

CSC2/455 Software Analysis and Improvement

Live variable analysis

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URCS

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;    /* def 1 */  
    int b = 0;    /* def 2 */  
  
    if(x > 1) {  
        a = b;    /* def 3 */  
    } else {  
        a = x;    /* def 4 */  
    }  
  
    return a;  
}
```

Must the compiler emit code to initialize a to 0?

Motivation

```
void example(int x) {
    int a = 0;    /* def 1 */
    int b = 0;    /* def 2 */

    if(x > 1) {
        a = b;    /* def 3 */
    } else {
        a = x;    /* def 4 */
    }

    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.
 - Alternatively: is this variable overwritten along all paths before a subsequent read?
- 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
```

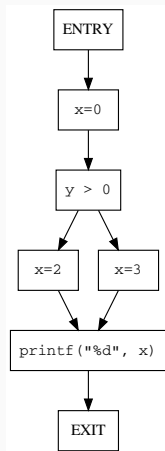
Code courtesy Compiler Explorer at godbolt.org (this is more convenient than `gcc -Wa` if you have access to the Internet)

```
test():  
    ret
```

Code courtesy Compiler Explorer at godbolt.org

Example 1

```
x = 0; /* d1 */  
  
if(y > 0)  
    x = 2; /* d2 */  
else  
    x = 3; /* d3 */  
  
printf("%d\n", x);
```

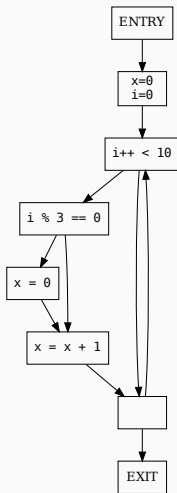


Example 2

```
x = 0          /* d1 */
i = 0          /* d2 */
while(i++ < 10) { /* d3 */
    if(i % 3 == 0) {
        x = 0; /* d4 */
    }

    x = x + 1; /* d5 */
}
```

- 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

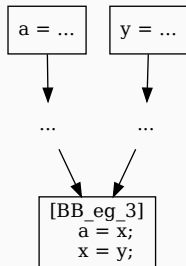
For the blocks below, what are the DEF and USE sets?

```
BB_eg_0:  
  i = i + 1
```

```
BB_eg_1:  
  a = x;  
  x = 3;
```

```
BB2_eg_2:  
  t = a;
```

Effects of definitions and reads



- 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?

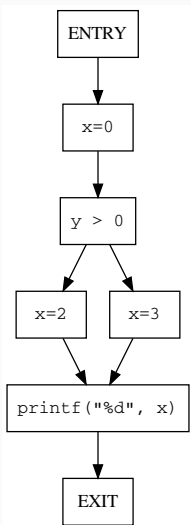
More definitions

- Upwardly exposed $UE(s)$ are those variables that are read *before* they are written to in basic block s .
 - e.g. x and y in BB_{eg_3} in the previous slide
- 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:
 - ?

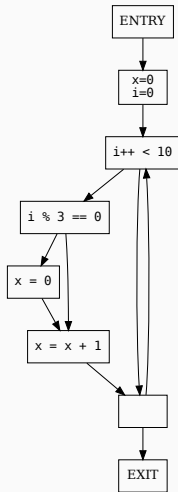
Finding out if a definition is live

- 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

Example #1



Example #2



Limitations

When does enumerating paths work in practice?

A More Practical Way: Iterative Data flow Analysis

- Setup data flow equations
- Solve these data flow equations

Outline

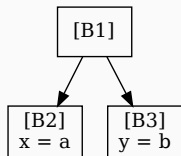
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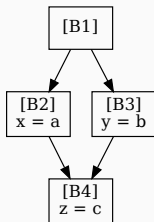
Postscript

Equations for Live Variables



- 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 n ?
 - it is live into a successor block m
 - 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 $LIVEOUT(s)$ only increases in size or remains the same in every iteration
 - What is the maximum size of $LIVEOUT(s)$?
- Correctness
 - When the algorithm terminates, all computed $LIVEOUT(s)$ 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
- Spare time reading (esp. for PhD students):
 - Frances E. Allen, John Cocke, 1971, A Catalogue of Optimizing Transforms