CSC2/455 Software Analysis and Improvement

Live variable analysis

Sreepathi Pai
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URCS
Outline

Review

Live Variable Analysis

Live Variables using Iterative Data flow Analysis

Postscript
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Postscript
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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Postscript
Must the compiler emit code to initialize \texttt{a} to 0?
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.

- Can we identify live variables just by analyzing basic blocks (i.e. local analysis)?
void test() {
    int i;

    // begin delay
    for(i = 0; i < 10000; i++);
    // end delay
}

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)
test():
  ret

Code courtesy Compiler Explorer at godbolt.org
Example 1

\begin{verbatim}
x = 0; /* d1 */
if(y > 0)
    x = 2; /* d2 */
else
    x = 3; /* d3 */
printf("%d\n", x);
\end{verbatim}
Example 2

```c
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

\begin{verbatim}
 i = 1;
L1:
  if(!(i < 10000)) goto L2;
i++;  
goto L1;
L2:
  return
\end{verbatim}

Where in the CFG must \( i \) be “dead” to eliminate it?
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 $\text{DEF}$ and $\text{USE}$ sets?

BB$_{eg\_0}$:
\[
i = i + 1
\]

BB$_{eg\_1}$:
\[
a = x; \\
x = 3;
\]

BB$_{2\_eg\_2}$:
\[
t = a;
\]
• 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 \textit{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

- 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?
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 ($\overline{\text{LIVEOUT}(m)} - \text{DEF}(m)$)

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?
References

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