# CSCI 742 - Compiler Construction

Lecture 33
Live Variable Analysis
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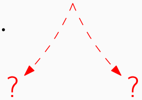
# Recap: Control Flow Graphs

- **Control Flow Graph (CFG):** graph representation of computation and control flow in the program
- Framework to statically analyze program control-flow
- Next: use CFG to statically extract information about program
- Reason at compile-time about run-time values of variables in all program executions
- Data-flow analysis: gather information about the possible set of values of variables at various points in a program

# Liveness

- Liveness is a data-flow property of variables:
  "Is the value of this variable needed?"
- Optimization: eliminate assignments to dead variables
  (i.e. variables that are never used after definitions)

```
int f(int x, int y) {
  int z = x + y;
...
```




- Live variable analysis is **undecidable** in general
- We compute a syntactic and conservative approximation of liveness
  - Like many other data-flow analysis techniques

```
int f(int x, int y) {
  int z = x + y;
  if (tricky-calculation) x = z;
  return x;
}
```

# Live Variable Analysis: Backward

- Liveness is naturally computed using **backward** data-flow analysis
- Usage information from future statements must be propagated backward through the program to discover which variables are live

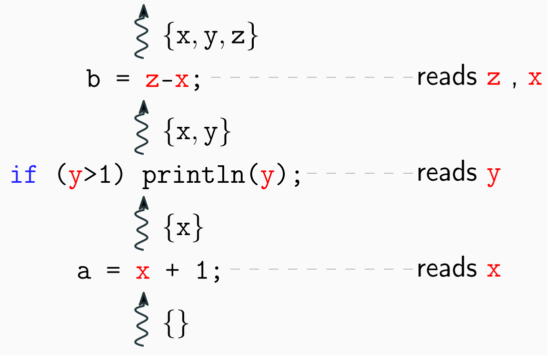
```
int f(int x, int y) {
   int z = x + y;
...

int t=z-2;    println(z);

         if(z!=2) ...;
```

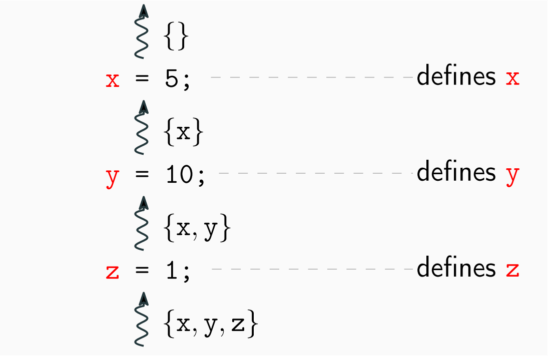
# Live Variable Analysis

- Variable liveness flows backward through the program
- Each statement has an effect on liveness information as it flows past
- A statement makes a variable **live** when it reads it



# Live Variable Analysis

- Variable liveness flows backward through the program
- Each statement has an effect on liveness information as it flows past
- A statement makes a variable **dead** when it defines (assigns to) it



# Live Variable Analysis

As liveness flows backwards past an statement, we modify liveness information:

- Add any variables which it reads (they become live)
- Remove any variables which it defines (they become dead)

$\{x, y\}$

$use(\texttt{println(x)}) = \{ \texttt{x} \}$

$\{y\}$

$\{y\}$

$def(\texttt{x = 3}) = \{ \texttt{x} \}$

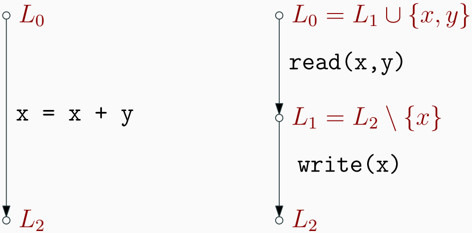
$\{x, y\}$

Variable $v$ is live before a statement $S$ if:

1. There is a statement $S'$ in CFG that *use*s $v$
2. There exists a path from $S$ to $S'$ passing through no *def* of $v$

# Live Variable Analysis

- If a statement both references and defines variables, remove the defined variables before adding the read ones
- $L_0$ Initial set of live variables




$$L_0 = \big(L_2 \setminus \{x\}\big) \ \cup \ \{x, y\}$$

In general:

- *in*$(S)$: set of live variables immediately before statement $S$
- *out*$(S)$: set of live variables immediately after statement $S$

$$\textit{in}(S) = \big(\textit{out}(S) \setminus \textit{def}(S)\big) \ \cup \ \textit{use}(S)$$

# Straight-Line Code

- In straight-line code each node has a unique successor
- Variables live at the exit of a node are exactly those variables live at the entry of its successor

$i_1$:

$out(i_1) = \{ \texttt{x} , \texttt{y} , \texttt{z} \}$

$in(i_2) = \{ \texttt{x} , \texttt{y} , \texttt{z} \}$

$i_2$: `x = x+y`

$out(i_2) = \{ \texttt{x} , \texttt{z} \}$

$in(i_3) = \{ \texttt{x} , \texttt{z} \}$

$i_3$: `println(x)`

$out(i_3) = \{ \texttt{z} \}$

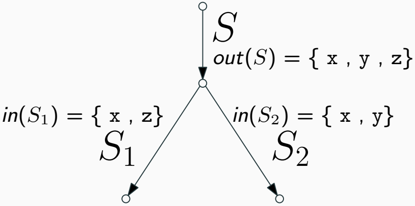
$in(i_4) = \{ \texttt{z} \}$

$i_4$:

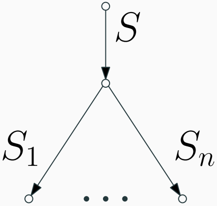
# Multiple Successors

- In general each node has an arbitrary number of successors
- Variables live at the exit of a node are exactly those variables live at the entry of all its successors

**Example:**




**General:**




$$out(S) = \bigcup_{S_i \in succ(S)} in(S_i)$$

# Data-flow Equations

- Start with CFG and derive a system of constraints between live variable sets

$$
\begin{aligned}
\mathit{in}(S) &= \big(\mathit{out}(S) \setminus \mathit{def}(S)\big) \ \cup\ \mathit{use}(S) \\
\mathit{out}(S) &= \bigcup_{S_i \in \mathit{succ}(S)} \mathit{in}(S_i)
\end{aligned}
$$

Solve constraints:

- Start with empty sets of live variables
- Iteratively apply constraints
- Stop when we reach a fixed point

# Constraint Solving Algorithm

**for** all statements $S$ **do**

$\quad$ $\mathit{in}(S) = \mathit{out}(S) = \emptyset$

**repeat**

$\quad$ **select** a statement $S$ such that

$$\mathit{in}(S) \neq (\mathit{out}(S) \setminus \mathit{def}(S)) \cup \mathit{use}(S)$$

$\quad$ or (respectively)

$$\mathit{out}(S) \neq \bigcup_{S_i \in \mathit{succ}(S)} \mathit{in}(S_i)$$

$\quad$ update $\mathit{in}(S)$ (or $\mathit{out}(S)$) accordingly

**until** no such change is possible

# Exercise

- Compute the set of live variables at each point of the program

```
x = 5;
y = 10;
z = 0;
while (x > 0) {
  x = x - 1;
  u = y;
  while (u > 0) {
    u = u - 1;
    z = z + 1;
  }
}
```

# Exercise

- Compute the set of live variables at each point of the program

```
x = 5;
y = 10;
z = 0;
while (x > 0) {
  x = x - 1;
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```

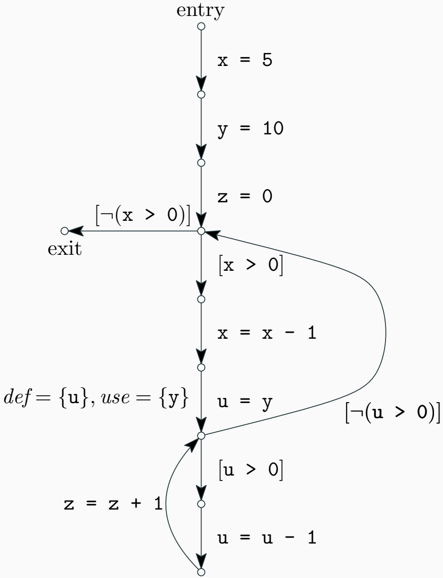


$$in(S) = \big(out(S) \setminus def(S)\big) \ \cup \ use(S)$$

$$out(S) = \bigcup_{S_i \in succ(S)} in(S_i)$$

# Intra/Inter-Procedural Analysis

- **Intra-procedural** Analysis: analyzing the body of a single procedure
- **Inter-procedural** Analysis: analyzing the whole program with function calls

```
x = 0;
  // is y live here? (yes iff used in procedure P)
P();
  // is x still equal to 0 here?
  // (yes iff not changed in P)
y = x;
```

# Intra/Inter-Procedural Analysis

A naïve and safe approach to inter-procedural analysis:

- Assume any function will read and write all global variables (worst case scenario)
- Every global variable is live before any function call!

- Leads to over-cautious optimizations
- There are more accurate inter-procedural analyses that consider the call graph of a program
  - (beyond the scope of the course)

# Aliases

- Most languages use variables containing addresses
  - e.g. pointers (C,C++), references (Java), call-by-reference parameters (Pascal, C++, Fortran)
- Pointer aliases: multiple names for the same memory location
  - Dereferencing the aliases returns the same object
- Problem: Don't know what variables read and written by accesses via pointer aliases
  (e.g. `*p=y; x=*p; p->f=y; x=p->f;` etc.)
- Need to know accessed variables to compute dataflow information after each instruction

# Aliases

- Worst-case scenarios:

> - `*p = y` may write any memory location
> - `x = *p` may read any memory location

- All the variables may be live before `x = *p`
- Leads to over-cautious optimizations
- There are more accurate pointer alias analyses
  - (beyond the scope of the course)