CS738: Advanced Compiler Optimizations

Interprocedural Data Flow Analysis

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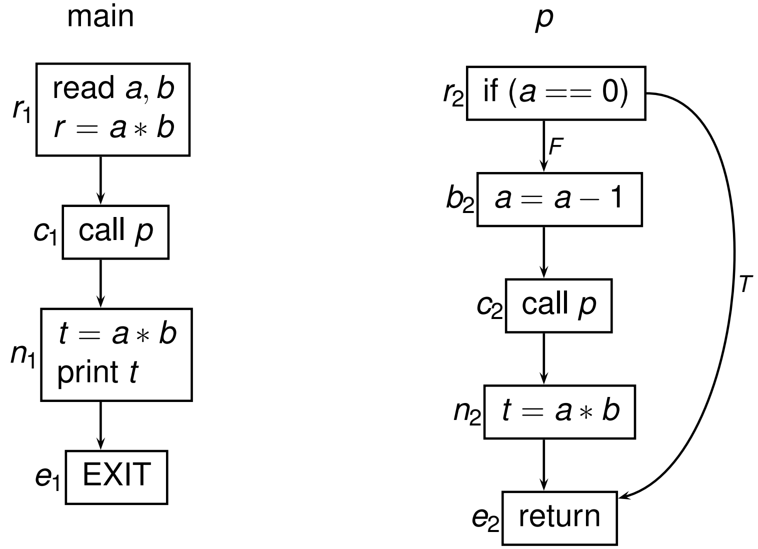
Interprocedural Analysis: WHY?

Is $a * b$ available at IN of n_1?



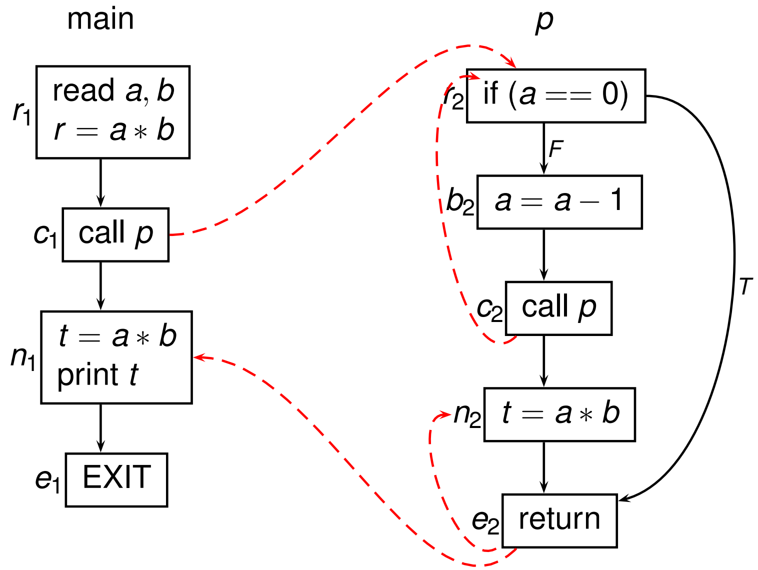
Challenges

- Infeasible paths
- Recursion
- Function pointers and virtual functions
- Dynamic functions (functional programs)

Infeasible Paths

How to avoid data flowing along invalid paths?

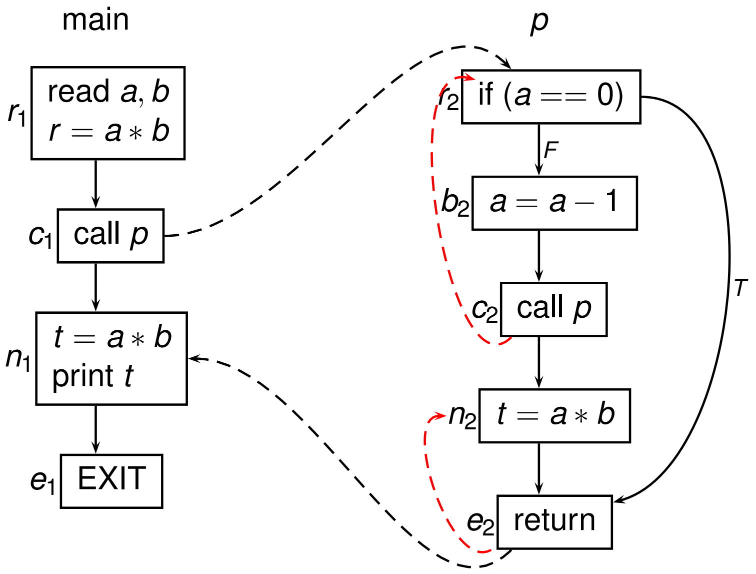
$r_1 \to c_1 \to r_2 \to b_2 \to c_2 \to r_2 \to e_2 \to n_1$



Recursion

How to handle Infinite paths?

$\ldots \rightarrow r_2 \rightarrow c_2 \rightarrow r_2 \rightarrow c_2 \rightarrow r_2 \ldots$



Function Variables

- Target of a function can not be determined statically
- Function Pointers (including virtual functions)

```
double (*fun)(double arg);
...
if (cond)
    fun = sqrt;
else
    fun = fabs;
...
fun(x);
```

- Dynamically created functions (in functional languages)
- No static control flow graph!

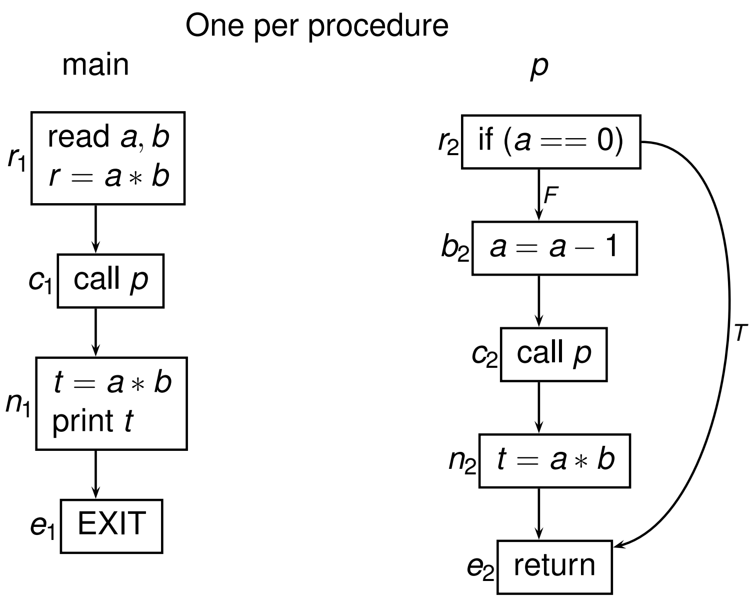
Two Approaches

- Functional approach
  - procedures as structured blocks
  - input-output relation (*functions*) for each block
  - *function* used at call site to compute the effect of procedure on program state
- Call-strings approach
  - single flow graph for whole program
  - value of interest tagged with the history of unfinished procedure calls

M. Sharir, and A. Pnueli. **Two Approaches to Inter-Procedural Data-Flow Analysis**. In Jones and Muchnik, editors, Program Flow Analysis: Theory and Applications. Prentice-Hall, 1981.

Notations and Terminology

Control Flow Graph



Control Flow Graph for Procedure p

- Single instruction basic blocks
- Unique exit block, denoted e_p
- Unique entry block, denoted r_p (root block)
- Edge (m, n) if direct control transfer from (the end of) block m to (the start of) block n
- Path: $(n_1, n_2, \ldots, n_k)$
  - $(n_i, n_{i+1}) \in$ Edge set for $1 \leq i < k$
  - $\text{path}_G(m, n)$: Set of all path in graph $G = (N, E)$ leading from m to n

Assumptions

- Parameterless procedures, to ignore the problems of
  - *aliasing*
  - recursion stack for formal parameters
- No procedure variables (pointers, virtual functions etc.)

Data Flow Framework

- (L, F): data flow framework
- L: a meet-semilattice
  - Largest element Ω
- F: space of propagation functions
  - Closed under composition and meet
  - Contains $id_L(x) = x$ and $f_\Omega(x) = \Omega$
- $f_{(m,n)} \in F$ represents propagation function for edge (m, n) of control flow graph $G = (N, E)$
  - Change of DF values from the *start* of m, through m, to the *start* of n

Data Flow Equations

$$x_r = BoundaryInfo$$
$$x_n = \bigwedge_{(m,n)\in E} f_{(m,n)}(x_m) \qquad n \in N - r$$

- MFP solution, approximation of MOP

$$y_n = \bigwedge \{f_p(BoundaryInfo) : p \in \text{path}_G(r,n)\} \quad n \in N$$

Functional Approach to Interprocedural Analysis

Functional Approach

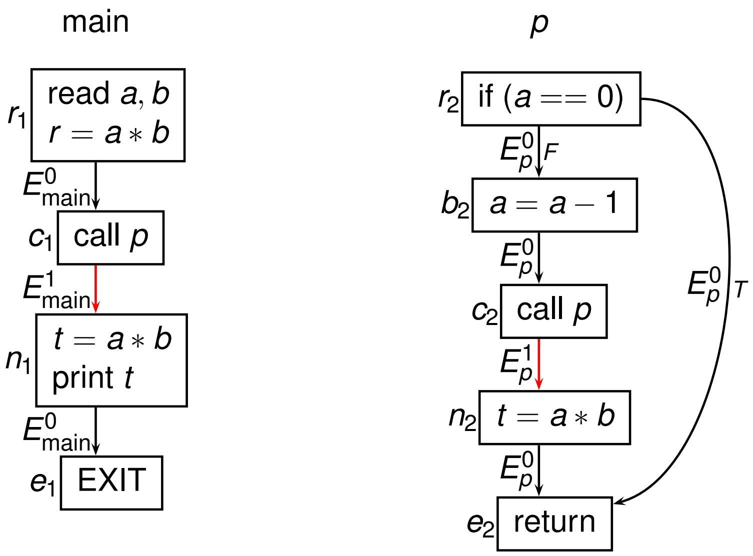
- Procedures treated as structures of blocks
- Computes relationship between DF value at entry node and related data at *any* internal node of procedure
- At call site, DF value propagated directly using the computed relation

Interprocedural Flow Graph

First Representation:

$$\begin{aligned}
G &= \bigcup\{G_p : p \text{ is a procedure in program}\}\\
G_p &= (N_p, E_p, r_p)\\
N_p &= \text{set of all basic block of } p\\
r_p &= \text{root block of } p\\
E_p &= \text{set of edges of } p\\
&= E_p^0 \cup E_p^1\\
(m,n) \in E_p^0 &\Leftrightarrow \text{direct control transfer from } m \text{ to } n\\
(m,n) \in E_p^1 &\Leftrightarrow m \text{ is a call block, and } n \text{ immediately follows } m
\end{aligned}$$

Interprocedural Flow Graph: 1^{st} Representation



Interprocedural Flow Graph

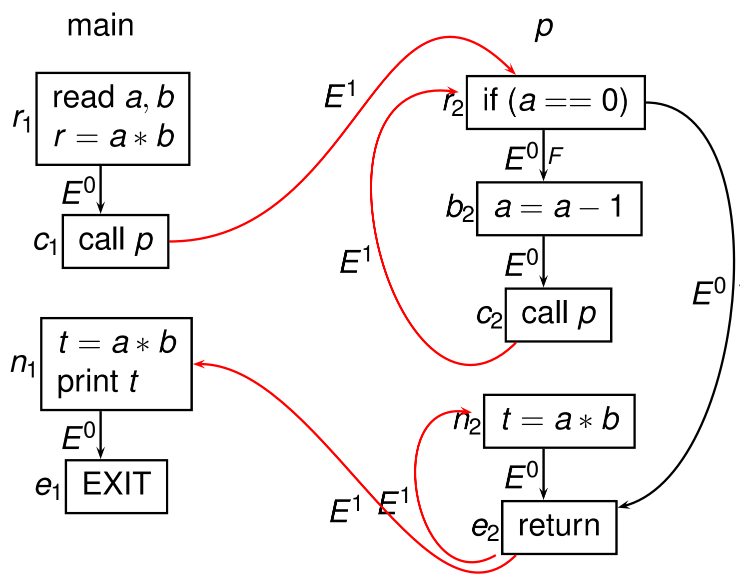
Second representation

$$G^* = (N^*, E^*, r_1)$$
$$r_1 = \text{root block of main}$$
$$N^* = \bigcup_p N_p$$
$$E^* = E^0 \cup E^1$$
$$E^0 = \bigcup_p E^0_p$$
$$(m, n) \in E^1 \Leftrightarrow (m, n) \text{ is either a } \textit{call} \text{ edge or a } \textit{return} \text{ edge}$$

Interprocedural Flow Graph

- Call edge (m, n):
  - m is a call block, say calling p
  - n is root block of p
- Return edge (m, n):
  - m is an exit block of p
  - n is a block immediately following a call to p
- Call edge (m, r_p) *corresponds* to return edge (e_q, n)
  - if $p = q$ and
  - $(m, n) \in E^1_s$ for some procedure s

Interprocedural Flow Graph: 2^{nd} Representation



Interprocedurally Valid Paths

- G^* ignores the special nature of call and return edges
- Not all paths in G^* are feasible
  - do not represent potentially valid execution paths
- $\text{IVP}(r_1, n)$: set of all interprocedurally valid paths from r_1 to n
- Path $q \in \text{path}_{G^*}(r_1, n)$ is in $\text{IVP}(r_1, n)$
  - iff sequence of all E^1 edges in q (denoted q_1)is *proper*

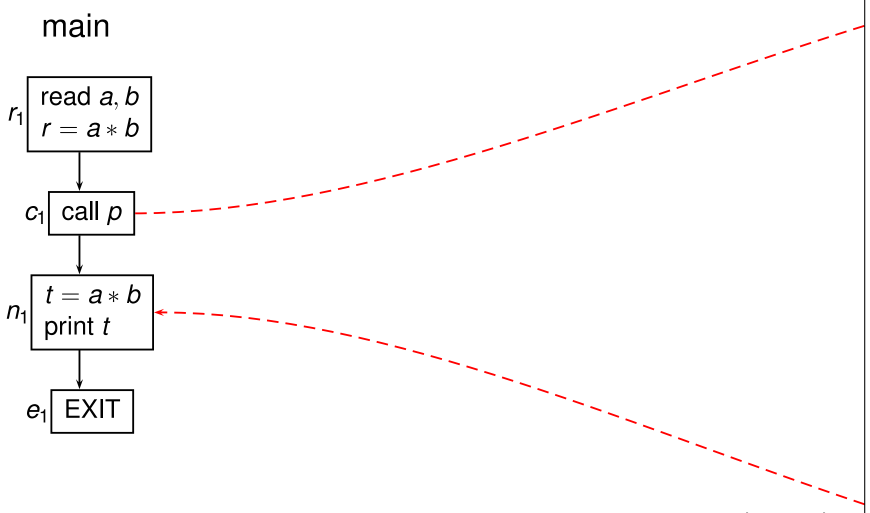
Proper sequence

- q_1 without any return edge is proper
- let $q_1[i]$ be the first return edge in q_1. q_1 is proper if
  - $i > 1$; and
  - $q_1[i-1]$ is call edge corresponding to $q_1[i]$; and
  - q_1' obtained from deleting $q_1[i-1]$ and $q_1[i]$ from q_1 is proper

Interprocedurally Valid Complete Paths

- $\text{IVP}_0(r_p, n)$ for procedure p and node $n \in N_p$
- set of all interprocedurally valid paths q in G^* from r_p to n s.t.
  - Each call edge has corresponding return edge in q restricted to E^1

IVPs



$r_1 \to c_1 \to r_2 \to c_2 \to r_2 \to e_2 \to n_2 \to e_2 \to n_1 \to e_1 \in \text{IVP}(r_1, e_1)$ r_1

Path Decomposition

$$
\begin{array}{rcl}
q & \in & \mathrm{IVP}(r_{\mathrm{main}}, n) \\
 & \Leftrightarrow & \\
q & = & q_1 \parallel (c_1, r_{p_2}) \parallel q_2 \parallel \cdots \parallel (c_{j-1}, r_{p_j}) \parallel q_j \\
 & & \text{where for each } i < j, q_i \in \mathrm{IVP}_0(r_{p_i}, c_i) \text{ and } q_j \in \mathrm{IVP}_0(r_{p_j}, n)
\end{array}
$$