CS 526
Advanced Compiler Construction

https://charithm.web.illinois.edu/cs526/sp2024/
(slides adapted from Sasa and Vikram)
Announcements

• Join CS 526 on CampusWire.
• We will be using it for mini-quizzes starting from the 3rd week.
• Build LLVM and get familiar with the infrastructure next week.
• We are using LLVM 8.0.1 for Project 1.
• We may try to upgrade before the project is released.
We will cover

• Control Flow Graphs
• Dominance
• Loops
• SSA form introduction
CONTROL FLOW ANALYSIS

The slides adapted from Vikram Adve
Flow Graphs

**Flow Graph:** A triple $G=(N,A,s)$, where $(N,A)$ is a (finite) directed graph, $s \in N$ is a designated “initial” node, and there is a path from node $s$ to every node $n \in N$.

- An *entry node* in a flow graph has no predecessors.
- An *exit node* in a flow graph has no successors.
- There is exactly one entry node, $s$. We can modify a general DAG to ensure this. *How?*
Control Flow Graph (CFG)

Flow Graph: A triple $G=(N,A,s)$, where $(N,A)$ is a (finite) directed graph, $s \in N$ is a designated “initial” node, and there is a path from node $s$ to every node $n \in N$.

Control Flow Graph (CFG) is a flow graph that represents all paths (sequences of statements) that might be traversed during program execution.

- Nodes in CFG are program statements, and edge $(S_1,S_2)$ denotes that statement $S_1$ can be followed by $S_2$ in execution.
- In CFG, a node unreachable from $s$ can be safely deleted. Why?
- Control flow graphs are usually sparse. I.e., $|A| = O(|N|)$. In fact, if only binary branching is allowed $|A| \leq 2|N|$. 

Control Flow Graph (CFG)

**Basic Block** is a sequence of statements $S_1 \ldots S_n$ such that execution control must reach $S_1$ before $S_2$, and, if $S_1$ is executed, then $S_2 \ldots S_n$ are all executed in that order.

- Unless a statement causes the program to halt

**Leader** is the first statement of a basic block.

**Maximal Basic Block** is a basic block with a maximum number of statements ($n$).
Control Flow Graph (CFG)

Let us refine our previous definition

CFG is a directed graph in which:

- Each node is a single basic block
- There is an edge $b_1 \rightarrow b_2$ if block $b_2$ may be executed after block $b_1$ in some execution

We typically define it for a single procedure

A CFG is a conservative approximation of the control flow! Why?
Example

Source Code

```c
unsigned fib(unsigned n) {
    int i;
    int f0 = 0, f1 = 1, f2;
    if (n <= 1) return n;
    for (i = 2; i <= n; i++) {
        f2 = f0 + f1;
        f0 = f1;
        f1 = f2;
    }
    return f2;
}
```

LLVM bitcode (ver 3.9.1)

```assembly
define i32 @fib(i32 %0) {
    %2 = icmp ult i32 %0, 2
    br i1 %2, label %12, label %3
    ; <label>:3:
    br label %4
    ; <label>:4:
    %5 = phi i32 [ %8, %4 ], [ 1, %3 ]
    %6 = phi i32 [ %5, %4 ], [ 0, %3 ]
    %7 = phi i32 [ %9, %4 ], [ 2, %3 ]
    %8 = add i32 %5, %6
    %9 = add i32 %7, 1
    %10 = icmp ugt i32 %9, %0
    br i1 %10, label %11, label %4
    ; <label>:11:
    br label %12
    ; <label>:12:
    %13 = phi i32 [%0, %1], [%8, %11]
    ret i32 %13
}
```
Dominance in Flow Graphs

Let \( d, d_1, d_2, d_3, n \) be nodes in \( G \).

\( d \) dominates \( n \) ("\( d \text{ dom} n \)"") iff every path from \( s \) to \( n \) contains \( d \)

\( d \) properly dominates \( n \) if \( d \) dominates \( n \) and \( d \neq n \)

\( d \) is the immediate dominator of \( n \) ("\( d \text{ idom} n \)"") if \( d \) is the last proper dominator on any path from initial node to \( n \),

\( \text{DOM}(x) \) denotes the set of dominators of \( x \),

**Dominator tree**: the children of each node \( d \) are the nodes \( n \) such that "\( d \text{ idom} n \)" (immediately dominates)
Dominator Properties

**Lemma 1:** $\text{DOM}(s) = \{ s \}$.

**Lemma 2:** $s \text{ dom } d$, for all nodes $d$ in $G$.

**Lemma 3:** The dominance relation on nodes in a flow graph is a *partial ordering*

- **Reflexive** — $n \text{ dom } n$ is true for all $n$.
- **Antisymmetric** — If $d \text{ dom } n$, then cannot be $n \text{ dom } d$
- **Transitive** — $d_1 \text{ dom } d_2 \land d_2 \text{ dom } d_3 \Rightarrow d_1 \text{ dom } d_3$

**Lemma 4:** The dominators of a node form a list.

**Lemma 5:** Every node except $s$ has a unique immediate dominator.
Finding Dominators in a Flow Graph

**Input**: A flow graph $G = (N, A, s)$.

**Output**: The sets $\text{DOM}(\text{node})$ for each node $\in N$.

\[
\begin{align*}
\text{DOM}(s) & := \{ s \} \\
\text{forall } n \in N - \{ s \} \text{ do} & \\
\quad \text{DOM}(n) & := N \\
\quad \text{od} \\
\text{while changes to any $\text{DOM}(n)$ occur do} & \\
\quad \text{forall } n \text{ in } N - \{ s \} \text{ do} & \\
\quad \quad \text{DOM}(n) & := \{ n \} \cup \bigcap_{p \rightarrow n} \text{DOM}(p) \\
\quad \quad \text{od} \\
\quad \text{od} \\
\end{align*}
\]
Finding Dominators in a Flow Graph

Input: A flow graph $G = (N, A, s)$.
Output: The sets $\text{DOM}(\text{node})$ for each node $\in N$.

\[
\text{DOM}(s) := \{ s \}
\]

forall $n \in N - \{s\}$ do
  $\text{DOM}(n) := N$
  od

while changes to any $\text{DOM}(n)$ occur do
  forall $n$ in $N - \{s\}$ do
    $\text{DOM}(n) := \{n\} \cup \bigcap_{p \rightarrow n} \text{DOM}(p)$
  od
  od

Initialize

Iterate
Loops

while (b) { ... } ⇒ ?
Loops

The right definition of “loop” is not obvious.

Obviously bad definitions

• **Cycle:** Not necessarily properly nested or disjoint
• **Strongly Connected Components:**
  Too coarse; no nesting information

What properties of the loops do we want to extract from CFG?
Natural Loops

Def. **Back Edge**: An edge $n \rightarrow d$ where $d$ dom $n$

Def. **Natural Loop**: Given a back edge, $n \rightarrow d$, the natural loop corresponding to $n \rightarrow d$ is the set of nodes \{d + all nodes that can reach n without going through d\}

Def. **Loop Header**: The node $d$ within the loop that dominates all nodes in the loop

- Header is unique for each natural loop **Why**?
- Implies $d$ is the unique entry point into the loop
- Uniqueness is very useful for many optimizations
Natural Loops

Pros:
+ Intuitive, and similar to SCC.
+ Single entry point: “loop header”.
+ Identifies nested loops (if different headers)

Cons:
- Nested loops are not (necessarily) disjoint.
- Some nodes are not part of any natural loop.
- Does not include some cycles in “irreducible” flow graphs.
Reducibility of Flow Graphs

Def. **Reducible** *flow graph*: a flow graph G is called reducible iff we can partition the edges into 2 disjoint sets:

- **forward edges**: should form a DAG in which every node is reachable from initial node s (or also header)
- **remaining edges must be back edges**: i.e., only those edges \( n \rightarrow d \) such that \( d \) dom \( n \)

**Idea:**
Every “cycle” has at least one back edge
⇒ All “cycles” are natural loops
Otherwise graph is called irreducible.

*Well-structured*
**Alternative to natural Loops**

**Natural loop**
- Defined using dominators

**Intervals**
- Defined in terms of reachability in flow graph (e.g. Muchnick, Sections 7.6 and 7.7)
- Main idea: split the flow graph in smaller regions (abstract nodes) that contain other nodes
STATIC SINGLE ASSIGNMENT

The slides adapted from Vikram Adve

Muchnick, Section 8.11 (partially covered).

Engineering a Compiler, Section 5.4.2 (partially covered).
Some Definitions

**Value**: expression that cannot be evaluated further (numbers, words, memory addresses, ...)  

**Storage location**: register or memory address  
- Machine and virtual registers  
- Stack and heap

**Variable**: named storage location (map from name to address)  

**Pointer**: variable whose value is another memory location

**Alias**: an alternative name of an entity (a variable, a location, ...)
What is SSA Form?

What is intermediate language?

Design tradeoffs:
• Expressive enough to represent source code information unambiguously
• Efficient for (numerous) optimizations and analyses
• Can easily generate backend code from it

Why do we study SSA?
What is SSA Form?

(Informally) A program can be converted into SSA form as follows:

• Each assignment to a variable is given a unique name
• All of the uses reached by that assignment are renamed.

Easy for straight-line code:

\[
\begin{align*}
V &\leftarrow 4 \\
\ldots &\leftarrow V + 5 \\
V &\leftarrow 6 \\
\ldots &\leftarrow V + 7
\end{align*}
\]
What is SSA Form?

(Informally) A program can be converted into SSA form as follows:

• Each assignment to a variable is given a unique name
• All of the uses reached by that assignment are renamed.

Easy for straight-line code:

\[ \mathbf{V}_0 \leftarrow 4 \]
\[ \ldots \leftarrow \mathbf{V}_0 + 5 \]
\[ \mathbf{V}_1 \leftarrow 6 \]
\[ \ldots \leftarrow \mathbf{V}_1 + 7 \]
SSA Straight-line Code

\[
\begin{align*}
X &= 1; \\
X &= X + 1; \\
Y &= X;
\end{align*}
\]
SSA Straight-line Code

\[ X_0 = 1; \]
\[ X_1 = X_0 + 1; \]
\[ Y = X_1; \]
SSA Straight-line Code

\[
X = 1; \\
Y = f(X); \\
X = Y + X;
\]
SSA Straight-line Code

\[ X_0 = 1; \]
\[ Y_0 = f(X_0); \]
\[ X_1 = Y_0 + X_0; \]
SSA and Branches

if (...
   X = 42;
else
   X = 7*7;

Y = X;
SSA and Branches

if (...)  
    \textcolor{red}{\texttt{X1 = 42;}}  
else  
    \textcolor{red}{\texttt{X2 = 7*7;}}  
\textcolor{red}{\texttt{X3 = \phi(X1, X2)}}  
\textcolor{red}{\texttt{Y = X;}}
SSA and Branches

if (...) 
    \( X_1 = 42; \)
else
    \( X_2 = 7*7; \)
\( X_3 = \varphi(X_1, X_2) \)
\( Y = X_3; \)
SSA and Branches

\[ X = 0; \]
\[ \text{if (...)} \]
\[ \quad X = 42; \]

\[ Y = X; \]
SSA and Branches

\[ X_1 = 0; \]
\[ \text{if (…)} \]
\[ X_2 = 42; \]
\[ X_3 = \varphi(X_1, X_2) \]
\[ Y = X; \]
SSA and Branches

\[ X_1 = 0; \]
\[
\text{if (\ldots)}
\]
\[
X_2 = 42;
\]
\[ X_3 = \phi(X_1, X_2) \]
\[ Y = X_3; \]
SSA and Branches

\[
X = 0;
\]

\[
\text{if ( \ldots )} \{
    \begin{align*}
    &\text{\quad if ( \ldots )} \\
    &\quad X = 42; \\
    &\text{else} \\
    &\quad X = 7*7;
    \end{align*}
\}
\]

\[
Y = X;
\]
SSA and Branches

\[
x_0 = 0;
\]

if (...) {

    if (...) {
        \[
x_1 = 42;
        \]
    }
    else {
        \[
x_2 = 7*7;
        \]
        \[
x_3 = \varphi(x_1, x_2)
        \]
    }

} \\
\[
x_4 = \varphi(x_0, x_3)
\]

\[
Y = X;
\]
SSA and Branches

\[ X_0 = 0; \]
if (...) {
    if (....)
        \[ X_1 = 42; \]
    else
        \[ X_2 = 7*7; \]
        \[ X_3 = \varphi(X_1, X_2) \]
} \[ X_4 = \varphi(X_0, X_3) \]
Y = X_4;
SSA and Loops

j=1;               j = 1;

while (j < X)      if (j >= X) goto E;
    ++j;          

N = j;            S:
                    j = j+1;

E:
    N = j;
SSA and Loops

\[ j = 1; \]

\[ \text{while (} j < X \text{)} \]
\[ \quad ++j; \]

\[ N = j; \]

\[ j0 = 1; \]

\[ \text{if (} j0 \geq X \text{)} \text{ goto E}; \]

\[ S: \]
\[ \quad j = j+1; \]
\[ \quad \text{if (} j < X \text{)} \text{ goto S}; \]

\[ E: \]
\[ \quad N = j; \]
SSA and Loops

\[ j = 1; \]
\[ \text{while } (j < X) \]
\[ \quad \text{++} j; \]
\[ N = j; \]

\[ j^0 = 1; \]
\[ \text{if } (j^0 \geq X) \text{ goto } E; \]
\[ S: \quad j^1 = \varphi(j^0, j^2) \]
\[ j^2 = j^1 + 1; \]
\[ \text{if } (j^2 < X) \text{ goto } S; \]
\[ E: \]
\[ N = j; \]
SSA and Loops

\( j=1; \)

\[ \text{while } (j < X) \]
\[ \quad ++j; \]

\( N = j; \)

\( j_0 = 1; \)

if \( (j_0 >= X) \) goto E;

S: \( j_1 = \varphi(j_0, j_2) \)
\( j_2 = j_1 + 1; \)
if \( (j_2 < X) \) goto S;

E: \( j_4 = \varphi(j_0, j_2) \)
\( N = j_4; \)
SSA and Switches

\[
X = 0;
\]

\[
\text{switch (..) of}
\]

\[
\text{a: } X = 1;
\]

\[
\text{b: } X = 2;
\]

\[
\text{c: } X = 3;
\]

\[
\text{Y = X;}
\]
SSA and Switches

\[ X_0 = 0; \]

\[
\text{switch (\ldots) of}
\]

\[
\begin{align*}
  \text{a: } & X_1 = 1; \\
  \text{b: } & X_2 = 2; \\
  \text{c: } & X_3 = 3;
\end{align*}
\]

\[ Y = X; \]
SSA and Switches

\[
\begin{align*}
X_0 &= 0; \\
\text{switch (...) of} & \\
\quad a: & \quad X_1 = 1; \\
\quad b: & \quad X_2 = 2; \\
\quad c: & \quad X_3 = 3; \\
X_4 &= \varphi(X_0, X_1, X_2, X_3) \\
Y &= X_4;
\end{align*}
\]
Definition of $\varphi$ Function

In a basic block $B$ with $N$ predecessors, $P_1, P_2, \ldots, P_N$, 

$$X = \varphi(V_1, V_2, \ldots, V_N)$$

assigns $X = V_i$ if control enters block $B$ from $P_i$, $1 \leq i \leq N$

Properties of $\varphi$-functions:

• $\varphi$ is not an executable operation.
• $\varphi$ has exactly as many arguments as the number of incoming basic block edges
• Think about the argument $V_i$ as being evaluated on CFG edge from predecessor $P_i$ to $B$
Which Variables to Convert?

Convert all variables to SSA form, except . . .

**Arrays**: Array elements do not have an explicit name (although note ArraySSA)

**Variables that may have aliases**: do not have a unique name

**Volatile variables**: can be modified “unexpectedly”

E.g., In LLVM, only scalar variables in virtual registers are in SSA form.
LLVM: Mem2reg

-mem2reg: Promote Memory to Register

“This file promotes memory references to be register references. It promotes alloca instructions which only have loads and stores as uses. An alloca is transformed by using dominator frontiers to place phi nodes, then traversing the function in depth-first order to rewrite loads and stores as appropriate. This is just the standard SSA construction algorithm to construct “pruned” SSA form.”

```llvm
int f(int x) {
    int y = x + 1;
    return y
}

After mem2reg
%3 = add nsw i32 %0, 1
ret i32 %3

No optimizations
...
%6 = alloca i32, align 4
%7 = load i32, i32* %0, align 4
%8 = add nsw i32 1, %7
store i32 %8, i32* %6, align 4
%9 = load i32, i32* %6, align 4
ret i32 %9
```
More Definitions

**Use of a variable:** A use of variable $X$ is a reference that may read the value stored in the location named $X$.

**Definition of a variable:** A definition (def) of a variable $X$ is a reference that may store a value into the location named $X$. *Examples:* Assignment; input I/O

**Ambiguity of definitions:**
Unambiguous definition (must): guaranteed to store to $X$
Ambiguous definition (may): may store to $X$

Q. Where does ambiguity come from?
We define ambiguous/unambiguous use similarly.
Def-Use Chains

- **Def-use chain**: The set of uses reached by a particular definition.

- **Use-def chain**: The set of definitions reaching a particular use
Definition of SSA Form

A program is in SSA form if:

• each variable is assigned a value in **exactly one** statement
• each **use** of a variable is **dominated** by the **definition**
Advantages of SSA Form

Makes def-use and use-def chains explicit:

These chains are foundation of many dataflow optimizations
• We will see some soon!

Compact, flow-sensitive* def-use information
• fewer def-use edges per variable: one per CFG edge

* Takes the order of statements into account
Advantages of SSA Form (cont.)

No anti- and output dependences on SSA variables

• Direct dependence: \( A = 1; B = A + 1 \)
• Antidependence: \( A = 1; B = A + 1; A = 2 \)
• Output dependence: \( A = 1; A = 2; B = A + 1 \)

Explicit merging of values (\( \phi \)): key additional information

Can serve as IR for code transformations (see LLVM)
Disadvantages of SSA Form

Size of SSA program is $O(N^2)$ for an ordinary program with $N$ variables.

Often not used for structures and arrays

May not be used for scalar variables with aliases

If used as IR, must be converted back to code (Not bad)

Otherwise, must be recomputed frequently (Often bad)