COMP 515: Advanced Compilation for Vector and Parallel Processors

Vivek Sarkar
Department of Computer Science
Rice University
vsarkar@rice.edu

http://www.cs.rice.edu/~vsarkar/comp515

COMP 515 Lecture 14 18 October, 2011

Acknowledgments

- Slides from previous offerings of COMP 515 by Prof. Ken Kennedy
  - http://www.cs.rice.edu/~ken/comp515/
- POPL 1996 tutorial by Krishna Palem & Vivek Sarkar

Control Dependences

Chapter 7 (contd)

Control Dependences (Recap from Lecture 12)

- **Constraints posed by control flow**

```
        DO 100 I = 1, N
S1         IF (A(I-1).GT. 0.0) GO TO 100
S2            A(I) = A(I) + B(I)*C
100  CONTINUE
```

$S_2 \ \delta_1 \ S_1$

If we vectorize by...

```
S2   A(1:N) = A(1:N) + B(1:N)*C
     DO 100 I = 1, N
S1      IF (A(I-1).GT. 0.0) GO TO 100
100 CONTINUE
```

...we get the wrong answer

- **We are missing dependences**
- **There is a dependence from S_1 to S_2 - a control dependence**

Control Dependences

- **Two strategies to deal with control dependences:**
  - **If-conversion:** expose by converting control dependences to data dependences. Used for vectorization
    - Also supported in SIMT hardware (e.g., GPGPUs) which automatically masks out statements with control conditions = false
  - Explicitly compute **control dependences**. Used for coarse-grained parallelism, or in cases where guarded execution is inefficient for vectorization.

Branch Classification

- **Forward Branch:** transfers control to a target that occurs lexically after the branch but at the same level of nesting
- **Backward Branch:** transfers control to a statement occurring lexically before the branch but at the same level of nesting
- **Exit Branch:** terminates one or more loops by transferring control to a target outside a loop nest
  - The break and return statements in C are examples of exit branches, when they occur inside a loop

Branch removal for If-conversion

- **Basic idea:**
  - Make a pass through the program.
  - Maintain a Boolean expression cc that represents the condition that must be true for the current expression to be executed
  - On encountering a branch, conjoin the controlling expression into cc
  - On encountering a target of a branch, its controlling expression is disjoined into cc

Branch Removal: Forward Branches

- Remove forward branches by inserting appropriate guards

```
        DO 100 I = 1,N
C1          IF (A(I).GT.10) GO TO 60
20              A(I) = A(I) + 10
C2              IF (B(I).GT.10) GO TO 80
40                  B(I) = B(I) + 10
60              A(I) = B(I) + A(I)
80          B(I) = A(I) - 5
        ENDDO
==>
      DO 100 I = 1,N
                m1 = A(I).GT.10
20              IF(.NOT.m1) A(I) = A(I) + 10
                IF(.NOT.m1) m2 = B(I).GT.10
40              IF(.NOT.m1.AND..NOT.m2) B(I) = B(I) + 10
60              IF(.NOT.m1.AND..NOT.m2.OR.m1)A(I) = B(I) + A(I)
80              IF(.NOT.m1.AND..NOT.m2.OR.m1.OR..NOT.m1
                      .AND.m2) B(I) = A(I) - 5
      ENDDO
```

Branch Removal: Forward Branches

- **We can simplify to:**

```
    DO 100 I = 1,N
                  m1 = A(I).GT.10
 20               IF(.NOT.m1) A(I) = A(I) + 10
                  IF(.NOT.m1) m2 = B(I).GT.10
 40               IF(.NOT.m1.AND..NOT.m2)
                          B(I) = B(I) + 10
 60               IF(m1.OR..NOT.m2)
                          A(I) = B(I) + A(I)
 80               B(I) = A(I) - 5
    ENDDO
```

- **and then vectorize to:**

```
      m1(1:N) = A(1:N).GT.10
 20   WHERE(.NOT.m1(1:N)) A(1:N) = A(1:N) + 10
      WHERE(.NOT.m1(1:N)) m2(1:N) = B(1:N).GT.10
 40   WHERE(.NOT.m1(1:N).AND..NOT.m2(1:N))
                        B(1:N) = B(1:N) + 10
 60   WHERE(m1(1:N).OR..NOT.m2(1:N))
                        A(1:N) = B(1:N) + A(1:N)
 80   B(1:N) = A(1:N) - 5
```

Removal of Forward Branches: Correctness

- To show correctness we must establish:
  - the guard for statement instance in the new program is true if and only if the corresponding statement in the old program is executed,
    - unless the statement has been introduced by the compiler to capture a guard variable value, which must be executed at the point the conditional expression would have been evaluated
  - the order of execution of statements in the new program with true guards is the same as the order of execution of those statements in the original program

Exit Branches

```
      DO J = 1, M
        DO I = 1, N
                    A(I,J) = B(I,J) + X
S                   IF (L(I,J)) GO TO 200
                    C(I,J) = A(I,J) + Y
        ENDDO
        D(J) = A(N,J)
200             F(J) = C(10,J)
      ENDDO
```

- **more complicated because they terminate a loop**
- **Solution: relocate exit branches and convert them to forward branches**

Exit Branches

```
      DO J = 1, M
            DO I = 1, N
                  A(I,J) = B(I,J) + X
S                 IF (L(I,J)) GO TO 200
                  C(I,J) = A(I,J) + Y
            ENDDO
          D(J) = A(N,J)
200       F(J) = C(10,J)
        ENDDO
```

```
      DO J = 1, M
            DO I = 1, N
                  IF (C1) A(I,J) = B(I,J) + X
Sa                Code to set C1 and C2
                  IF (C2) C(I,J) = A(I,J) + Y
            ENDDO
Sb           IF (.NOT.C1.OR..NOT.C2) GO TO 200
            D(J) = A(N,J)
200         F(J) = C(10,J)
        ENDDO
```

Exit Branches

- **Statements in the inner loop should be executed only if exit branch was not taken on any previous iteration**
- **For the i^{th} iteration, C_1 and C_2 should be**

  lm = AND(¬ L(k, J)), 1 ≤ k ≤ i-1

```
      DO J = 1, M
                  lm = .TRUE.
                  DO I = 1, N
                            IF (lm) A(I,J) = B(I,J) + X
                            IF (lm) m1 = .NOT. L(I,J)
                            lm = lm .AND. m1
                            IF (lm) C(I,J) = A(I,J) + Y
                  ENDDO
                  m2 = lm
                  IF (m2) D(J) = A(N,J)
 200              F(J) = C(10,J)
      ENDDO
```

Exit Branches

- **After forward substitution and expansion of lm, we get:**

```
    DO J = 1, M
           lm(0,J) = .TRUE.
           DO I = 1, N
                 IF (lm(I-1,J)) A(I,J) = B(I,J) + X
                 IF (lm(I-1,J)) m1 = .NOT.L(I,J)
                 lm(I,J) = lm(I-1,J) .AND. m1
                 IF (lm(I,J)) C(I,J) = A(I,J) + Y
           ENDDO
           IF (lm(N,J)) D(J) = A(N,J)
200              F(J) = C(10,J)
    ENDDO
```

- **codegen will produce four vectorized loops…**

Exit Branches

- **After running codegen:**

```
DO J = 1, M
    lm(0,J) = .TRUE.
          DO I = 1, N
             IF (lm(I-1,J)) m1 =.NOT.L(I,J)
              lm(I,J) = lm(I-1,J) .AND. m1
          ENDDO
ENDDO
WHERE(lm(0:N-1,1:M)) A(1:N,1:M)=B(1:N,1:M)+X
WHERE(lm(1:N,1:M)) C(1:N,1:M)=A(1:N,1:M)+Y
WHERE(lm(N,1:M)) D(1:M) = A(N,1:M)
200         F(1:M) = C(10,1:M)
```

- Procedure relocate_branches()

Control Dependence

- **Disadvantages of if-conversion:**
  - Unnecessarily complicates code when code cannot be vectorized
  - Cannot a priori analyze code to decide whether if-conversion will lead to parallel code.

- **Alternate approach: explicitly expose constraints due to control flow as control dependences**

Control Flow Graph Definition (Recap)

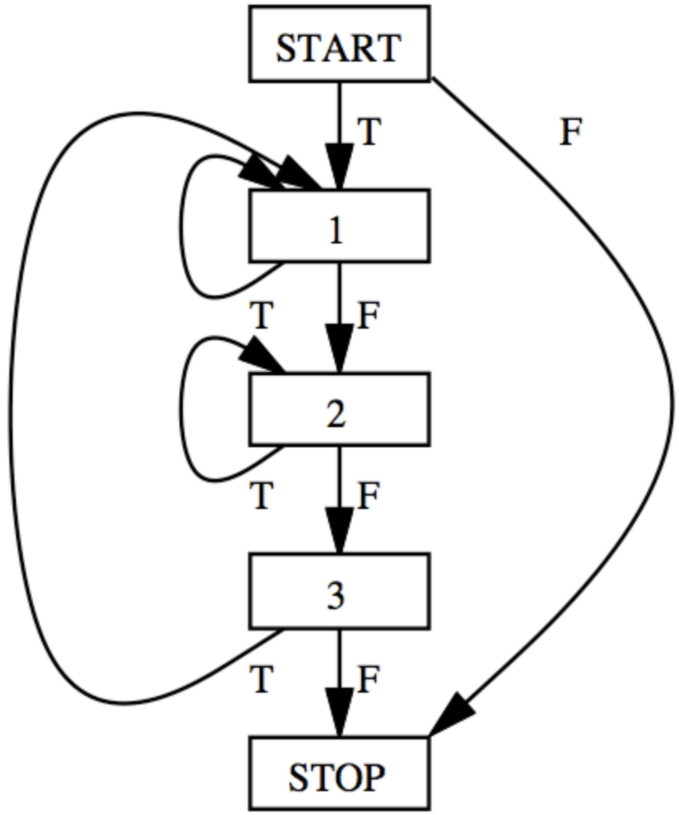
A *control flow graph* $CFG = (N_c, E_c, T_c)$ consists of

- N_c, a set of nodes. A node represents a straight-line sequence of operations with no intervening control flow i.e a basic block.
- $E_c \subseteq N_c \times N_c \times$ *Labels*, a set of *labeled* edges.
- T_c, a node type mapping. $T_c(n)$ identifies the type of node n as one of: *START*, *STOP*, *OTHER*.

We assume that *CFG* contains a unique *START* node and a unique *STOP* node, and that for any node N in *CFG*, there exist directed paths from *START* to N and from N to *STOP*.

Control Flow Graph: Example

```
do {
  S1;
  if ( C1 ) continue;
  do {
    S2;
  } while ( C2 );
  S3;
} while ( C3 );
```



CONTROL FLOW GRAPH

Dominators: Definition

Node V *dominates* another node $W \neq V$ if and only if every directed path from *START* to W in *CFG* contains V.

Define $dom(W) = \{V \mid V \text{ dominates } W\}$, the set of *dominators* of node W.

Consider any simple path from *START* to W containing W's dominators in the order $V_1, \ldots, V_k$. Then all simple paths from *START* to W must contain W's dominators in the same order. The element closest to W, $V_k = idom(W)$, is called the *immediate dominator* of W.

The $idom$ relation can be represented as a directed tree with root = *START*, and *parent*$(W) = idom(W)$.

Postdominators: Definition

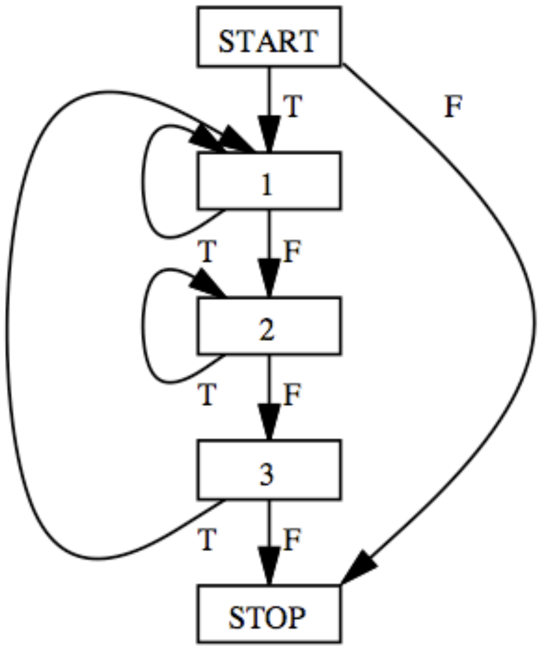
Node W *postdominates* another node $V \neq W$ if and only if every directed path from V to *STOP* in *CFG* contains W.

Define $pdom(V) = \{W \mid W \text{ postdominates } V\}$, the set of *postdominators* of node V.

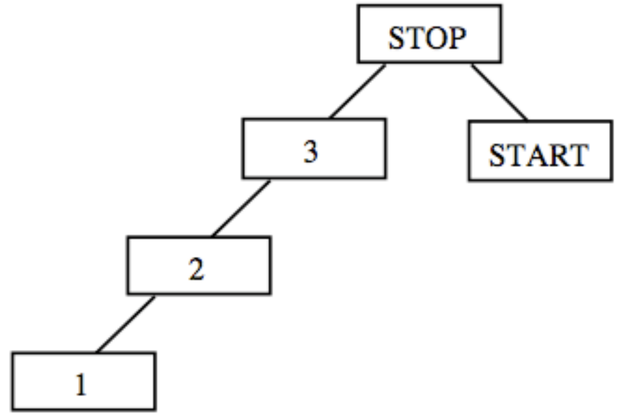
Consider any simple path from V to *STOP* containing V's postdominators in the order $W_1, \ldots, W_k$. Then all simple paths from V to *STOP* must contain V's postdominators in the same order. The element closest to V, $W_1 = ipdom(V)$, is called the *immediate postdominator* of V.

The $ipdom$ relation can be represented as a directed tree with root $=$is *STOP* and *parent*$(V) = ipdom(V)$.

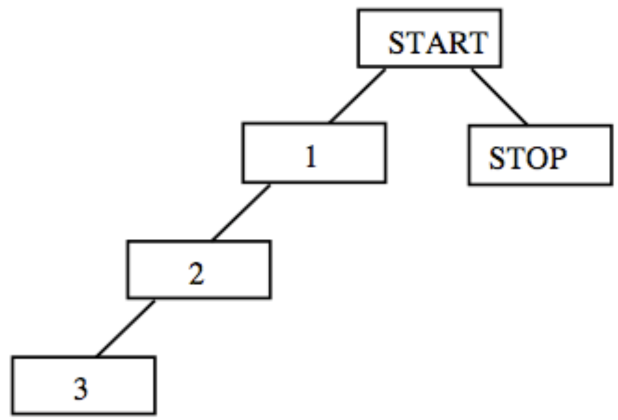
Examples of Dominator and Postdominator Trees



CONTROL FLOW GRAPH



POST–DOMINATOR TREE



DOMINATOR TREE

Control Dependence: Definition

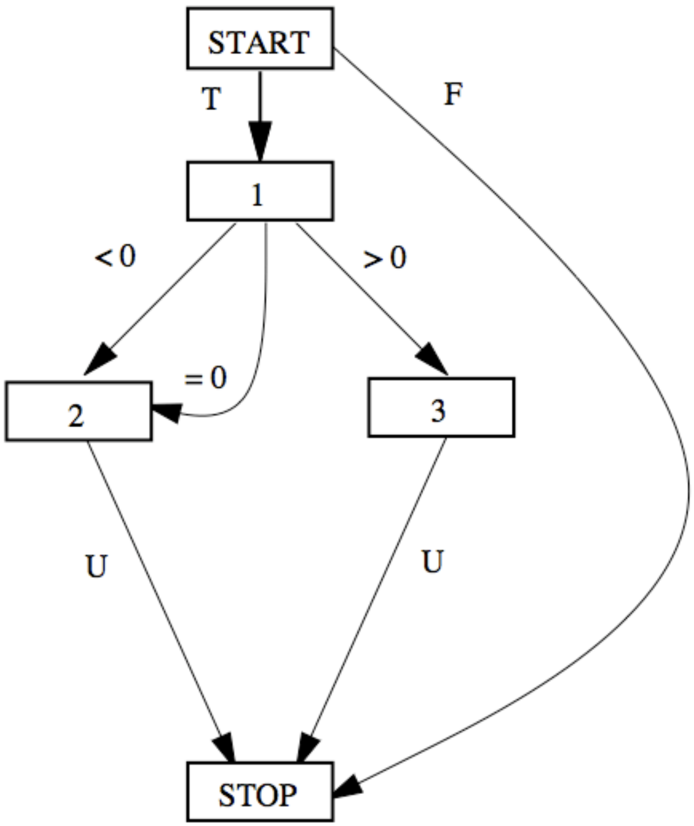
Node Y is *control dependent* on node X with label L in *CFG* if and only if

1. there exists a nonnull path $X \longrightarrow Y$, starting with the edge labeled L, such that Y post-dominates every node, W, strictly between X and Y in the path, and

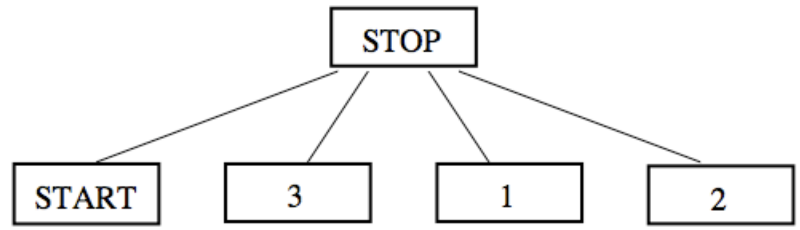
2. Y does not post-dominate X.

Reference: "The Program Dependence Graph and its Use in Optimization", J. Ferrante et al, *ACM TOPLAS, 1987*

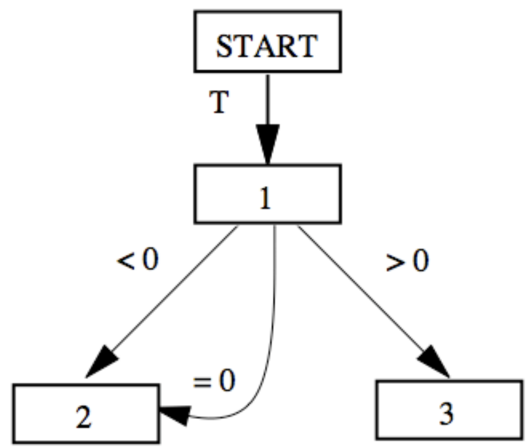
Example: Acyclic CFG and its Control Dependence Graph (CDG)



CONTROL FLOW GRAPH



POSTDOMINATOR TREE



CONTROL DEPENDENCE GRAPH

Control Dependence: Discussion

- A node x in directed graph G with a single exit node postdominates node y in G if any path from y to the exit node of G must pass through x.
- A statement y is said to be control dependent on another statement x if:
  - there exists a non-trivial path from x to y such that every statement $z \neq x$ in the path is postdominated by y and
  - x is not postdominated by y.
- In other words, a control dependence exists from S1 to S2 if one branch out of S1 forces execution of S2 and another doesn't
- Note that control dependences also can be seen at as a property of basic blocks (depends on CFG granularity)

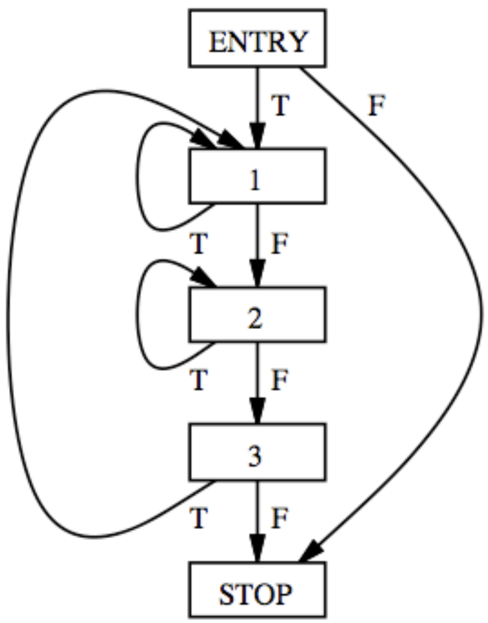
Program Dependence Graph

Program Dependence Graph (PDG) consists of

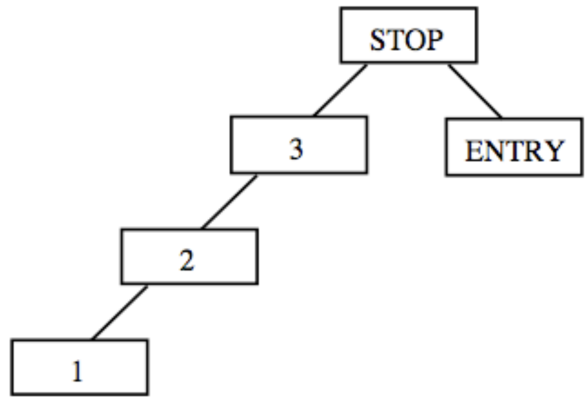
1. Set of nodes, as in the CFG
2. Control dependence edges
3. Data dependence edges

Together, the control and data dependence edges dictate whether or not a proposed code transformation is legal.

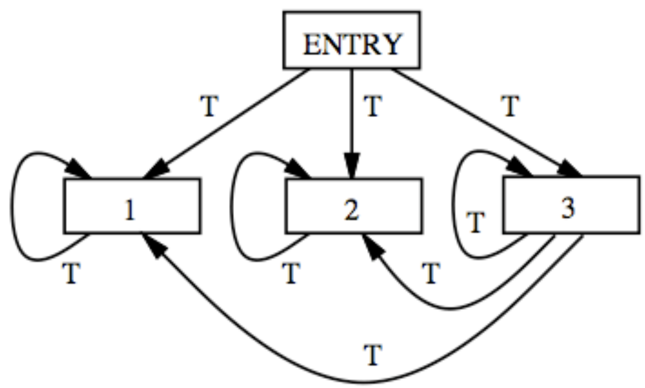
Example: Cyclic CFG and its CDG



CONTROL FLOW GRAPH



POST-DOMINATOR TREE



CONTROL DEPENDENCE GRAPH

CDG for a Cyclic CFG

Problem: CFG and CDG can have different loop/interval structures, in general

Solution: Compute CDG only for acyclic CFG's e.g.

1. Restrict construction and use of CDG's to innermost intervals with acyclic CFG's.

2. Compute CDG for acyclic Forward Control Flow Graph), which captures CFG's loop structure by insertion of pseudo nodes and edges. [Cytron, Ferrante, Sarkar 1990]

3. Compute CDG for each interval with an acyclic CFG, treating subintervals as atomic nodes.