Extended Basic Blocks (cont)

Reverse extended basic blocks

– Useful for "backward flow" problems

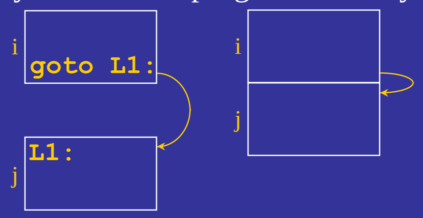


January 28, 2015 Control Flow Analysis 18

Building a CFG from Basic Blocks

Basic idea

- 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)



Building a CFG from Basic Blocks (cont)

Input: A list of m basic blocks (block)
Output: A CFG where each node is a basic block

```
for i = 1 to m
  x = last instruction of block[i]
  if instr x is a branch
        for each target (to block j) of instr x
                create an edge from block i to block j
  if instr x  is not an unconditional branch
        create an edge from block i to block i+1
```

Details

Multiple edges between two nodes

```
      ...
      if (a<b) goto L2
L2:  ...
```

– Combine these edges into one edge

Unreachable code

```
      ...
      goto L1
L0:  a = 10
L1:  ...
```

– Perform DFS from entry node
– Mark each basic block as it is visited
– Unmarked blocks are unreachable and can be deleted

Challenges

When is CFG construction more complex?

Languages with user-defined control structures

– *e.g.*, Cecil

```
if ( &{x = 3}, &{a := a + 1}, &{a := a - 1} );
```

Languages where branch targets may be unknown

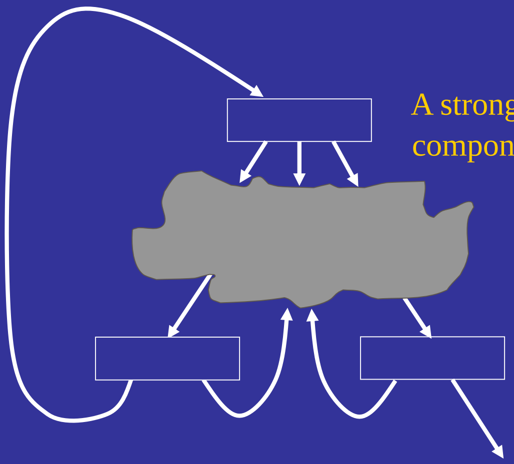
– *e.g.*, Executable code

```
ld $8, 104($7)
jmp $8
```

Binary translation

– Can't statically distinguish code from data with x86 ISA

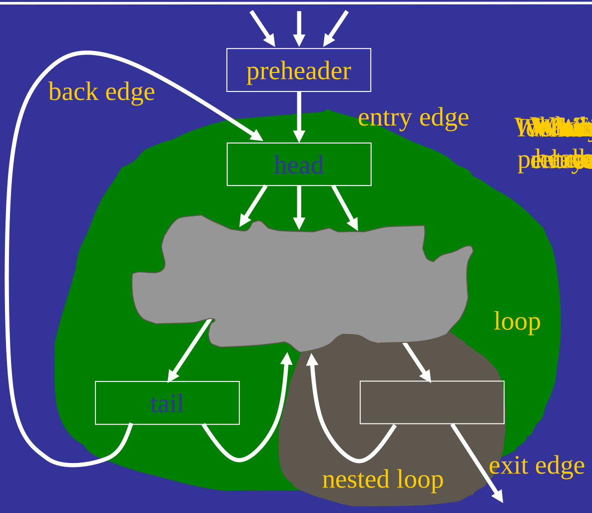
What is a Loop?



A strongly connected component of a CFG

January 28, 2015 Control Flow Analysis 23

Loop Concepts

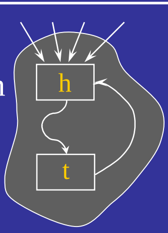


January 28, 2015 Control Flow Analysis 24

The Value of Preheader Nodes

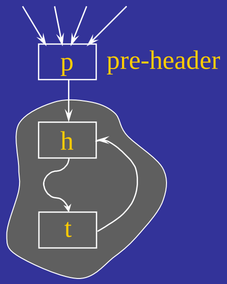
Not all loops have preheaders
- Sometimes it is useful to create them

Without preheader node
- There can be multiple entry edges



With single preheader node
- There is only one entry edge

Useful when moving code outside the loop
- Don’t have to replicate code for multiple entry edges



Loop Concepts

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

Loop Concepts (cont)

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

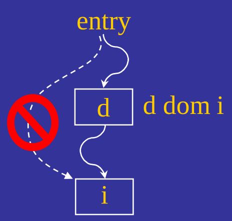
Many approaches

- 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

Dominance

d **dom** i if all paths from entry to node i include d

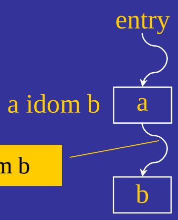


Strict dominance

d **sdom** i if d dom i and d ≠ i

Immediate dominance

a **idom** b if a **sdom** b and there does not exist a node c such that c ≠ a, c ≠ b, a dom c, and c dom b



not ∃ c, a sdom c and c sdom b

Exercise

Immediate dominance

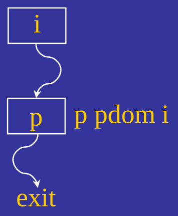
– If x idom y, is x necessarily a predecessor of y?

Dominators (cont)

Post dominators

p **pdom** i if every possible path from i to exit includes p

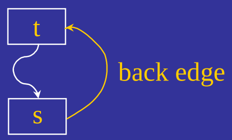
(p dom i in the flow graph whose arcs are reversed and entry and exit are interchanged)



Identifying Natural Loops with Dominators

Back edges

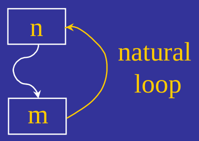
– A back edge of a natural loop is one whose target dominates its source



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

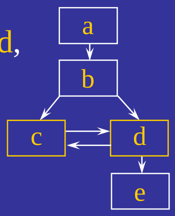
– Why do we need this last clause?



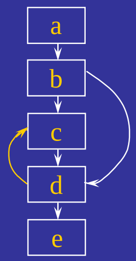
Natural Loops

Counterexamples

– This loop has two entry points, c and d, so it is not a natural loop



– The target, c, of the edge (d→c) does not dominate its source, d, so (d→c) does not define a natural loop



Computing Dominators

Input: Set of nodes N (in CFG) and an entry node s

Output: Dom[i] = set of all nodes that dominate node i

Dom[s] = {s}

for each n $\in$ N – {s}

Dom[n] = N

repeat

change = false

for each n $\in$ N – {s}

D = {n} $\cup$ ($\cap_{p \in pred(n)}$ Dom[p])

if D $\neq$ Dom[n]

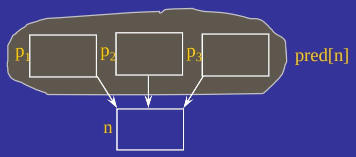
change = true

Dom[n] = D

until !change

Key Idea

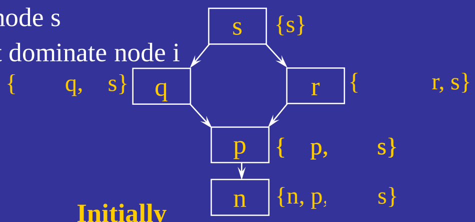
If a node dominates all predecessors of node n, then it also dominates node n



$x \in Dom(p_1) \wedge x \in Dom(p_2) \wedge x \in Dom(p_3) \Rightarrow x \in Dom(n)$

Computing Dominators: Example

Input: Set of nodes N and an entry node s
Output: Dom[i] = set of all nodes that dominate node i



Dom(s) = {s}

for each n $\in$ N – {s}
  Dom[n] = N
repeat
  change = false
  for each n $\in$ N – {s}
    D = {n} $\cup$ ($\cap_{p \in pred(n)}$ Dom[p])
    if D $\neq$ Dom[n]
      change = true
      Dom[n] = D
until !change

Initially
Dom[s] = {s}
Dom[q] = {n, p, q, r, s}. . .

Finally
Dom[q] = {q, s}
Dom[r] = {r, s}
Dom[p] = {p, s}
Dom[n] = {n, p, s}

Reducibility

Definition

– 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 $\Leftrightarrow$ irreducibility

Structured control-flow constructs give rise to reducible CFGs

Reducibility (cont)

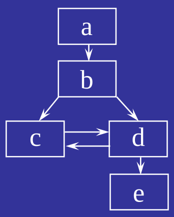
Value of reducibility

– Can use dominance to identify loops
– Simplifies code transformations (every loop has a single header)
– Permits interval analysis

Example

Is the following CFG reducible?

– No. The loop between c and d has two entry points

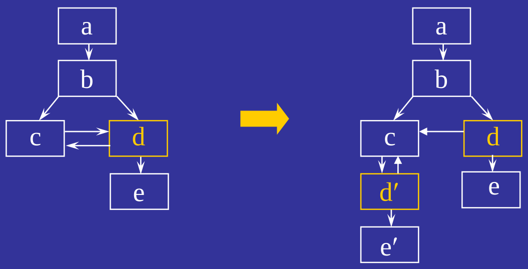


– Can we convert this CFG to a reducible CFG?

Handling Irreducible CFG's

Node splitting

– Can turn irreducible CFGs into reducible CFGs



Why Go To All This Trouble?

Modern languages provide structured control flow

– Shouldn't the compiler remember this information rather than throw it away and then re-compute it?

Answers?

– We may want to work on the binary code in which case such information is unavailable

– Most modern languages still provide a `goto` statement

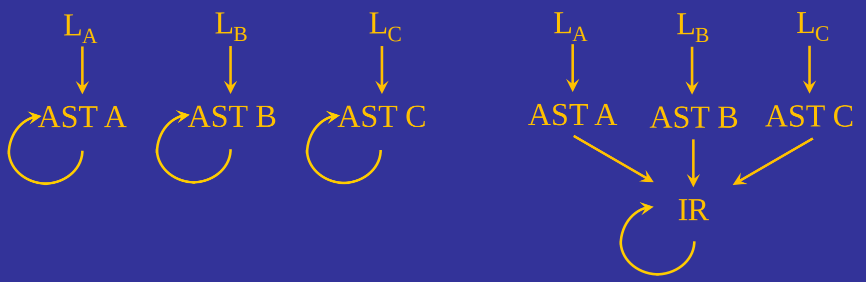
– Languages typically provide multiple types of loops. This analysis lets us treat them all uniformly

Calvin Lin
The University of Texas at Austin

Why Go To All This Trouble? (cont)

Answers? (cont)

– Reduce engineering effort for compilers that support multiple languages



January 28, 2015 Control Flow Analysis 41

Concepts

Control-flow analysis

Basic blocks

– Computing basic blocks

– Extended basic blocks

Control-flow graph (CFG)

Loop terminology

Identifying loops

Dominators

Reducibility

January 28, 2015 Control Flow Analysis 42

Next Time

Lecture

– Introduction to data-flow analysis

January 28, 2015 Control Flow Analysis 43