Similarly, in Java:

```
a[1] = 1;
b[1] = 0;
print(a[1]);
```

is 1 or 0 printed?

Points-to analysis aims to determine what variables or heap objects a pointer or reference may access. Exact analysis is impossible (why?). But fast and reasonably accurate analyses are known.

Review of Compiler Optimizations

1. Redundant Expression Elimination (Common Subexpression Removal)

   Use an address or value that has been previously computed. Consider control and data dependencies.

2. Partially Redundant Expression (PRE) Elimination

   A variant of Redundant Expression Elimination. If a value or address is redundant along *some* execution paths, add computations to other paths to create a fully redundant expression (which is then removed).

   Example:

```
if (i > j)
   a[i] = a[j];
a[i] = a[i] * 2;
```


3. Constant Propagation

   If a variable is known to contain a particular constant value at a particular point in the program, replace references to the variable at that point with the constant value.

4. Copy Propagation

   After the assignment of one variable to another, a reference to one variable may be replaced with the value of the other variable (until one or the other of the variables is reassigned).

   (This may also “set up” dead code elimination. Why?)

5. Constant Folding

   An expression involving constant (literal) values may be evaluated and simplified to a constant result value. Particularly useful when constant propagation is performed.

6. Dead Code Elimination

   Expressions or statements whose values or effects are unused may be eliminated.

7. Loop Invariant Code Motion

   An expression that is *invariant* in a loop may be moved to the loop’s header, evaluated once, and reused within the loop.

   Safety and *profitability* issues may be involved.

8. Scalarization (Scalar Replacement)

A field of a structure or an element of an array that is repeatedly read or written may be copied to a local variable, accessed using the local, and later (if necessary) copied back.

This optimization allows the local variable (and in effect the field or array component) to be allocated to a register.

9. Local Register Allocation

Within a *basic block* **(a straight line sequence of code) track register contents and reuse variables and constants from registers.**

10. Global Register Allocation

Within a subprogram, frequently accessed variables and constants are allocated to registers. Usually there are *many more* **register candidates than available registers.**

11. Interprocedural Register Allocation

Variables and constants accessed by more than one subprogram are allocated to registers. This can *greatly* **reduce call/ return overhead.**

12. Register Targeting

Compute values directly into the intended target register.

13. Interprocedural Code Motion

Move instructions across subprogram boundaries.

14. Call Inlining

At the site of a call, insert the body of a subprogram, with actual parameters initializing formal parameters.

15. Code Hoisting and Sinking

If the same code sequence appears in two or more alternative execution paths, the code may be *hoisted* **to a common ancestor or** *sunk* **to a common successor. (This reduces code size, but does not reduce instruction count.)**

16. Loop Unrolling

Replace a loop body executed N times with an expanded loop body consisting of M copies of the loop body. This expanded loop body is executed N/M times, reducing loop overhead and increasing optimization possibilities within the expanded loop body.

17. Software Pipelining

A value needed in iteration *i* **of a loop is computed during iteration** *i-1* **(or** *i-2*, **...). This allows long latency operations (floating point divides and square roots, low hit-ratio loads) to execute in parallel with other operations. Software pipelining is sometimes called** *symbolic loop unrolling***.**

18. Strength Reduction

Replace an expensive instruction with an equivalent but cheaper alternative. For example a division may be replaced by multiplication of a reciprocal, or a list append may be replaced by cons operations.

19. Data Cache Optimizations

- **Locality Optimizations**

  Cluster accesses of data values both spacially (within a cache line) and temporally (for repeated use). *Loop interchange* **and** *loop tiling* **improve temporal locality.**

- **Conflict Optimizations**

  Adjust data locations so that data used consecutively and repeatedly don't share the same cache location.

20. Instruction Cache Optimizations

Instructions that are repeatedly executed should be accessed from the instruction cache rather than the secondary cache or memory. Loops and "hot" instruction sequences should fit within the cache.

Temporally close instruction sequences should not map to conflicting cache

Basic Blocks

A basic block is a linear sequence of instructions containing no branches except at the very end.

A basic block is always executed sequentially as a unit.

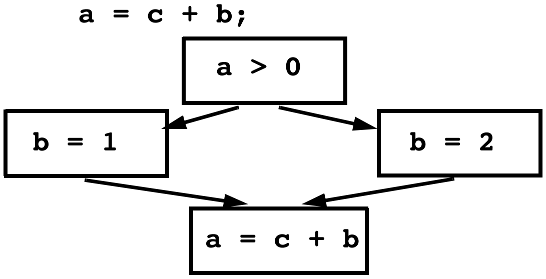
Control Flow Graphs

A Control Flow Graph (CFG) models possible execution paths through a program.

Nodes are basic blocks and arcs are potential transfers of control.

For example,

```
if (a > 0)
       b = 1;
else   b = 2;
a = c + b;
```



For a Basic Block b:

Let Preds(b) = the set of basic blocks that are Immediate Predecessors of b in the CFG.

Let Succ(b) = the set of basic blocks that are Immediate Successors to b in the CFG.

Data Flow Problems

A data flow problem is a program analysis computed on a control flow graph.

A data flow problem may be *forward* (following a program's control flow) or *reverse* (opposite a program's control flow).

Informally, forward analyses "remember the past" while reverse analyses "predict the future."

Some analyses determine that an event *may* have occurred, while others determine that an event *must* have occurred.

Some analyses compute a set of values, while others are Boolean-valued.

Two important data flow problems are *Reaching Definitions* and *Liveness*.

For a given use of a variable v reaching definitions tell us which assignments to v may reach (affect) the current value of v. Reaching definition analysis is useful in both optimization and debugging.

Liveness analysis tells us at a particular point in a program whether the current value of variable v will ever be used. A variable that is not live is dead. A dead value need not be kept in memory, or perhaps even be computed.

Reaching Definitions

For a Basic Block b and Variable V:

Let DefsIn(b) = the set of basic blocks that contain definitions of V that reach (may be used in) the beginning of Basic Block b.

Let DefsOut(b) = the set of basic blocks that contain definitions of V that reach (may be used in) the end of Basic Block b.

The sets Preds and Succ are derived from the structure of the CFG.

They are given as part of the definition of the CFG.

DefsIn and DefsOut must be computed, using the following rules:

1. If Basic Block b contains a definition of V then
   DefsOut(b) = {b}
2. If there is no definition to V in b then
   DefsOut(b) = DefsIn(b)
3. For the First Basic Block, b_0:
   $DefsIn(b_0) = \phi$
4. For all Other Basic Blocks
   $$DefsIn(b) = \bigcup_{p \in Preds(b)} DefsOut(p)$$

Liveness Analysis

For a Basic Block b and Variable V:

LiveIn(b) = true if V is Live (will be used before it is redefined) at the beginning of b.

LiveOut(b) = true if V is Live (will be used before it is redefined) at the end of b.

LiveIn and LiveOut are computed, using the following rules:

1. If Basic Block b has no successors then

LiveOut(b) = false

2. For all Other Basic Blocks

$$\text{LiveOut}(b) = \bigvee_{s \in \text{Succ}(b)} \text{LiveIn}(s)$$

3. LiveIn(b) =

If V is used before it is defined in Basic Block b

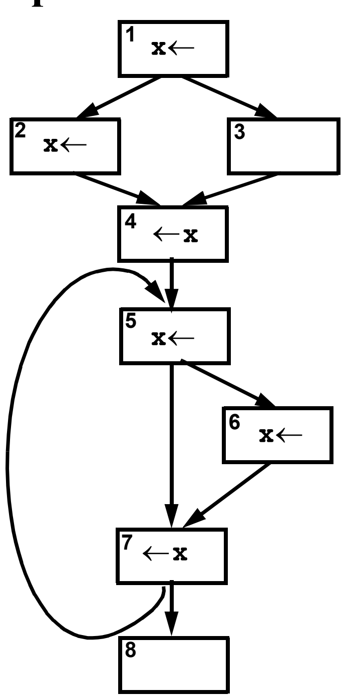
Then true

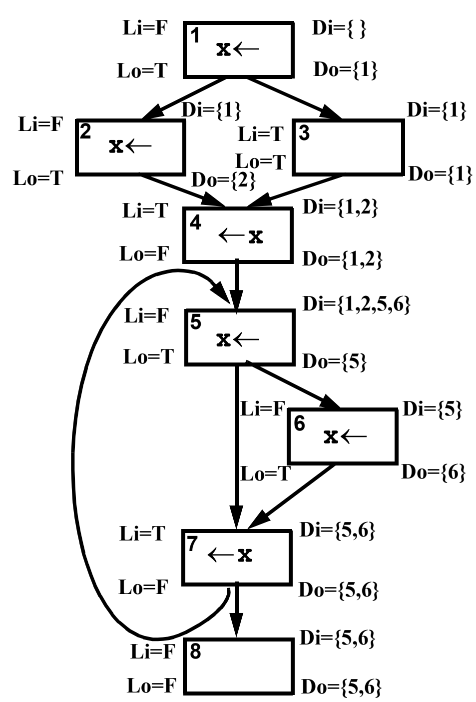
Elsif V is defined before it is used in Basic Block b

Then false

Else LiveOut(b)

Example





Reading Assignment

- Section 14.3 - 14.4 of CaC

Data Flow Frameworks

- **Data Flow Graph:**

  Nodes of the graph are basic blocks or individual instructions.

  Arcs represent flow of control.

  Forward Analysis:

  Information flow is the same direction as control flow.

  Backward Analysis:

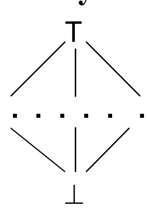
  Information flow is the opposite direction as control flow.

  Bi-directional Analysis:

  Information flow is in both directions. (Not too common.)

- **Meet Lattice**

  Represents solution space for the data flow analysis.



- **Meet operation**
  (And, Or, Union, Intersection, etc.)

  Combines solutions from predecessors or successors in the control flow graph.

- **Transfer Function**

  Maps a solution at the top of a node to a solution at the end of the node (forward flow)
  or
  Maps a solution at the end of a node to a solution at the top of the node (backward flow).

Example: Available Expressions

This data flow analysis determines whether an expression that has been previously computed may be reused.

Available expression analysis is a forward flow problem—computed expression values flow forward to points of possible reuse.

The best solution is True—the expression may be reused.

The worst solution is False—the expression may not be reused.

The Meet Lattice is:

T (Expression is Available)
|
F (Expression is Not Available)

As initial values, at the top of the start node, nothing is available. Hence, for a given expression,

AvailIn(b_0) = F

We choose an expression, and consider all the variables that contribute to its evaluation.

Thus for e_1=a+b-c, a, b and c are e_1's *operands*.

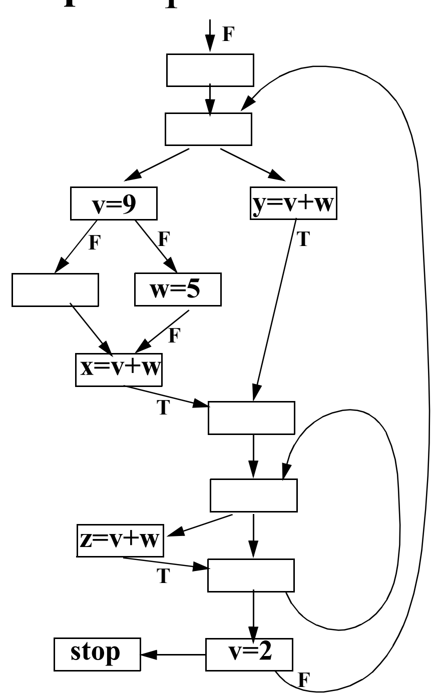
The transfer function for e_1 in block b is defined as:

If e_1 is computed in b after any assignments to e_1's operands in b
Then AvailOut(b) = T
Elsif any of e_1's operands are changed after the last computation of e_1 or e_1's operands are changed without any computation of e_1
Then AvailOut(b) = F
Else AvailOut(b) = AvailIn(b)

The meet operation (to combine solutions) is:

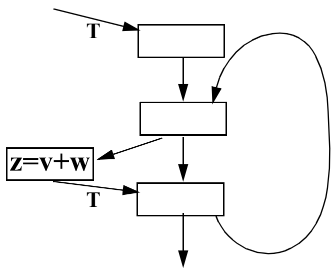
$$\text{AvailIn}(b) = \underset{p \in \text{Pred}(b)}{\text{AND}} \text{AvailOut}(p)$$

Example: e_1=v+w



Circularities Require Care

Since data flow values can depend on themselves (because of loops), care is required in assigning initial “guesses” to unknown values.



Consider

If the flow value on the loop backedge is initially set to false, it can never become true. (Why?)

Instead we should use True, the *identity* for the AND operation.