University of BRISTOL

Program Analysis for Security

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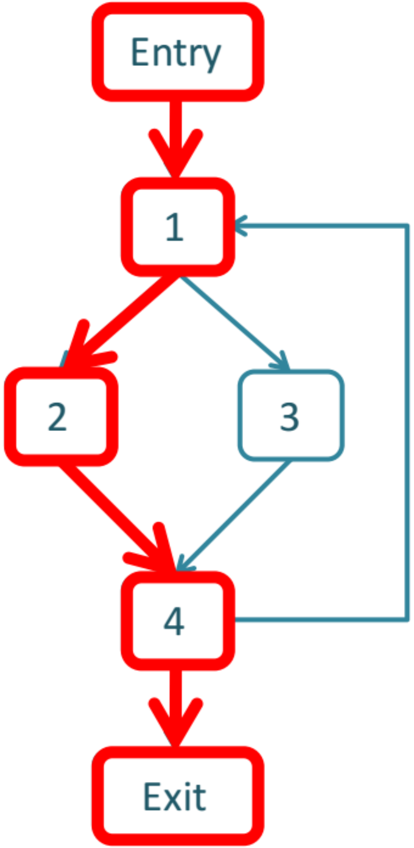
Adopted from courses from L. Mounier, Y. Lakhnech (& S. Rawat) of Verimag & J. Michell of Stanford.

Lecture Agenda

- Motivation for Program analysis
- Types of program analysis
  - Static
  - Dynamic
- A quick tour for static analysis techniques

Motivation

- Why do we need *secure software development lifecycle*-- at large-scale, it is not easy to find bugs manually which are more accessible now.
  - Heartbleed, WhatsApp double-free, Facebook account deletion bug etc.
- How can you tell whether software you Develop or buy is safe to install and run?
  - Analyzing it? But...



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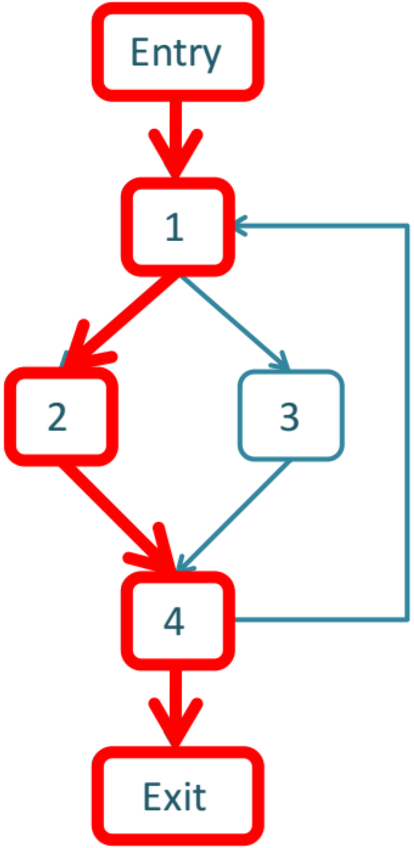
Software



Software

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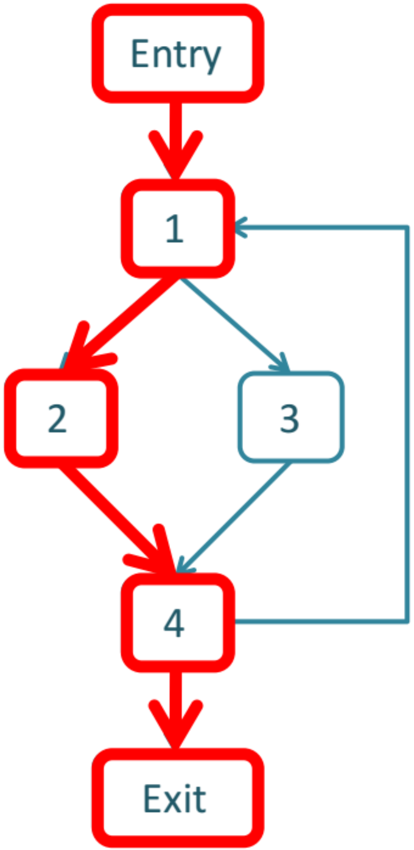
Behaviors



Software

1 → 2 → 4

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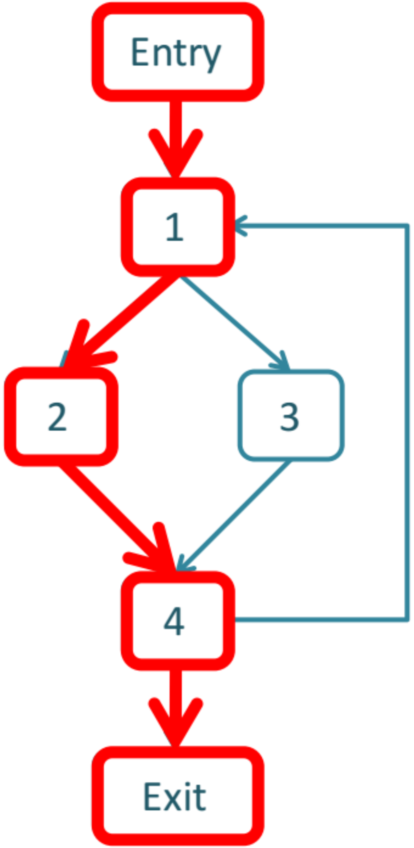

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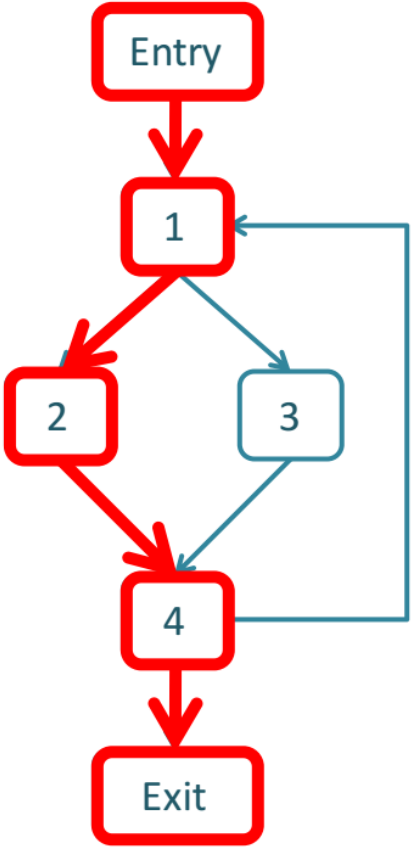

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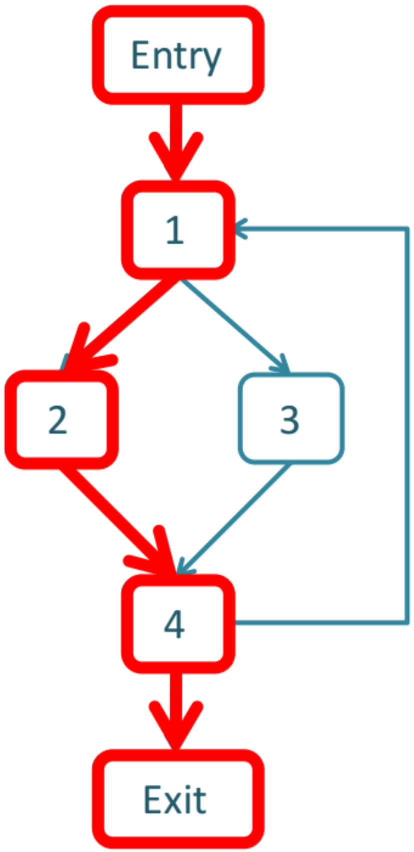

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Manual testing only examines small subset of behaviors

Behaviors

Real-world example….

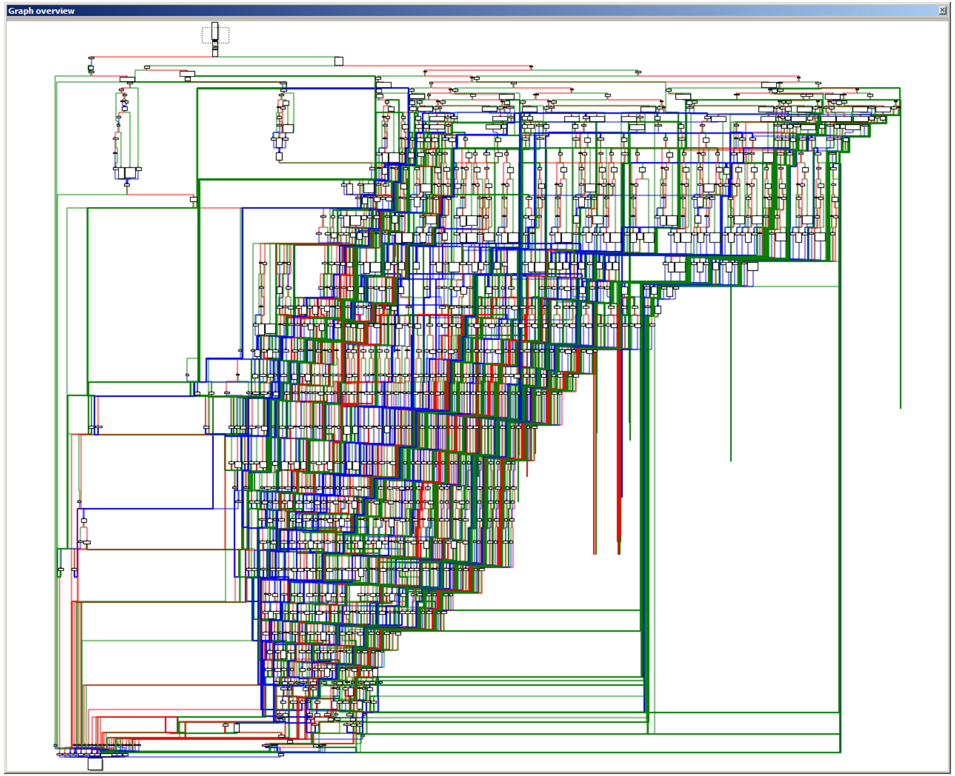

Image: stackoverflow

Definition

- Program analysis is the process of automatically analysing the behaviour of computer programs regarding a property such as correctness, reliability, safety and security.
- Traditionally, it focuses on program optimization (as in compilers) and program correctness (as in verification). However, the same techniques are applied to other domains. So, we will study the code techniques first, irrespective of domain of application.
- Types:
  - Static analysis: performed without executing the program.
  - Dynamic Analysis: performed at runtime.
  - Hybrid: a mix of the above.

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Static Program Analysis

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- Compilers make heavy use of such analyses.
- ***Given the availability of the code, it can analyse every component and path of the application.***
- Tools:
  - **LLVM** provides a very robust platform to perform several static analyses (on source code).
  - For binary code, there exist several tools– IDA, Ghidra, Miasm, angr etc.
- Typical examples–
  - data-flow analysis, abstract interpretation, type system, model checking.
- For this course, we will be using **Ghidra** for learning some binary code analysis!

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- Often used with static/dynamic instrumentation (We will talk about dynamic binary Instrumentation).

  Existing tools– Intel Pin, Dyninst, Valgrind etc.

  From security standpoint-- Fuzzing (we will talk about it.)

  For this course, we will be using Intel Pintool.

Soundness, Completeness

Property	Definition
Soundness	"Sound for reporting correctness" Analysis says no bugs → No bugs or equivalently Analysis says bug → It is a bug Analysis says True → True
Completeness	"Complete for reporting correctness" No bugs → Analysis says no bugs True → analysis says True

	Complete	Incomplete
Sound		
Unsound		

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Common Program Analysis Techniques

Objectives

- give some indications on general optimization techniques:
  - **data-flow analysis**
  - register allocation
  - software pipelining
  - Etc.
- describe the main data structures used:
  - Call graph
  - control flow graph
  - intermediate code (e.g., 3-address code)
  - Static Single Assignment form (SSA)
  - etc

Generic Approach

- Decide – Intraprocedural or Interprocedural
  - Intraprocedural-- per function analysis (disregarding side effect of function calls)
  - Interprocedural- function analysis with considering side effects of function calls
- generation of a control flow graph (CFG)
- (optional) generation of interprocedural CFG (ICFG)
- Data-flow analysis of the (I)CFG

IR: 3-address code (TAC mode)

- Intermediate Representation “high-level” assembly code:
  - binary logic and arithmetic operators
  - use of temporary memory location ti
  - assignments to variables, temporary locations
  - a label is assigned to each instruction

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```
var1= (var2+ var3) + func(A)   ⇒   L1: t1 = var2 + var3
                                   L2: t2 = func(A)
                                   L3: var1= t1+t2
```

Basic Block (BB)

- A maximal sequence of instructions with single entry and single exit
  - => execution of BB is *atomic* (under normal condition)

Control Flow Graph (CFG)

- A representation of how the execution may progress inside a given function

$\rightarrow$ a graph (V, E) such that:

$$
\begin{aligned}
V &= \{B_i \mid B_i \text{ is a basic block}\} \\
E &= \{(B_i, B_j) \mid \\
&\quad \text{“last inst. of } B_i \text{ is a jump to 1st inst of } B_j\text{”} \vee \\
&\quad \text{“1st inst of } B_j \text{ follows last inst of } B_i \text{ in the TAC”}\}
\end{aligned}
$$

Call Graph

- Computed for a whole program (i.e. interprocedural by definition)
- Represented as a directed graph (V,E)
- where $V = \{F_i | F_i \text{ is a function}\}$
  - $E = \{(F_i, F_j) | F_i \text{ calls } F_j\}$

Intraprocedural Computation over CFG

- associate (local) properties to entry/exit points of Bbs, e.g. set of active variables, set of available expressions, etc.)
- propagate them along CFG paths
- (context- sensitivity adds precision, but difficult”)
- update each BB (and CFG edges) according to these global properties

Dataflow Analysis

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Rks:

- forward vs backward propagation (depending on φ_i)
- cycles inside the control flow $\Rightarrow$ fix-point equations !

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a solution of this equation system:

$\rightarrow$ assigns "globaly consistent" values to each φ_i

Rk: such a solution may not exist . . .

Example: redundant Expression

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An expression e is redundant at location i iff

- it is computed at location i
- this expression is computed on every path going from the initial location to location i
  Rk: we consider here syntactic equality
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Optimization is performed as follows:

1. computation of available expressions (data-flow analysis)
2. $x := e$ is redundant at loc i if e is available at i
3. $x := e$ is replaced by $x := t$
   (where t is a temp. memory containing the value of e)

Example conti..

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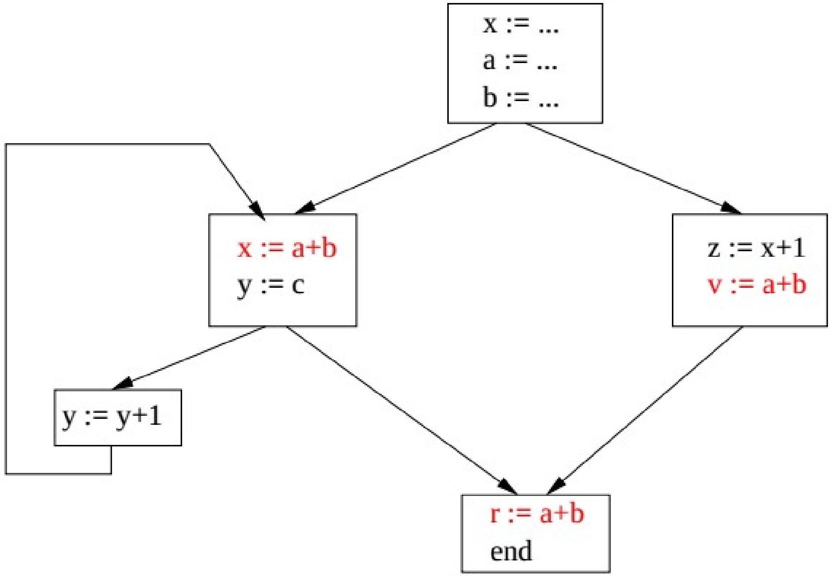

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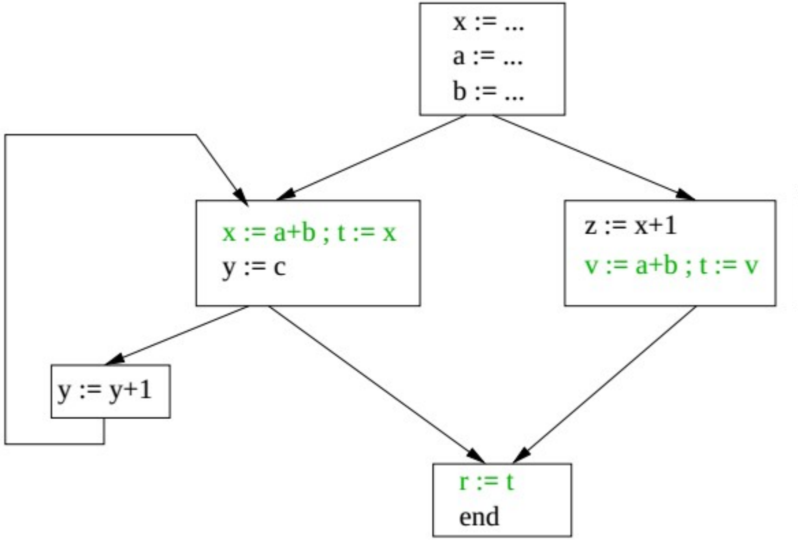


Dataflow Eqn for available expressions 1/2

For a basic block b, we note:

- $In(b)$: available expressions when entering b
- $Kill(b)$: expressions made non available by b (because an operand of e is modified by b)
- $Gen(b)$: expressions made available by block b (computed in b, operands not modified afterwards)
- $Out(b)$: available expressions when exiting b

$$Out(b) = (In(b) \setminus Kill(b)) \cup Gen(b) = F_b(In(b))$$

F_b = transfer function of block b

Dataflow Eqn for available expressions 2/2

How to compute $In(b)$?

- if b is the initial block:

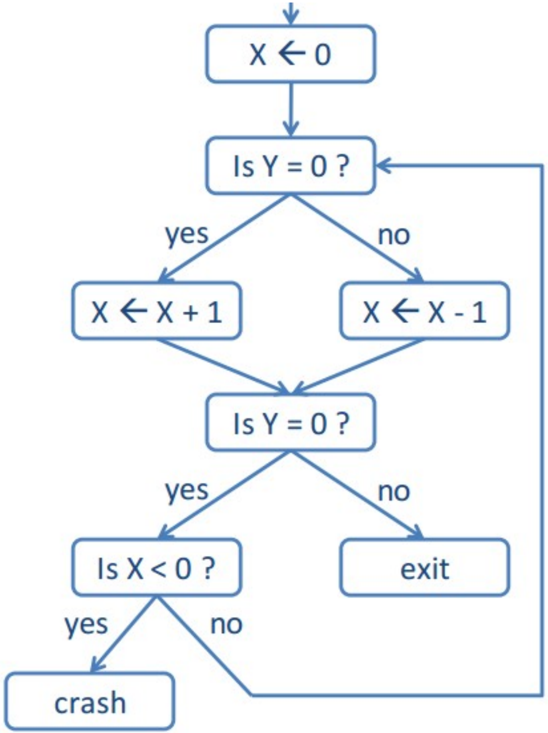
$$In(b) = \emptyset$$

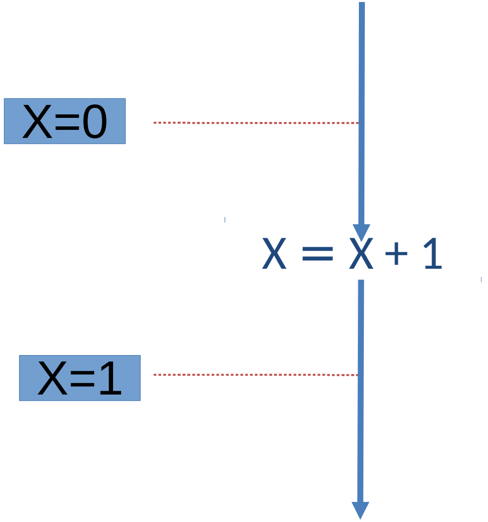
- if b is not the initial block:
  An expression e is available at its entry point iff it is available at the exit point of each predecessor of b in the CFG

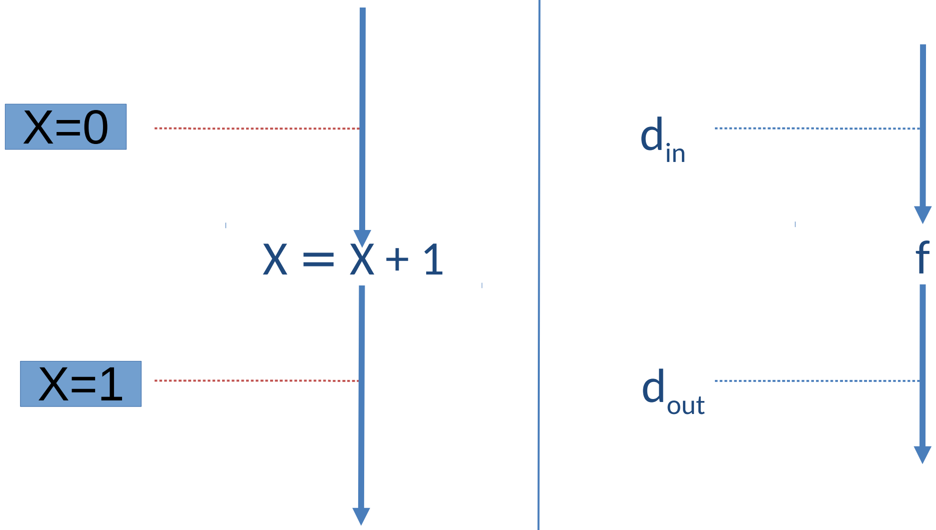
$$In(b) = \bigcap_{b' \in Pre(b)} Out(b')$$

$\Rightarrow$ forward data-flow analysis along the CFG paths

Simple Program




X=0
X = X + 1
X=1



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d
in
f
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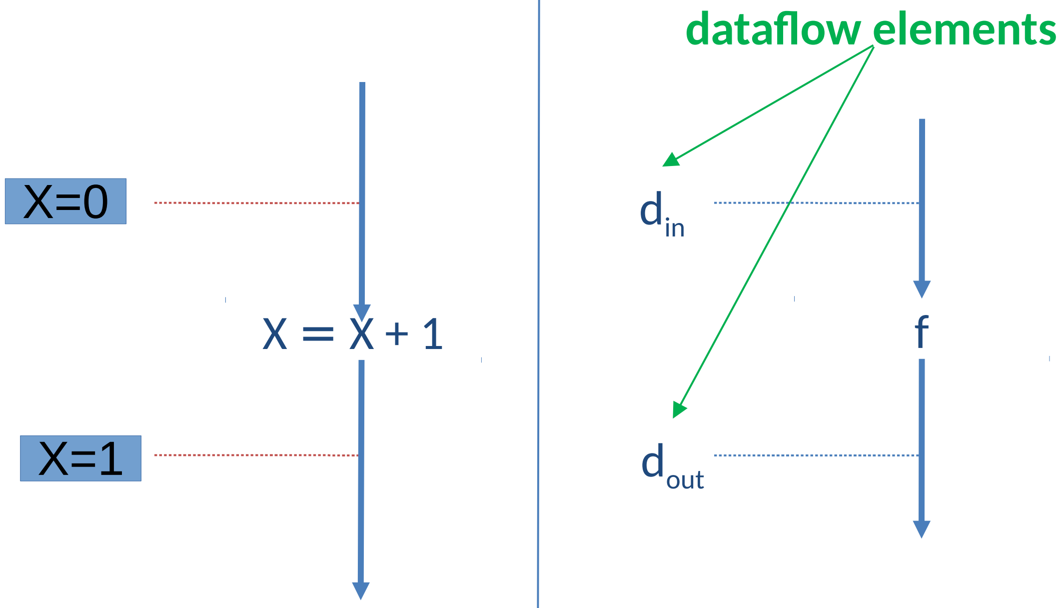

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dataflow elements
d
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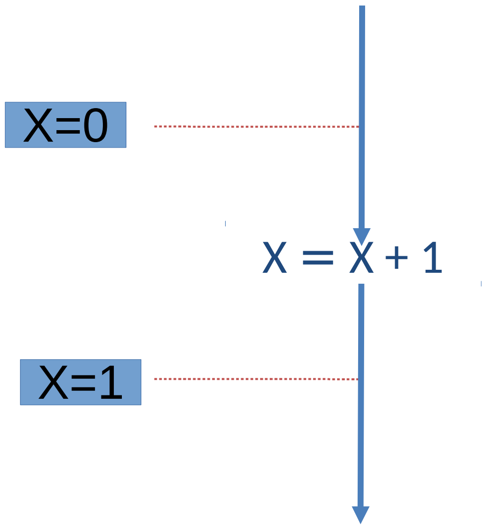
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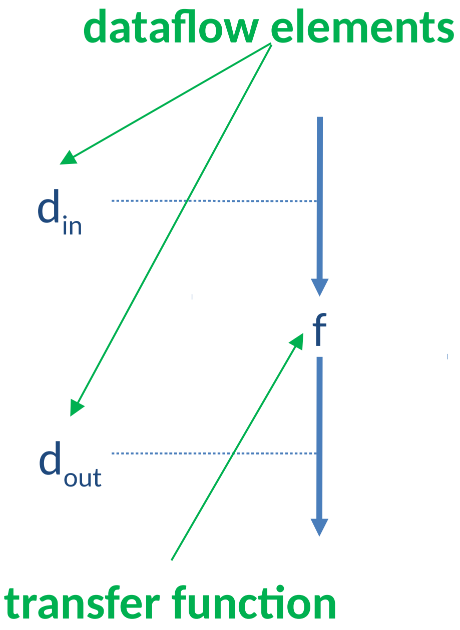
dataflow elements
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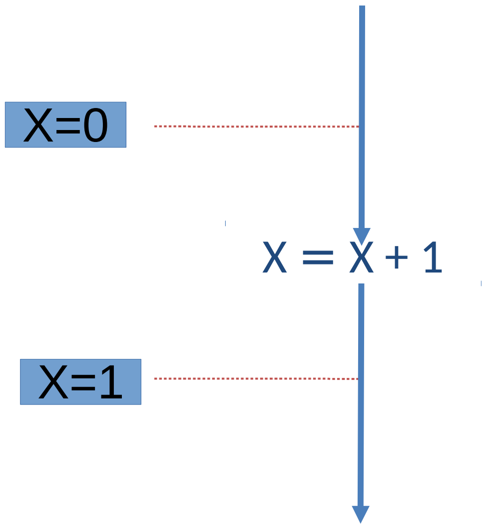
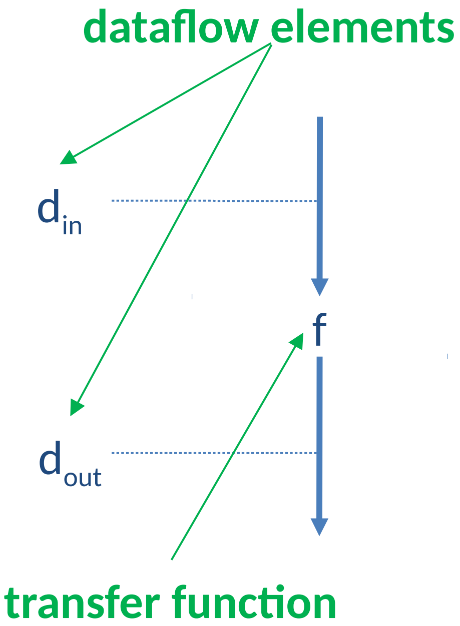
d out
transfer function





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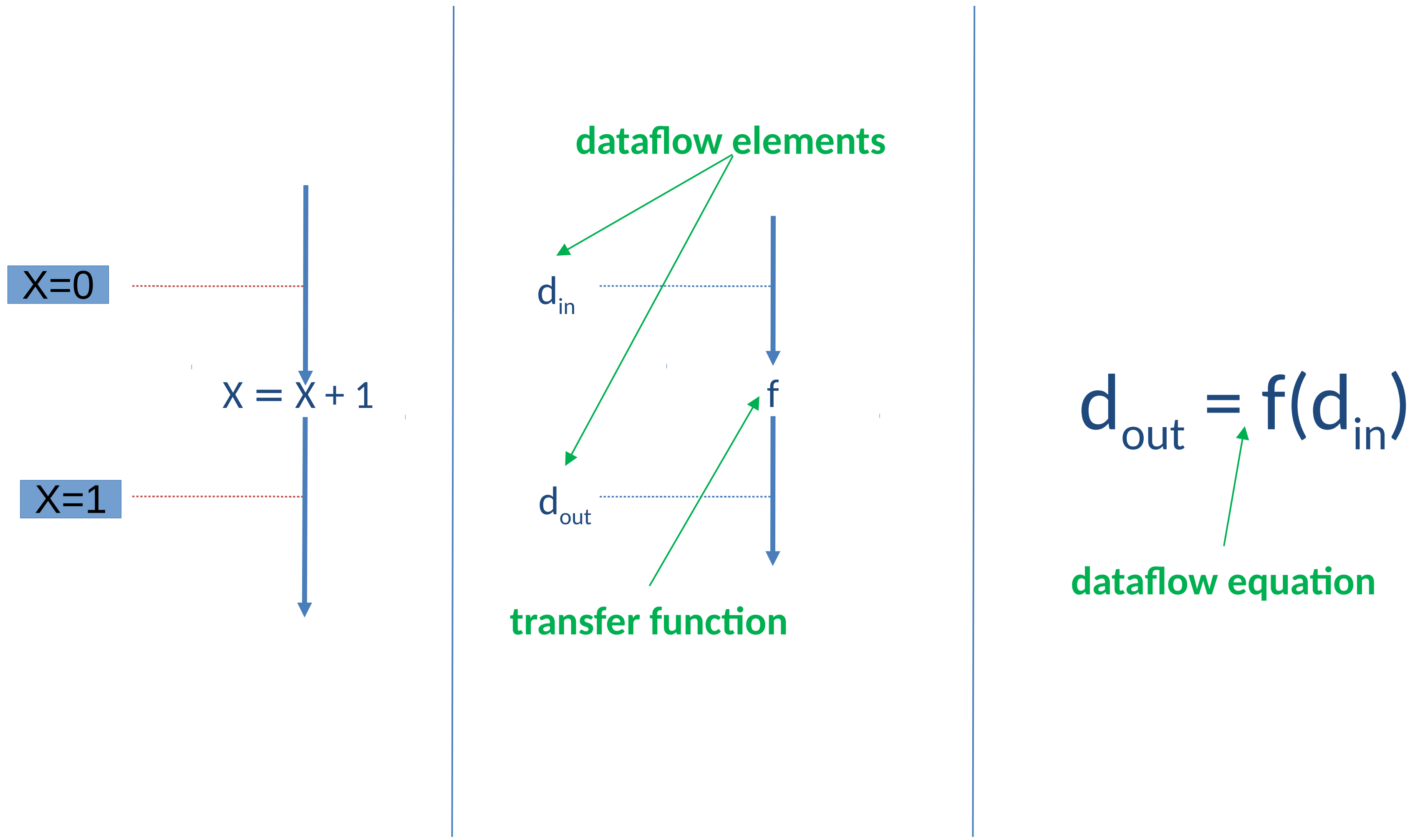

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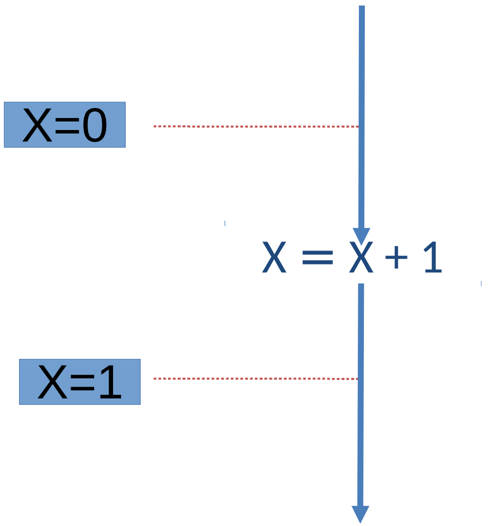
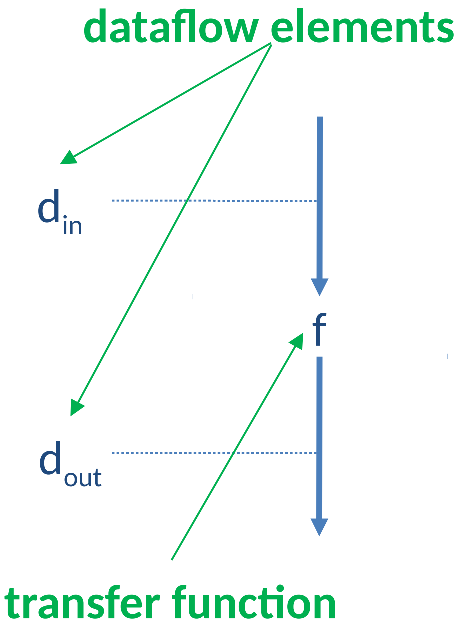
dataflow equation





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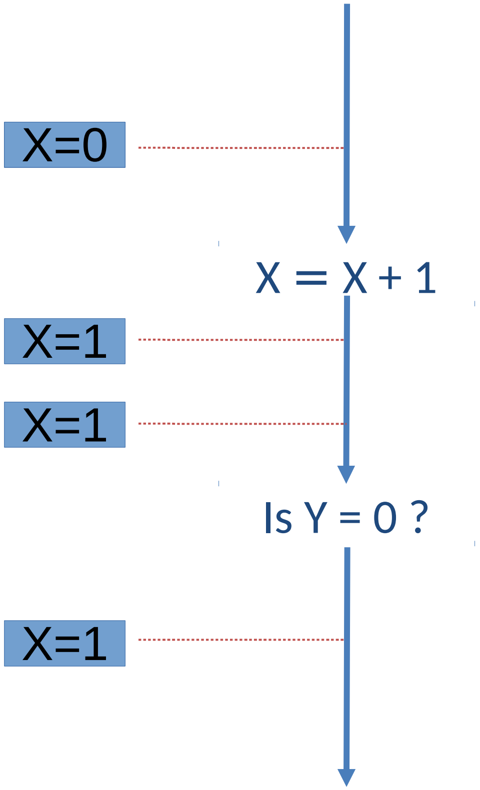

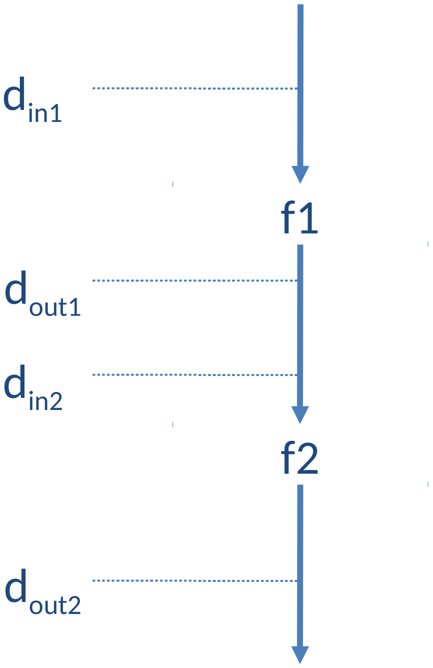

$$d_{out1} = f_1(d_{in1})$$

$$d_{in2} = d_{out1}$$

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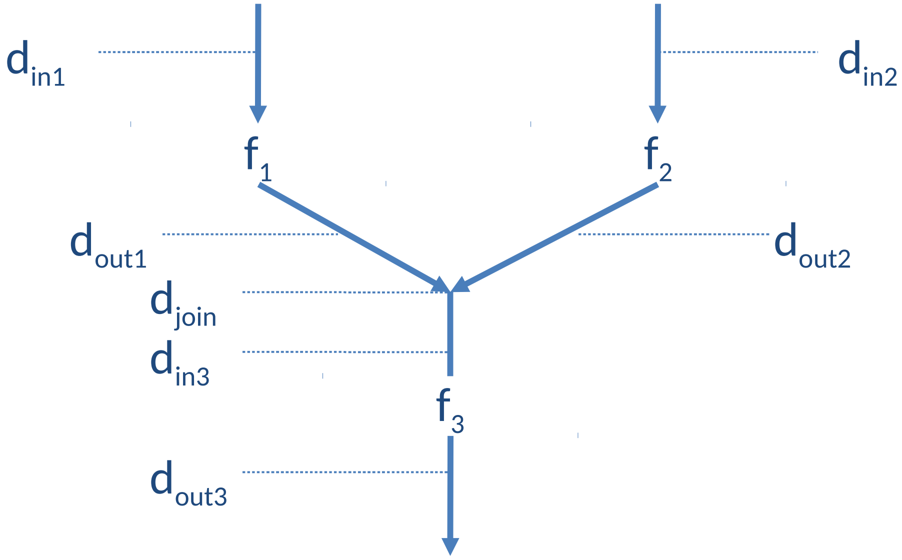

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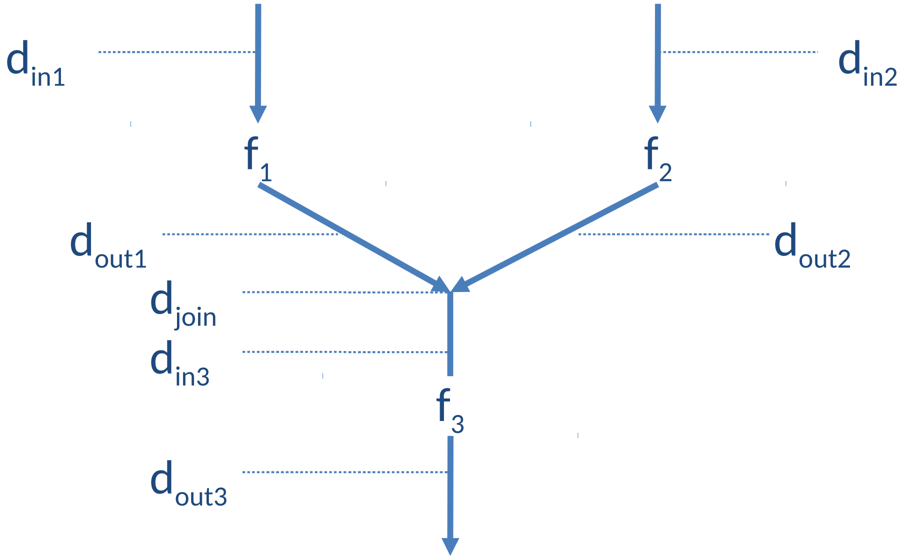

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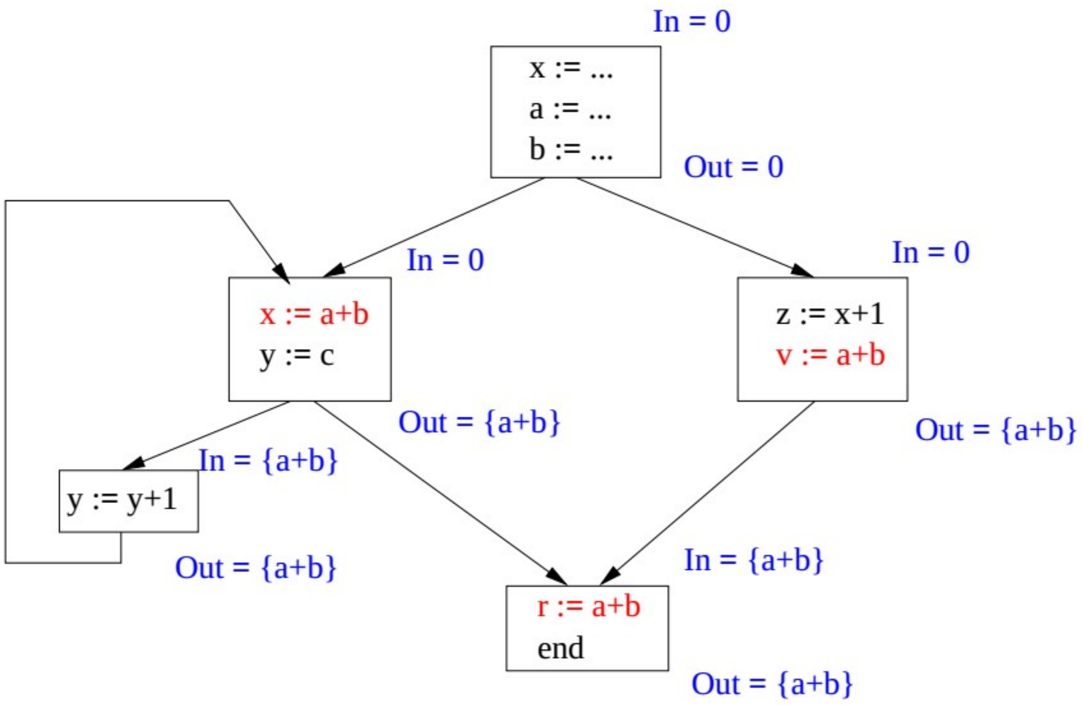
least upper bound operator
Example: union of possible values

Back to Example



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    ($\sqcap$ for "$\forall$ paths", $\sqcup$ for "$\exists$ path")
- For a backward analysis:
  - property is "false" ($\perp$) at exit of final block
  - $\mathtt{In}(b) = F_b(\mathtt{Out}(b))$
  - `Out`(b) depends on `In`(b'), where $b' \in Succ(b)$

Forward Analysis

Forward analysis, least fix-point	$\mathtt{In}(b) = \begin{cases} \bot & \text{if b is initial} \\ \bigsqcup_{b' \in Pre(b)} \mathtt{Out}(b') & \text{otherwise.} \end{cases}$ $\mathtt{Out}(b) = F_b(\mathtt{In}(b))$
Forward analysis, greatest fix-point	$\mathtt{In}(b) = \begin{cases} \bot & \text{if } b \text{ is initial} \\ \bigsqcap_{b' \in Pre(b)} \mathtt{Out}(b') otherwise. \end{cases}$ $\mathtt{Out}(b) = F_b(\mathtt{In}(b))$

Backward Analysis

Backward analysis, least fix-point	$\mathtt{Out}(b) = \begin{cases} \bot & \text{if } b \text{ is final} \\ \bigsqcup_{b' \in Succ(b')} \mathtt{In}(b') otherwise. \end{cases}$ $\mathtt{In}(b) = F_b(\mathtt{Out}(b))$
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Reaching Definition

- Every assignment is a definition.
- A **definition** d **reaches** a point p if **there** exists a path from the point immediately following d to p such that d is not killed (overwritten) along that path.
- in terms of Gen and $Kill$, every assignment generates and another assignment of the same variable kills the previous assignment and generates the newer one.

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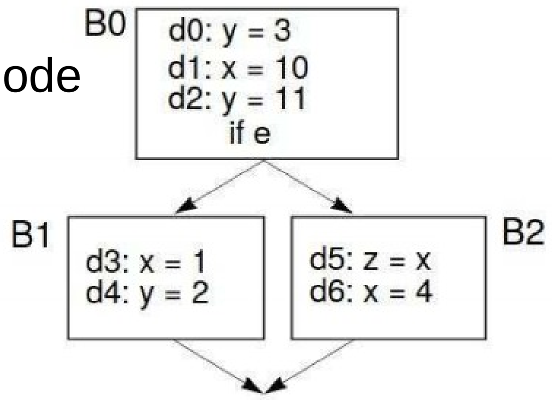

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```
fn(int a, int b)
{
    int i, j, k, x;
    i = a;
    j = b;
    if(i<j)
      k=j-i;
    if(j<i)
      k=i-j;
    x = 100+k;
    return x;
}
```

Bug Detection- Uninitialized use

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Reaching def. Type analysis,

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```

Bug Detection- Uninitialized use

- A variable is used before it is defined → undefined behaviour class of bugs

Reaching def. Type analysis,
but with greatest fixed-point, i.e. all paths

```
fn(int a, int b)
{
   int i, j, k, x;
   i = a;
   j = b;
   if(i<j)
     k=j-i;
   if(j<i)
     k=i-j;
   x = 100+k;
   return x;
}
```

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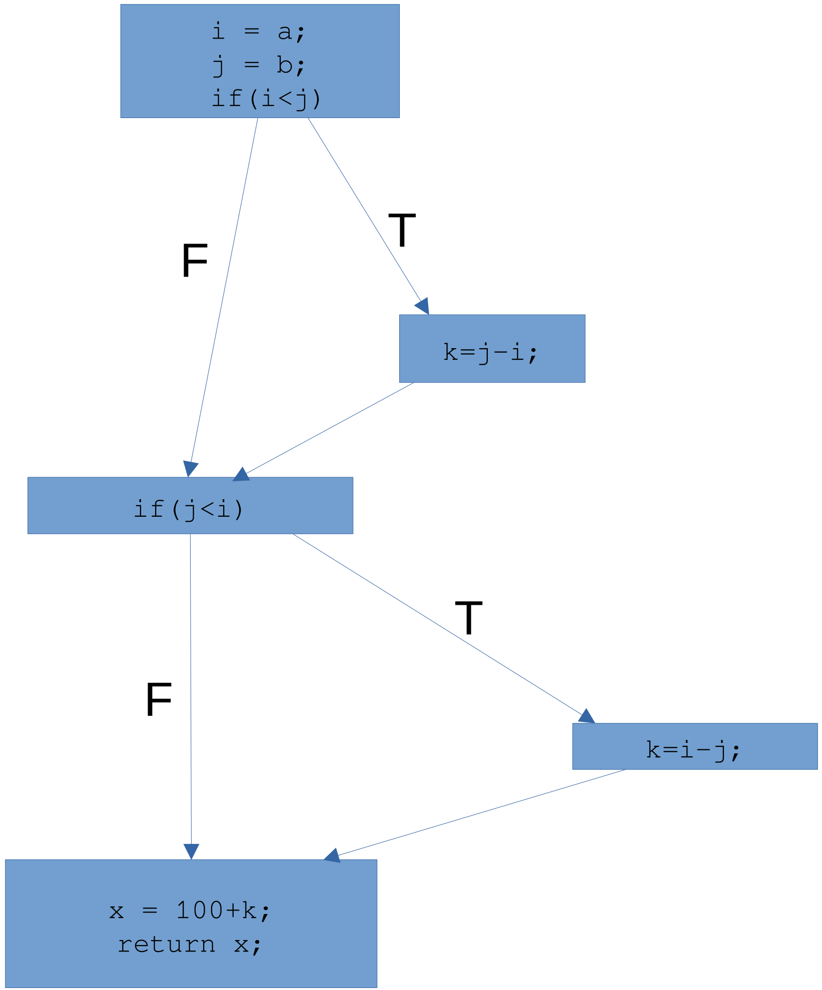
We stop when we do not get reaching def of a variable being used in a instruction.



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F
T
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F
T
k=i-j;
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Use-after-free

- Vulnerability:
  - Using (dereferencing) a pointer (memory) after it has been freed (i.e. `free(p)`)
  - The same logic works with the following dataflow:
    - Creating a pointer (malloc or stack variable) defines (*Gen*) a pointer
    - Freeing the pointer *Kill* it.
    - Meet is greatest fixed-point i.e. all paths
    - For every dereference, reaching def should be present.