CSC2/455 Software Analysis and Improvement
Live variable analysis

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URCS

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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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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)?
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

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

ENTRY

```
x=0
```

EXIT

```
y > 0
```

```
x=2
x=3
```

```
printf("%d", x)
```

EXIT
Example 2

```c
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?
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 $s$:

- $\text{DEF}(s)$ (for “defined”) is the set of variables written by $s$
- $\text{USE}(s)$ is the set of variables read by $s$

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

- $\text{BB\_eg\_0}$:
  
  $$i = i + 1$$

- $\text{BB\_eg\_1}$:
  
  $$a = x;$$
  $$x = 3;$$

- $\text{BB2\_eg\_2}$:
  
  $$t = a;$$

In general, which variables are kept “alive” and which are “killed” by a basic block in terms of its DEF and USE sets?
More definitions

- Upwardly exposed $\text{UE}(s)$ are those variables that are read *before* they are written to in basic block $s$.
- A variable is alive in a basic block if:
  - ?
- A variable is killed in a basic block if:
  - ?
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
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: \( \text{LIVEOUT}(n) = \bigcup_m \text{UE}(m) \) (where \( m \in \text{succ}(n) \))
  ▶ what are we missing?
LIVEOUT(n) = \bigcup_{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 \( (\text{LIVEOUT}(m) - \overline{\text{DEF}(m)}) \)

How would you begin solving this equation?
Live variables is a *backwards dataflow analysis*

- ‘Facts’ flow from a node’s successors to it

**Initialization:**
- Compute $\text{DEF}(s)$ for all blocks $s$
- Compute $\text{UE}(s)$ for all blocks $s$
- Set $\text{LIVEOUT}(s) = \emptyset$ for all $s$

**Repeat (iterate):**
- Compute $\text{LIVEOUT}(s)$ for all blocks $s$
- Until no set $\text{LIVEOUT}(s)$ 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