

Data Flow Analysis

Example, Method, Lattice, Precision, Sensitivity

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Lecture #7 out of 10

80 minutes

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Motivating Example

Method

Sensitivities

Most Common Types

Further Reading/Watching

Chapter #1:

Motivating Example

Unassigned Variable

Which code snippet has an error (“use of unassigned variable”)?

```
int f(int x) {  
    int a;  
    if (x > 10)  
        a = 42;  
    while (x++ < 5)  
        a = x;  
    return a + 1;  
}
```

```
int f(int x) {  
    int a;  
    if (x > 3)  
        a = 42;  
    while (x++ < 12)  
        a = x;  
    return a + 1;  
}
```

ChatGPT vs. Clang Tidy

 Do you see any problems in this C++ code:

```
int f(int x) {
  int a;
  if (x > 10) { a = 42; }
  while (x++ < 5) { a = x; }
  return a + 1;
}
```

 Yes, there is a problem with this C++ code.

The variable `a` is not initialized if the condition `x > 10` is not met, which means that its value is undefined in the `while` loop. This can lead to undefined behavior in the program.

In C++, uninitialized variables can have unpredictable values, so it's important to always initialize them before they are used.

To fix this issue, we can initialize `a` to a default value before the `if` statement:

```
int f(int x) {
  int a = 0;
  if (x > 10) { a = 42; }
  while (x++ < 5) { a = x; }
  return a + 1;
}
```

With this change, the code should behave as expected without any undefined behavior.

```
/code/temp/cpp$ clang-tidy a.cpp --
1 warning generated.
/code/temp/cpp/a.cpp:5:12: warning: The left operand of '+' is a garbage value [clang-analyzer-core.UndefinedBinaryOperatorResult]
  return a + 1;
         ~ ^
/code/temp/cpp/a.cpp:2:3: note: 'a' declared without an initial value
  int a;
  ~~~~
/code/temp/cpp/a.cpp:3:7: note: Assuming 'x' is <= 10
  if (x > 10) { a = 42; }
  ~~~~~
/code/temp/cpp/a.cpp:3:3: note: Taking false branch
  if (x > 10) { a = 42; }
  ^
/code/temp/cpp/a.cpp:4:10: note: Assuming the condition is false
  while (x++ < 5) { a = x; }
  ~~~~~
/code/temp/cpp/a.cpp:4:3: note: Loop condition is false. Execution continues on line 5
  while (x++ < 5) { a = x; }
  ^
/code/temp/cpp/a.cpp:5:12: note: The left operand of '+' is a garbage value
  return a + 1;
         ~ ^
```

UndefinedBehaviorSanitizer

Clang UndefinedBehaviorSanitizer (the dynamic analyzer) can detect the issue in runtime:

```
rultor@m2262:~$ cat > a.cpp
int f(int x) {
    int a;
    if (x > 10) { a = 42; }
    while (x++ < 5) { a = x; }
    return a + 1;
}
int main() {
    return f(7);
}
rultor@m2262:~$ clang -fsanitize=memory a.cpp -g
rultor@m2262:~$ ./a.out
==1494430==WARNING: MemorySanitizer: use-of-uninitialized-value
    #0 0x4950e4 in main /home/rultor/a.cpp:8:2
    #1 0x7fa900daf082 in __libc_start_main (/lib/x86_64-linux-gnu/libc.so.6+0x24082)
    #2 0x41c26d in _start (/home/rultor/a.out+0x41c26d)

SUMMARY: MemorySanitizer: use-of-uninitialized-value /home/rultor/a.cpp:8:2 in main
Exiting
```

IntelliJ IDE

IntelliJ IDEA doesn't see the difference:

```
int f(int x) {  
    int a;  
    if (x > 3) { a = 42; }  
    while (x++ < 12) { a = x; }  
    return a + 1;  
}
```

Variable 'a' might not have been initialized
Initialize variable 'a' ↵⌘⌘ More actions... ↵⌘
int a
eo-maven-plugin

Java Compiler

javac doesn't see the difference either:

```
/code/temp/java$ cat > A.java
class A {
    int f(int x) {
        int a;
        if (x > 3) { a = 42; }
        while (x++ < 12) { a = x; }
        return a + 1;
    }
}
/code/temp/java$ javac A.java
A.java:6: error: variable a might not have been initialized
        return a + 1;
               ^
1 error
```

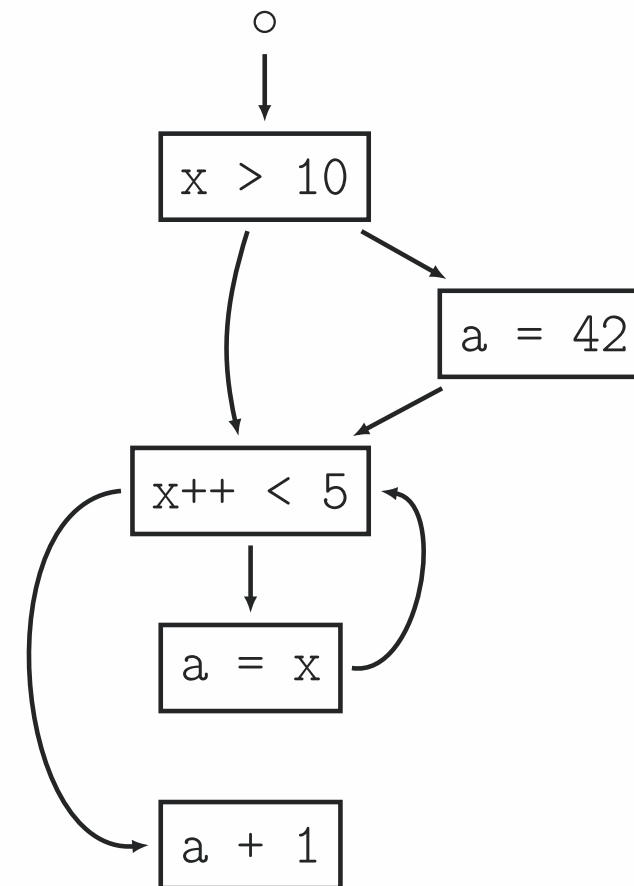

Chapter #2: Method

[[CFG](#) Properties Over-approximation Meet GEN/KILL Low]

Control Flow Graph

First, we represent the program as a Control Flow Graph (CFG):

```
int f(int x) {  
    int a;  
    if (x > 10)  
        a = 42;  
    while (x++ < 5)  
        a = x;  
    return a + 1;  
}
```



Example [Method](#) Sensitivities Types Literature

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[[CFG](#) Properties Over-approximation Meet GEN/KILL Low]

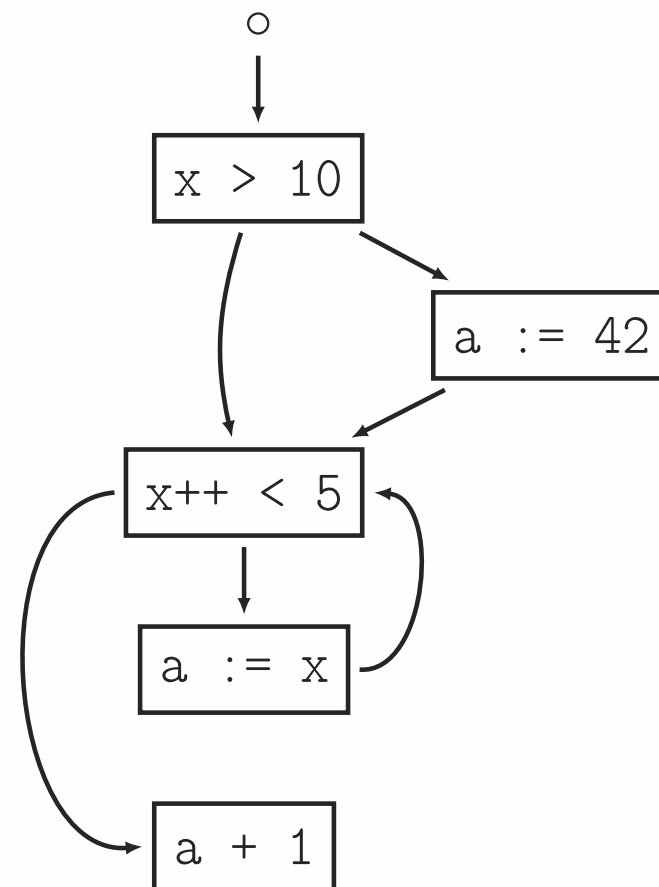
Six Properties of Data Flow Analysis

Data flow analysis *propagates* information (*data*) along the control flow graph, with the following six properties in mind:

1. Domain (of *data flow facts*)
2. Direction (forward or backward)
3. *Transfer Function* (sometimes with GEN and KILL sets)
4. *Confluence Operator* ("meet" or "join")
5. Boundary Condition (start data for the entry node)
6. Initial Values (start data for each node)

[CFG Properties [Over-approximation](#) Meet GEN/KILL Low]

Over-approximation

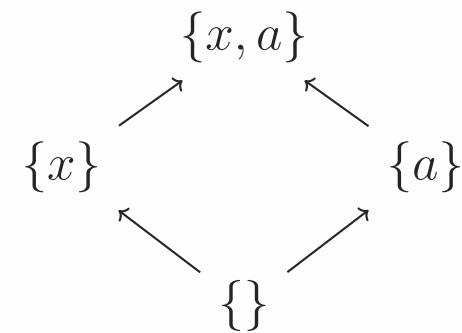
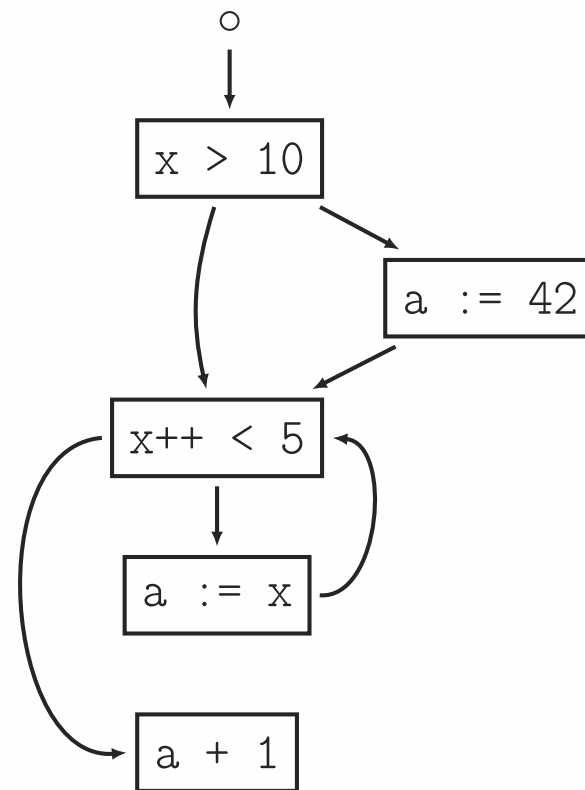


1. Domain:
variable names
2. Direction:
forward
3. Transfer Function:
add on “:=”
4. Confluence Operator:
meet, intersection
5. Boundary Condition:
 $\{x\}$
6. Initial Values:
empty sets

[CFG Properties Over-approximation [Meet](#) GEN/KILL Low]

Meet Operator

The *meet operator* is coming from the lattice that abstracts the data that flows (remember *abstract interpretation*):



$$\{x, a\} \sqcap \{x\} \rightarrow \dots$$

$$\{a\} \sqcap \{\} \rightarrow \dots$$

$$\{a\} \sqcap \{x\} \rightarrow \dots$$

Example [Method](#) Sensitivities Types Literature

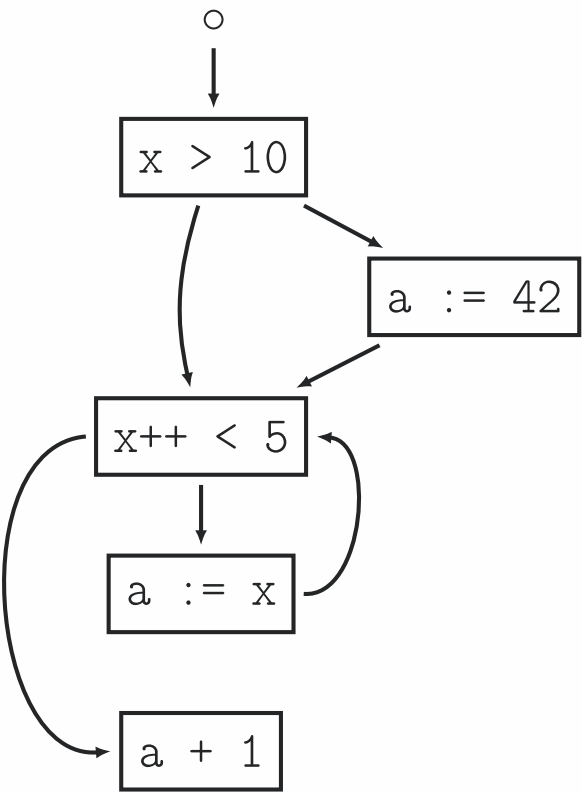
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[CFG Properties Over-approximation [Meet](#) GEN/KILL Low]

[CFG Properties Over-approximation Meet [GEN/KILL](#) Low]

GEN and KILL Functions

A transfer function may be defined by defining GEN and KILL functions:

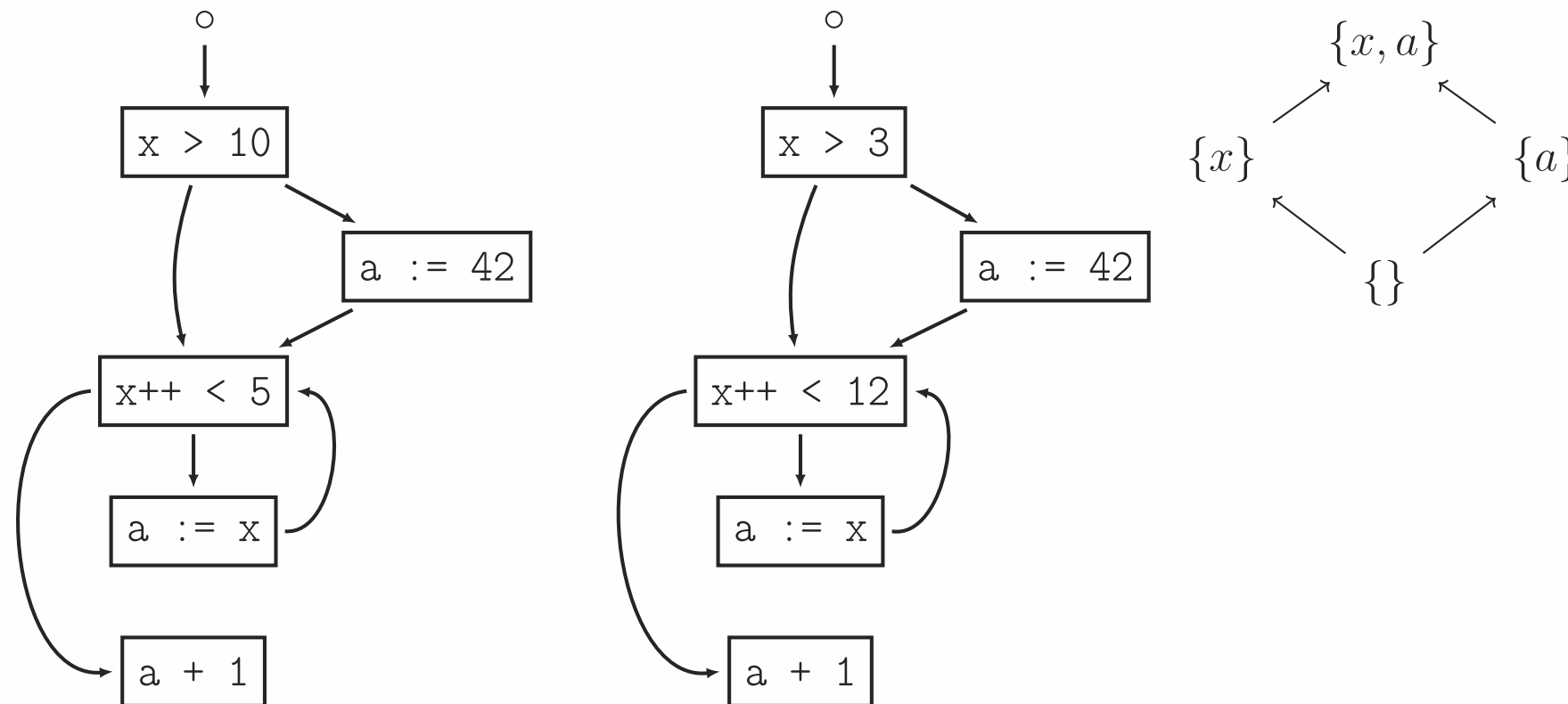


s	$GEN(s)$	$KILL(s)$
$x > 10$	$\{\}$	$\{\}$
$a := 42$	$\{a\}$	$\{\}$
$x++ < 5$	$\{\}$	$\{\}$
$a := x$	$\{a\}$	$\{\}$
$a + 1$	$\{\}$	$\{\}$

[CFG Properties Over-approximation Meet GEN/KILL [Low](#)]

Over-approximation = Low Precision

From the perspective of *path insensitive* data flow analysis, there are bugs in both CFGs, but it's wrong:



Example [Method](#) Sensitivities Types Literature

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[CFG Properties Over-approximation Meet GEN/KILL [Low](#)]

Chapter #3:

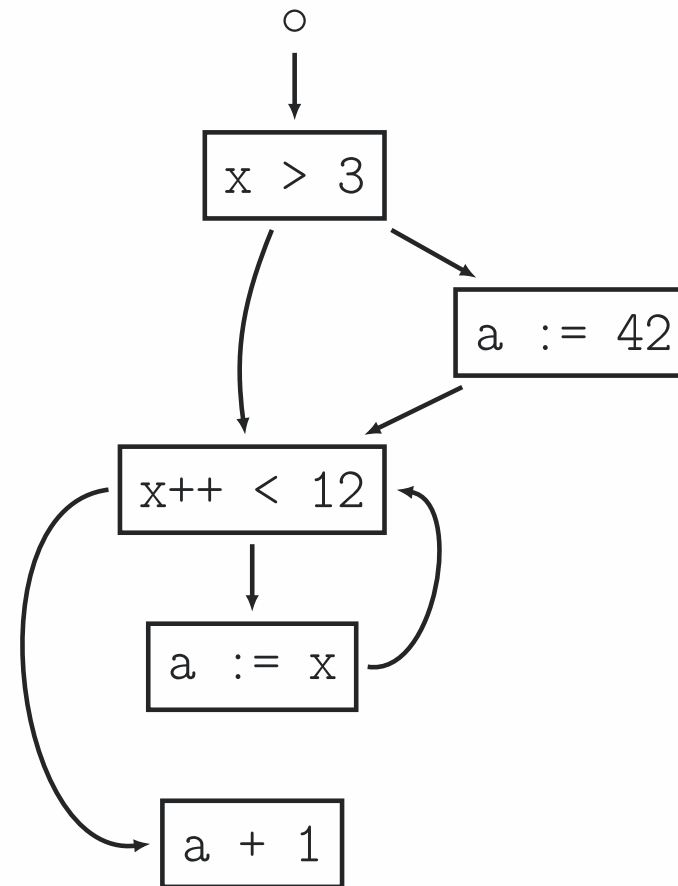
Sensitivities

[[Path-Sensitive Analysis](#) Flow-Sensitive Analysis Context-Sensitive Analysis]

Path-Sensitive Analysis

A *path-sensitive* analysis computes different pieces of analysis information dependent on the *predicates* at conditional branch instructions.

[[Path-Sensitive Analysis](#) Flow-Sensitive Analysis Context-Sensitive Analysis]



Flow-Sensitive Analysis

A *flow-sensitive* analysis takes into account the order of statements in a program.

The analysis we did before was flow sensitive. Flow *insensitive* analysis example:

```
1 | a = 0;  
2 | a = 5;  
3 | a = a + 1;  
4 | // What is a possible value of 'a'?
```

Context-Sensitive Analysis

A *context-sensitive* analysis is an interprocedural analysis that considers the calling context when analyzing the target of a function call.

```
1 | f(5, 6); // call-site #1
2 | f(6, 5); // call-site #2
3 | void f(x, y) {
4 |     // Is it possible to have x == y?
5 | }
```

Chapter #4:

Most Common Types

[[Reaching](#) Liveness Assignment Available Constants]

Reaching Definitions Analysis

Reaching definitions is a data-flow analysis which statically determines which definitions may reach a given point in the code.

```
1 float price(int book) {  
2     float p = load_from_database();  
3     if (book < 100)  
4         p = 14.99;  
5     if (book > 50)  
6         p = 9.99;  
7     float discount = 0.90;  
8     return p * discount;  
9 }
```

Do you see any problems with this code?

[Reaching [Liveness](#) Assignment Available Constants]

Liveness Analysis

Live variable analysis calculates the variables that are live at each point in the program (they hold values that may be needed in the future).

```
1 int price(int book_id) {  
2     int p;  
3     int discount;  
4     if (book_id > 400)  
5         discount = 10;  
6     p = load_price_from_database(book_id);  
7     p = ( p * 95 ) / 100;  
8     return p;  
9 }
```

Do you see any problems in the code?

[Reaching Liveness [Assignment](#) Available Constants]

Definite Assignment Analysis

Definite assignment analysis conservatively ensures that a variable or location is always assigned before it is used.

```
1 int salary(int user_id) {  
2     int s;  
3     if (user_id > 400) {  
4         s = get_salary_from_mysql(user_id);  
5     } else if (user_id < 400) {  
6         s = 0;  
7     }  
8     return s;  
9 }
```

Is there an error in this code?

Available Expression Analysis

Available expression analysis determines for each point in the program the set of expressions that need not be recomputed.

```
1 int price(int book_id) {  
2     int p = 14;  
3     if (stock(book_id) < 100) {  
4         p = 19;  
5     } else if (stock(book_id) > 1000) {  
6         p = 9;  
7     }  
8     return p;  
9 }
```

Shall we compute `stock(book_id)` twice?

[Reaching Liveness Assignment Available [Constants](#)]

Constant Propagation Analysis

Constant propagation analysis at every statement tells which variables is a constant: every execution that reaches that point, gives that variable the same value.

```
1 float discount(float price) {  
2     float d = 0.8;  
3     if (price < 14.99)  
4         d = 0.93;  
5     else  
6         d = d + 0.13;  
7     return price * d;  
8 }
```

Is there an error in this code?

Chapter #5:

Further Reading/Watching

Book and slides by Anders Møller et al.

Lectures of Michael Pradel on YouTube.

Bibliography