CSCI 742 - Compiler Construction

Lecture 38
More Data-flow Analysis
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May 5, 2017

Recap: Lattices

- Lattice: set augmented with a partial order relation $\preccurlyeq$
- Each two-element subset has a lub and a glb
- Can define: meet $\sqcap$ and join $\sqcup$
- Use lattice to express information about a point in a program
- $x \preccurlyeq y$ means "x is less or equally precise as y"
- To compute information: build constraints that describe how the lattice information changes
  - Effect of instructions: transfer functions
  - Effect of control flow: meet operation

Recap: Transfer Functions

- L: data-flow information lattice
- Transfer function $F_S : L \to L$ for each instruction S
- Describes how S modifies the information in the lattice
- If *in*(S) is info before S and *out*(S) is info after S then
- Forward analysis: $\quad out(S) = F(in(S))$
- Backward analysis: $\quad in(S) = F(out(S))$

Recap: Control Flow

- Meet operation models how to combine information at split/join points in the control flow
- Forward analysis:

$$\mathit{in}(S) = \bigsqcap \{\mathit{out}(S') | S' \in \mathit{pred}(S)\}$$

- Backward analysis:

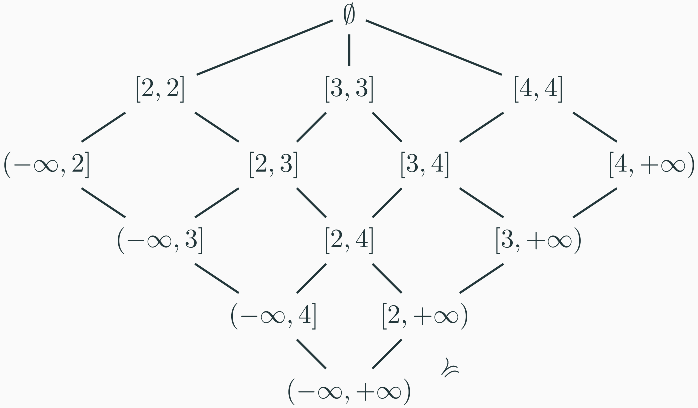
$$\mathit{out}(S) = \bigsqcap \{\mathit{in}(S') | S' \in \mathit{succ}(S)\}$$

Range Analysis

- Try to determine the possible range of integer values of a variable
- Elements: $[a, b]$ where $a \leq b$ or $\emptyset$
- We allow $a = -\infty$ and/or $b = \infty$
  - $(-\infty, +\infty)$ set of all integers
- $[a, b] \cup [a', b'] = [\mathit{min}(a, a'), \mathit{max}(b, b')]$
- Forward analysis with $\cup$ as the meet operator

Domain of Intervals

Domain of Intervals $[a, b]$ where $a, b \in \{-\infty, 2, 3, 4, \infty\}$



Transfer Function: Addition

- Suppose we have only two integer variables: x , y

$x : [a, b] \quad y : [c, d]$

$$x = x + y$$

$x : [a', b'] \quad y : [c', d']$

if $a \leq x \leq b$ and $c \leq y \leq d$
and we execute $x = x + y$ then
$x' = x + y$ and $y' = y$

- So we can let

$$a' = a + c \qquad b' = b + d$$
$$c' = c \qquad d' = d$$

Transfer Function: Subtraction

- Suppose we have only two integer variables: x , y

$x : [a, b] \quad y : [c, d]$

$$y = x - y$$

$x : [a', b'] \quad y : [c', d']$

if $a \leq x \leq b$ and $c \leq y \leq d$
and we execute $y = x - y$ then
$x' = x$ and $y' = y - x$

- So we can let

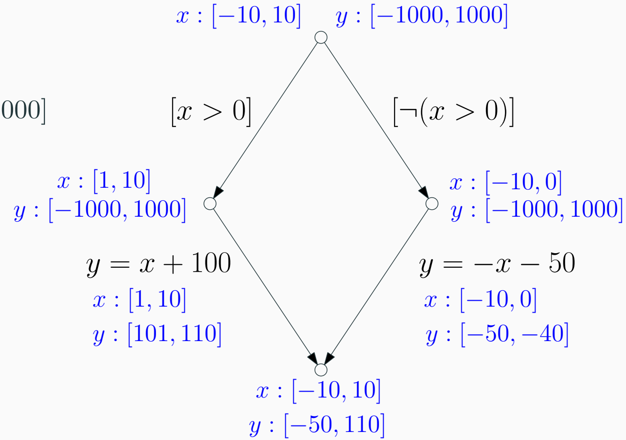
$$a' = a \qquad b' = b$$

$$c' = a - d \qquad d' = b - c$$

Combine Data-flow Facts

x : $[-10, 10]$ y : $[-1000, 1000]$

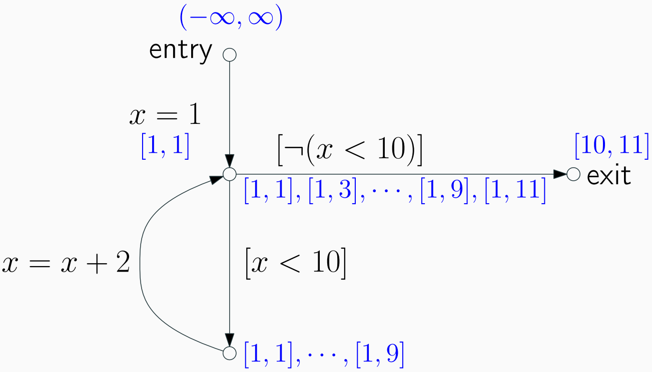
```
if (x > 0) {
  y = x + 100;
} else {
  y = -x - 50;
}
```



Handling Loops

Iterate until stabilizes

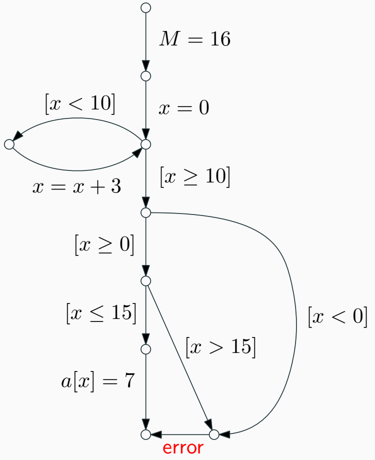
```
x = 1;
while (x < 10) {
  x = x + 2;
}
```



Exercise

- Run range analysis, prove error is unreachable

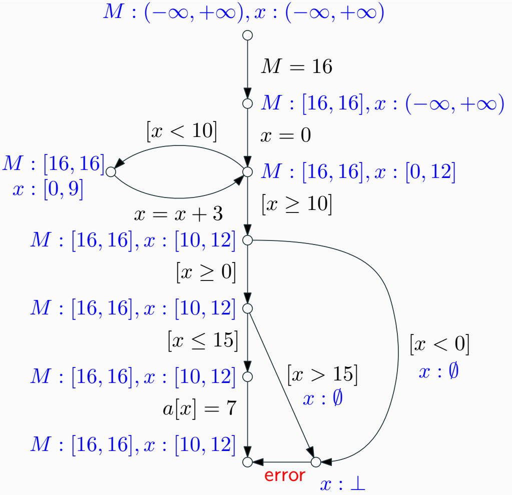
```
int M = 16;
int a[] = new int[M];
int x = 0;
while (x < 10) {
  x = x + 3;
}
if (x >= 0) {
  if (x <= 15)
    a[x]=7;
  else
    error;
} else {
  error;
}
```



Exercise

- Run range analysis, prove error is unreachable

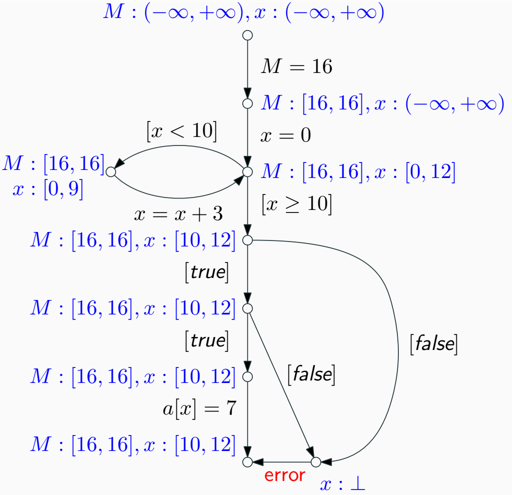
```
int M = 16;
int a[] = new int[M];
int x = 0;
while (x < 10) {
  x = x + 3;
}
if (x >= 0) {
  if (x <= 15)
    a[x]=7;
  else
    error;
} else {
  error;
}
```



Exercise

- Run range analysis, prove error is unreachable

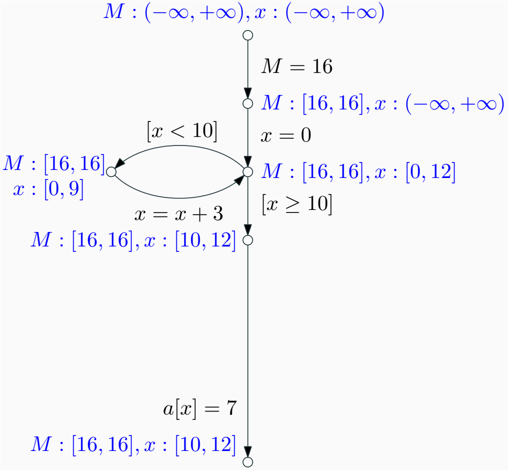
```
int M = 16;
int a[] = new int[M];
int x = 0;
while (x < 10) {
  x = x + 3;
}
if (x >= 0) {
  if (x <= 15)
    a[x]=7;
  else
    error;
} else {
  error;
}
```



Exercise

- Run range analysis, prove error is unreachable

```
int M = 16;
int a[] = new int[M];
int x = 0;
while (x < 10) {
  x = x + 3;
}
if (x >= 0) {
  if (x <= 15)
    a[x]=7;
  else
    error;
} else {
  error;
}
```



- Benefits: faster execution (no checks)
- Program cannot crash with error

Initialization Analysis

```
class Test {
 static void test(int p) {
  int n;
  p = p - 1;
  if (p > 0) {
    n = 100;
  }
  while (n != 0) {
    System.out.println(n);
    n = n - p;
  }
 }
}
```

- Does `javac` compile this program without error?

Initialization Analysis

```
class Test {
 static void test(int p) {
  int n;
  p = p - 1;
  if (p > 0) {
    n = 100;
  }
  while (n != 0) {
    System.out.println(n);
    n = n - p;
  }
 }
}
```

- Does `javac` compile this program without error?

```
Test.java:8:error:variable n might not have been initialized
while (n != 0) {
       ^
```

Initialization Analysis

```
class Test {
 static void test(int p) {
  int n;
  p = p - 1;
  if (p > 0) {
    n = 100;
  } else {
      n = -100;
  }
  while (n != 0) {
    System.out.println(n);
    n = n - p;
  }
 }
}
```

- We would like variables to be initialized on all execution paths
- Otherwise, the program execution could be undesirably affected by the value that was in the variable initially
- We can enforce such check using initialization analysis

Initialization Analysis

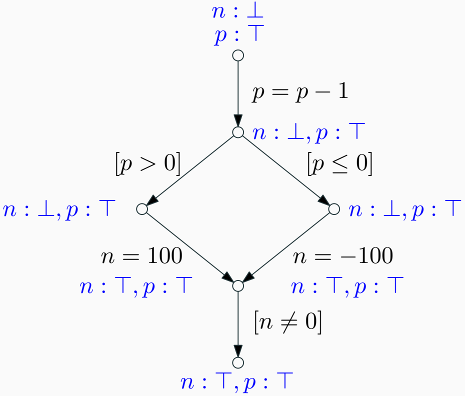
- Does `javac` compile this program without error?

```
static void test(int p) {
  int n;
  p = p - 1;
  if (p > 0) {
    n = 100;
  }
  System.out.println("Hello!");
  if (p > 0) {
    while (n != 0) {
      System.out.println(n);
      n = n - p;
    }
  }
}
```

Initialization Analysis

```
class Test {
 static void
    test(int p) {
  int n;
  p = p - 1;
  if (p > 0) {
    n = 100;
  } else {
      n = -100;
  }
  while (n != 0) {
    System.out.println(n);
    n = n - p;
  }
 }
}
```

- $\bot$ indicates presence of flow from states where variable was not initialized
- If variable is possibly uninitialized, we use $\bot$
- Otherwise (initialized, or unreachable): $\top$



If var occurs anywhere but LHS of an assignment and has value $\bot$, report error

Sketch of Initialization Analysis

- Domain: for each variable, for each program point: $D = \{\bot, \top\}$
- At program entry, local variables: $\bot$, parameters: $\top$
- At other program points: each variable: $\top$
- An assignment `x = e` sets variable `x` to $\top$
- glb ($\sqcap$) of any value with $\bot$ gives $\bot$
- Uninitialized values are contagious along paths
- $\top$ value for `x` means there is definitely no possibility for accessing uninitialized value of `x`

Exercise

Run initialization analysis

```
int n;
p = p - 1;
if (p > 0) {
  n = 100;
}
while (n != 0) {
  n = n - p;
}
```