

CSC2/455 Software Analysis and Improvement

Live variable analysis

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Outline

Review

Live Variable Analysis

Live Variables using Iterative Data flow Analysis

Postscript

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What we know how to do so far

- ▶ Basic blocks to Control Flow Graphs
 - ▶ Section 5.4.3 in Cooper and Turczon
- ▶ Local optimizations (Value Numbering)

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Motivation

```
void example(int x) {  
    int a = 0;  
    int b = 0;  
  
    if(x > 1) {  
        a = b;  
    } else {  
        a = x;  
    }  
  
    return a;  
}
```

Must the compiler emit code to initialize a to 0?

Motivation

```
void example(int x) {  
    int a = 0;  
    int b = 0;  
  
    if(x > 1) {  
        a = b;  
    } else {  
        a = x;  
    }  
  
    return a;  
}
```

a is *defined* (i.e. written) thrice in the code above. Which definitions are “alive” at return a ?

Terminology

- ▶ A variable x is live at a definition (i.e. a write) if there is a subsequent read of the variable along a program path from that definition.
- ▶ Can we identify live variables just by analyzing basic blocks (i.e. local analysis)?

More Motivation(?)

```
void test() {  
    int i;  
  
    // begin delay  
    for(i = 0; i < 10000; i++);  
    // end delay  
}
```

GCC without optimization

```
test():
    push    rbp
    mov     rbp, rsp
    mov     DWORD PTR [rbp-4], 0
.L3:
    cmp     DWORD PTR [rbp-4], 9999
    jg     .L4
    add     DWORD PTR [rbp-4], 1
    jmp    .L3
.L4:
    nop
    pop     rbp
    ret
```

Code courtesy Compiler Explorer at godbolt.org (this is more convenient than `gcc -Wa` if you have the Internet)

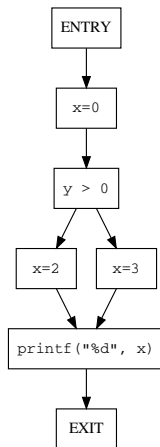
GCC with -O3

```
test():  
    ret
```

Code courtesy Compiler Explorer at godbolt.org

Example 1

```
x = 0;  
  
if(y > 0)  
    x = 2;  
else  
    x = 3;  
  
printf("%d\n", x);
```

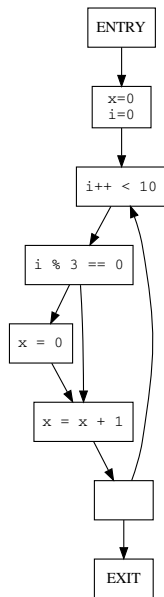


Example 2

```
x = 0
i = 0
while(i++ < 10) {
    if(i % 3 == 0) {
        x = 0;
    }

    x = x + 1;
}
```

- ▶ Which definition(s) of x are live at entry of loop?
- ▶ Which definition(s) of x are live in the loop?
- ▶ Which definition(s) of x are live at exit of loop?



Relook at the Loop example

```
    i = 1;  
L1:  if(!(i < 10000)) goto L2;  
    i++;  
    goto L1;  
  
L2:  
    return
```

Where in the CFG must i be “dead” to eliminate it?

Some Definitions

For a basic block s :

- ▶ $DEF(s)$ (for “defined”) is the set of variables written by s
- ▶ $USE(s)$ is the set of variables read by s

For the blocks below, what are the DEF and USE sets?

BB_eg_0:

$i = i + 1$

BB_eg_1:

$a = x;$

$x = 3;$

BB2_eg_2:

$t = a;$

Effects of definitions and reads

```
BB_eg_3:  
  a = x;  
  x = y;
```

- ▶ What happens to a definition of `a` in a basic block that is before `BB_eg_3` on some path through the CFG?
- ▶ What can we say about definitions of `y` in other basic blocks that are before `BB_eg_3` on some path through the CFG?

More definitions

- ▶ Upwardly exposed $UE(s)$ are those variables that are read *before* they are written to in basic block s .
- ▶ A variable is alive in a basic block if it is in the set:
 - ▶ ?
- ▶ A variable is killed in a basic block if it is in the set:
 - ▶ ?

Finding out if a definition is live

- ▶ Start from the definition, and see if it “reaches” a use
 - ▶ i.e., it is not killed on *some* path (in the CFG) to a use
- ▶ Start from a use, and walk backwards to see if you can reach the definition
 - ▶ Repeat for all uses

When does enumerating paths work in practice?

A More Practical Way: Iterative Data flow Analysis

- ▶ Setup data flow equations
- ▶ Solve these data flow equations

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Equations for Live Variables

- ▶ Remember that each basic block has “incoming” edges (from predecessors) and “outgoing” edges (to successors).
- ▶ When is an “incoming” variable live “into” a block?
 - ▶ it is in UE for that block
- ▶ When is a variable live out of a block?
 - ▶ it is live into a successor block
 - ▶ first try: $LIVEOUT(n) = \cup_m UE(m)$ (where $m \in succ(n)$)
 - ▶ what are we missing?

Complete equation

$$\text{LIVEOUT}(n) = \cup_{m \in \text{succ}(n)} \text{UE}(m) \cup (\text{LIVEOUT}(m) \cap \overline{\text{DEF}(m)})$$

The variables live out of block n must:

- ▶ be upwardly exposed in a successor m
- ▶ OR be live out of m and NOT be killed by m (i.e. $\overline{\text{DEF}(m)}$)
 - ▶ note this is equivalent to $(\text{LIVEOUT}(m) - \text{DEF}(m))$

How would you begin solving this equation?

Iterative Data flow Analysis Algorithm for Live Variables

- ▶ Live variables is a *backwards dataflow analysis*
 - ▶ ‘Facts’ flow from a node’s successors to it
- ▶ Initialization:
 - ▶ Compute $DEF(s)$ for all blocks s
 - ▶ Compute $UE(s)$ for all blocks s
 - ▶ Set $LIVEOUT(s) = \emptyset$ for all s
- ▶ Repeat (iterate):
 - ▶ Compute $LIVEOUT(s)$ for all blocks s
 - ▶ Until no set $LIVEOUT(s)$ changes – i.e. until a fixpoint is reached.

Termination and correctness

- ▶ Termination
 - ▶ Note $\text{LIVEOUT}(s)$ only increases in size or remains the same in every iteration
 - ▶ What is the maximum size of $\text{LIVEOUT}(s)$?
- ▶ Correctness
 - ▶ When the algorithm terminates, all computed $\text{LIVEOUT}(s)$ sets satisfy the equation
 - ▶ and hence meet the definition of “liveness” .

Quality of solution?

How does the iterative solution differ from the path-based solution?

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References

- ▶ Chapter 8 of Cooper and Turczon
 - ▶ Section 8.6.1
- ▶ Also recommended:
 - ▶ Aho, Lam, Sethi and Ullman, Chapter 9, Section 9.2.5