# Declare Your Language

# Chapter 11: Data-Flow Analysis

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**IN4303 Compiler Construction**
**TU Delft**
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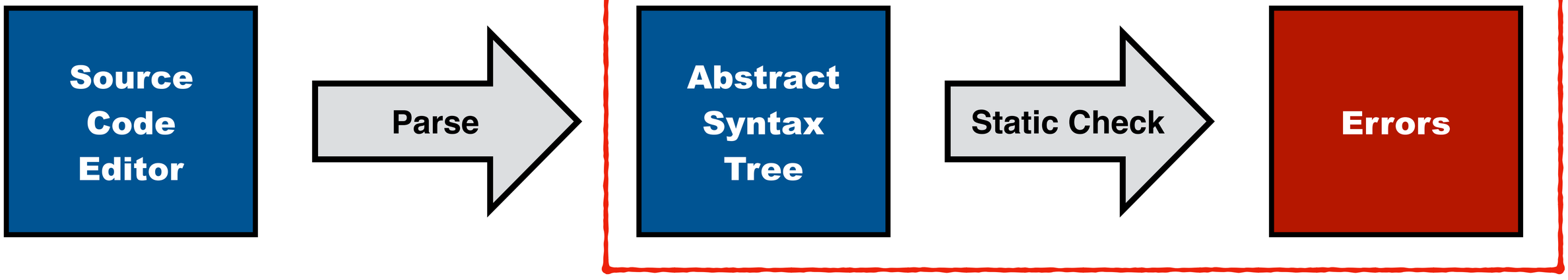
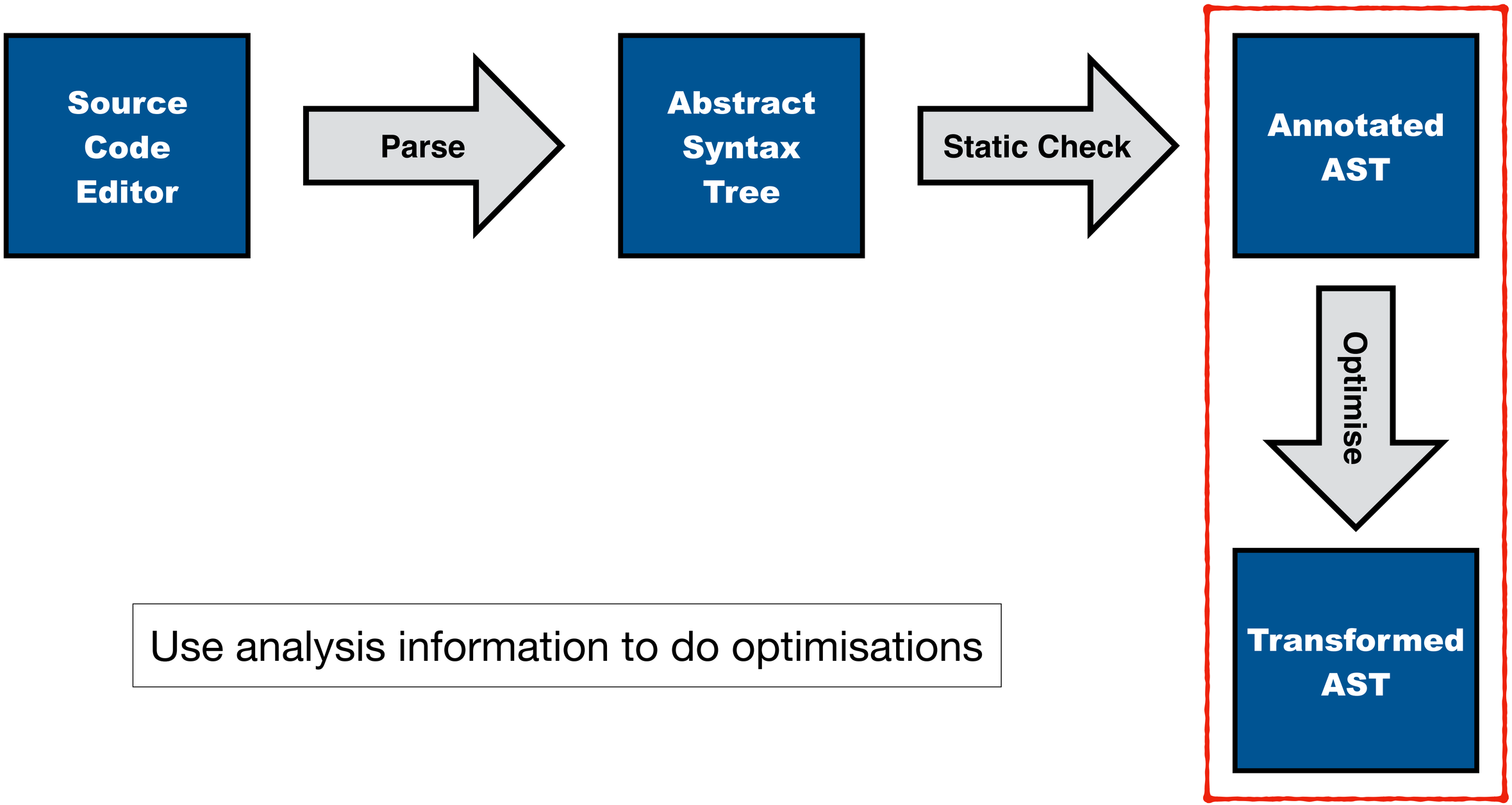
TU Delft




Check such things as final fields being initialised by a constructor



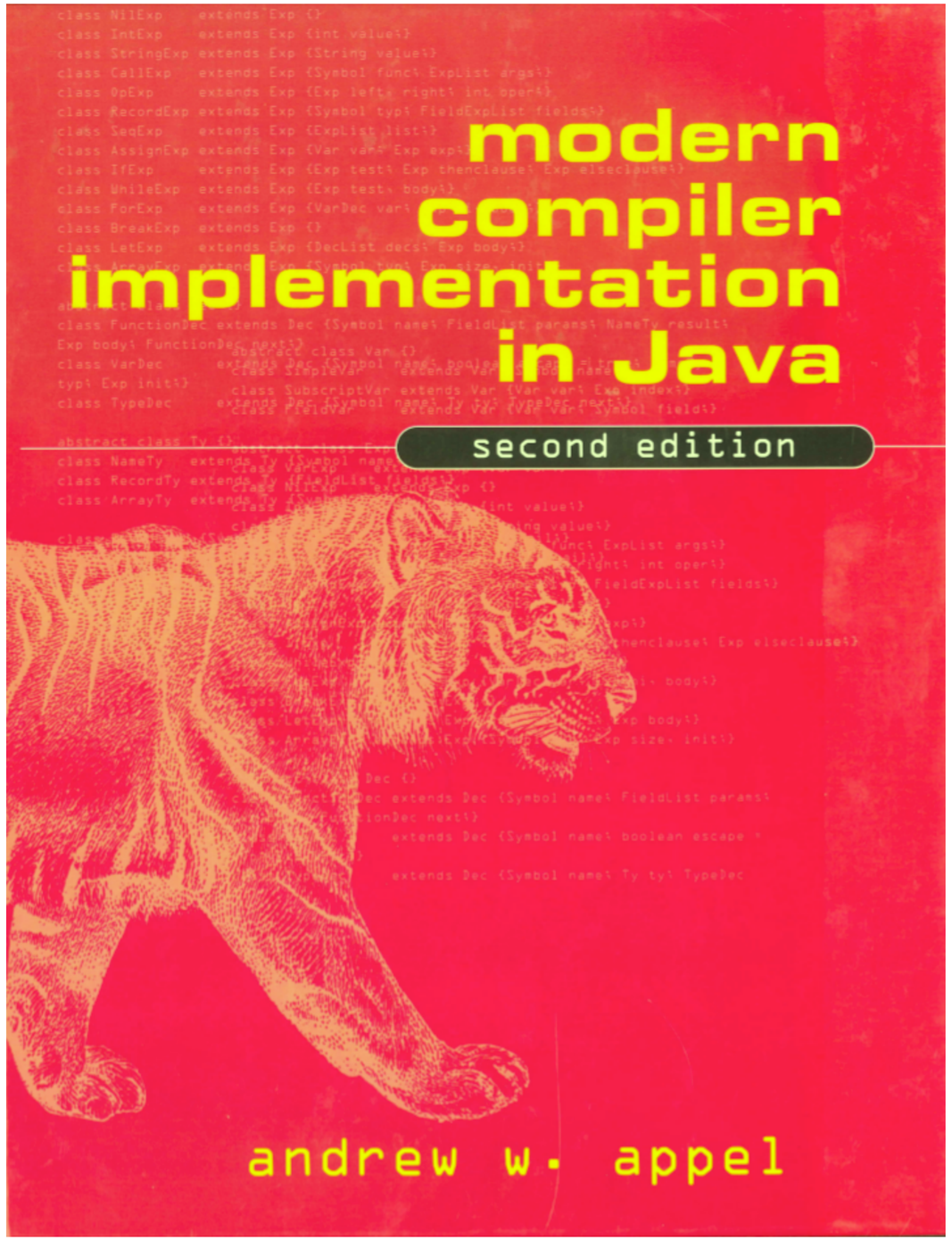

Use analysis information to do optimisations

# Reading Material

Chapter 10: Liveness Analysis

Chapter 17: Dataflow Analysis

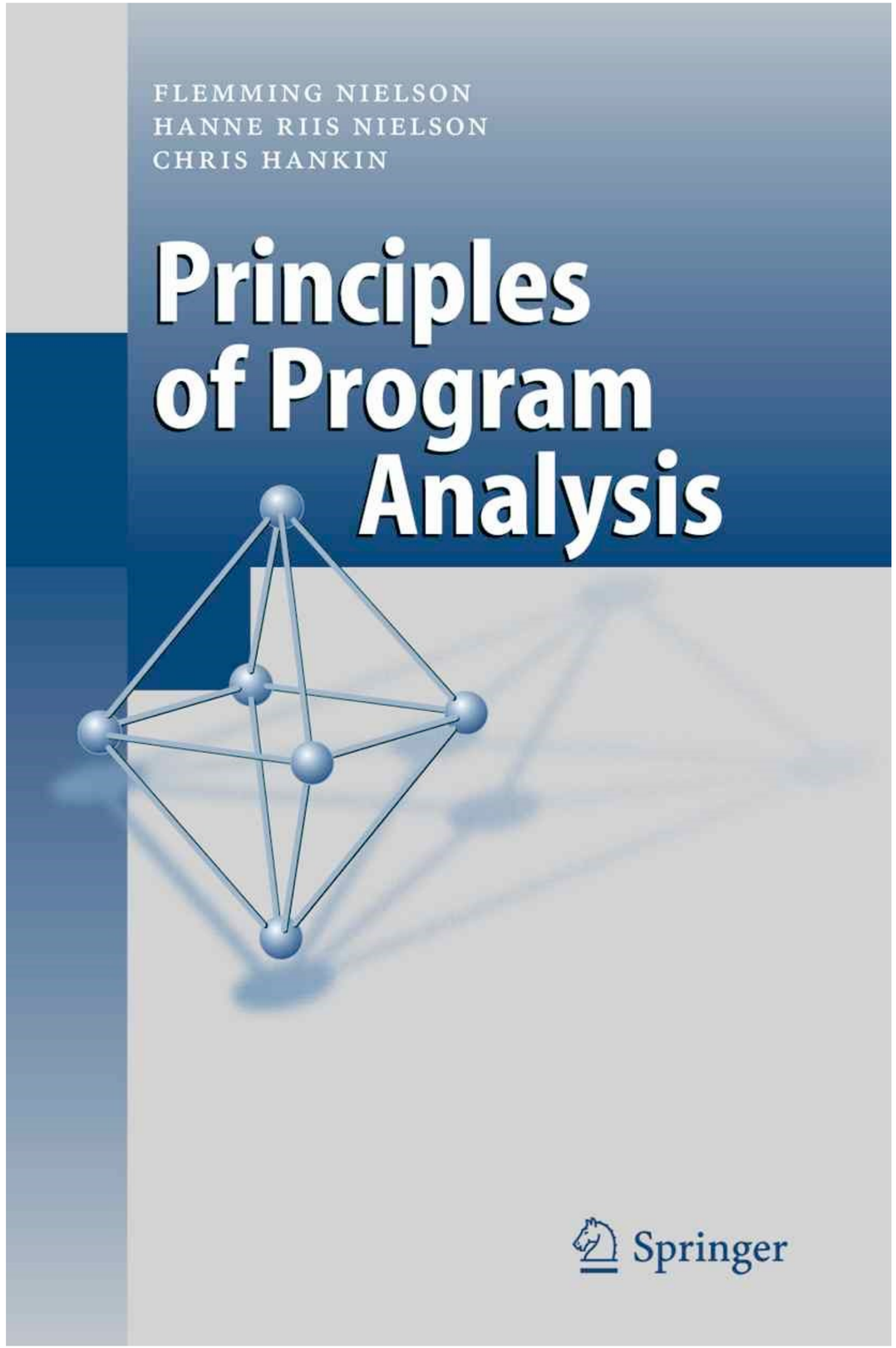
The *applied*/“cookbook” version



Chapter 1: Introduction

Chapter 2: Data Flow Analysis

The theoretical/“general” version



# Data-Flow

# Examples in Tiger

# Available Expressions

```
let
  var x : int := a + b
  var y : int := a * b
 in
  while y > a + b do
    (
      a := a + 1;
      x := a + b
    )
end
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Common subexpression elimination

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a + b
a + b, a * b
a + b

# Live Variables

```
x := 2;
y := 4;
x := 1;
if y > x then
  z := y
else
  z := y * y;
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x := 2;
y := 4;
x := 1;
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# Live Variables

Dead code elimination

```
y := 4;
x := 1;
if y > x then
  z := y
else
  z := y * y;
x := z
```

# What is Data-Flow Analysis?

**Data-flow analysis** is a technique for gathering information about the possible set of values calculated at various points in a computer program. A program's control flow graph (CFG) is used to determine those parts of a program to which a particular value assigned to a variable might propagate. The information gathered is often used by compilers when optimizing a program. A canonical example of a data-flow analysis is reaching definitions.

**https://en.wikipedia.org/wiki/Data_flow_analysis**

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## Gathering information about

- The *possible* set of values at various point in a program
- The program's *control flow graph* is used to …

**https://en.wikipedia.org/wiki/Data_flow_analysis**

# Control Flow Graphs

# What is a Control Flow Graph?

A **control flow graph** (**CFG**) in computer science is a representation, using graph notation, of all paths that might be traversed through a program during its execution.

**https://en.wikipedia.org/wiki/Control_flow_graph**

# Control Flow Graphs

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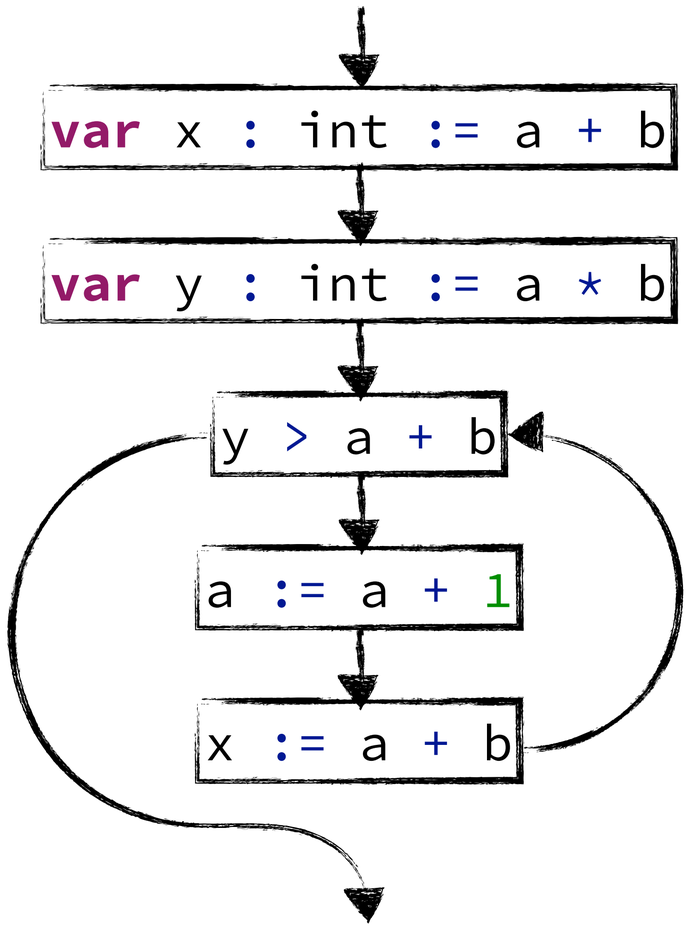
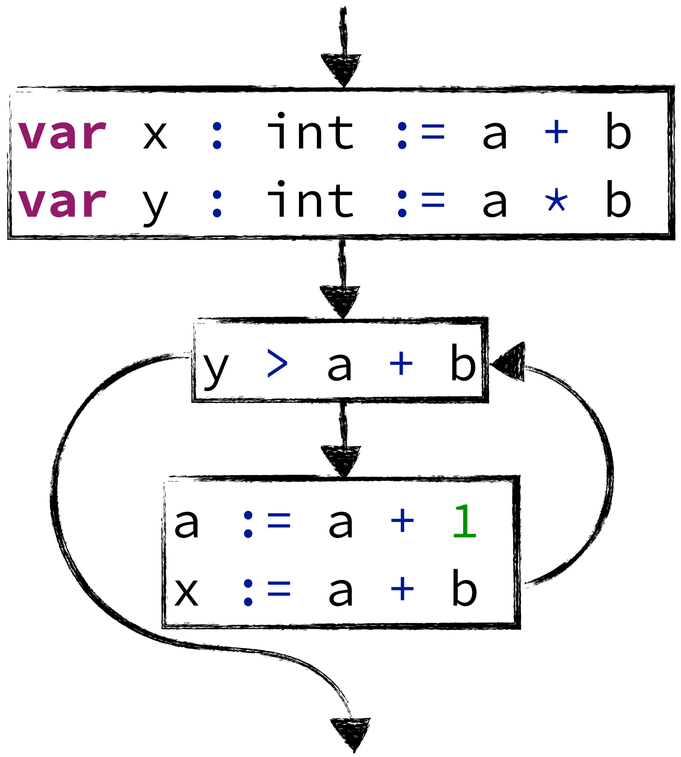
# Control Flow Graphs

Full flow graph



# Control Flow Graphs

## Basic Blocks



# Control Flow Graphs

Ingredients

## Control Nodes

- Usually outermost statements and expressions
- Or blocks for consecutive statements

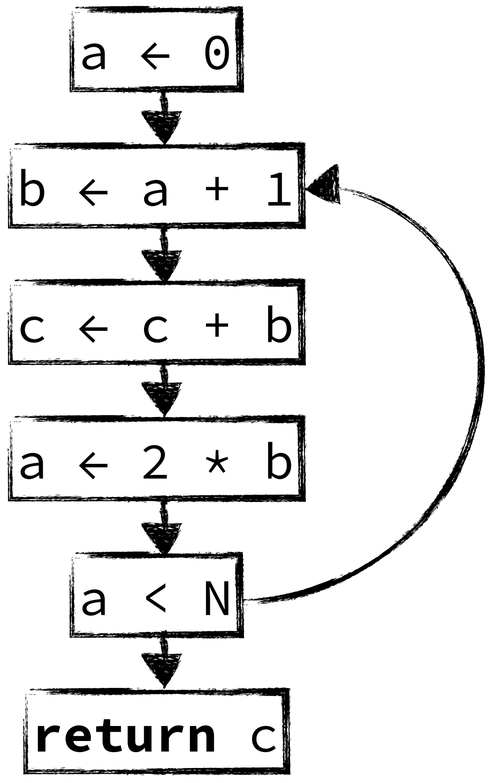
## Control Edges

- Back edges: show loops
- Splits: conditionally split the control flow
- Merges: combine previously split control flow

# Control Flow Graphs

Supports unstructured control flow

```
    a ← 0
L1: b ← a + 1
    c ← c + b
    a ← 2 * b
    if a < N goto L1
    return c
```



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A simple way to perform data-flow analysis of programs is to set up data-flow equations for each node of the control flow graph and solve them by repeatedly calculating the output from the input locally at each node until the whole system stabilizes, i.e., it reaches a fixpoint. This general approach was developed by Gary Kildall while teaching at the Naval Postgraduate School.[1]

**https://en.wikipedia.org/wiki/Data_flow_analysis**

# What is Data-Flow Analysis?

**Possible set of values**

- at various points in a computer program

**Data-flow equations**

- for each node of the control flow graph

**Solve them by repetition**

- i.e., it reaches a fixpoint

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**Calculate a fixpoint**

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**Calculate a fixpoint**

- because loops

# Traditional Gen/Kill Sets

# Traditional set base analysis

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Depends on the direction of the analysis

# Available Expressions

"An **expression** is **available** if it *must* have already been computed, and not later modified, on all paths to the program point"

```
kill(Assign(var, e1)) :=
  { e2 ∈ AllAE | var ∈ FV(e2) }
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gen(Assign(var, e1)) :=
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**AllAE**

- All Available Expressions in the program

**FV**

- Free Variables of the argument

**SE**

- Subexpressions of the argument

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This mistake can be prevented by making the control flow more explicit in the graph: First we execute the right-hand side, then we do the assignment.

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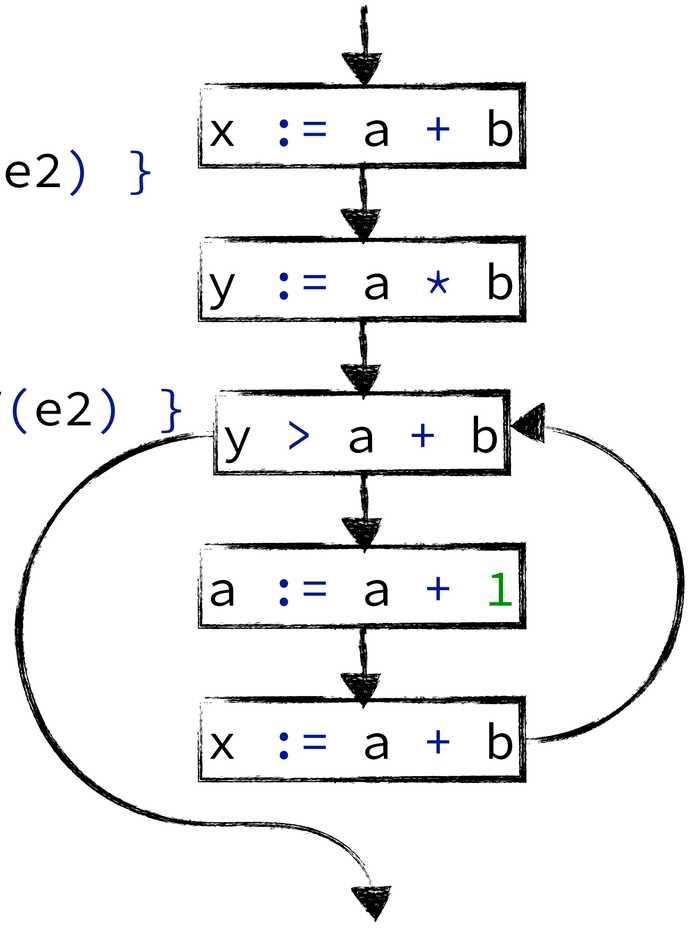

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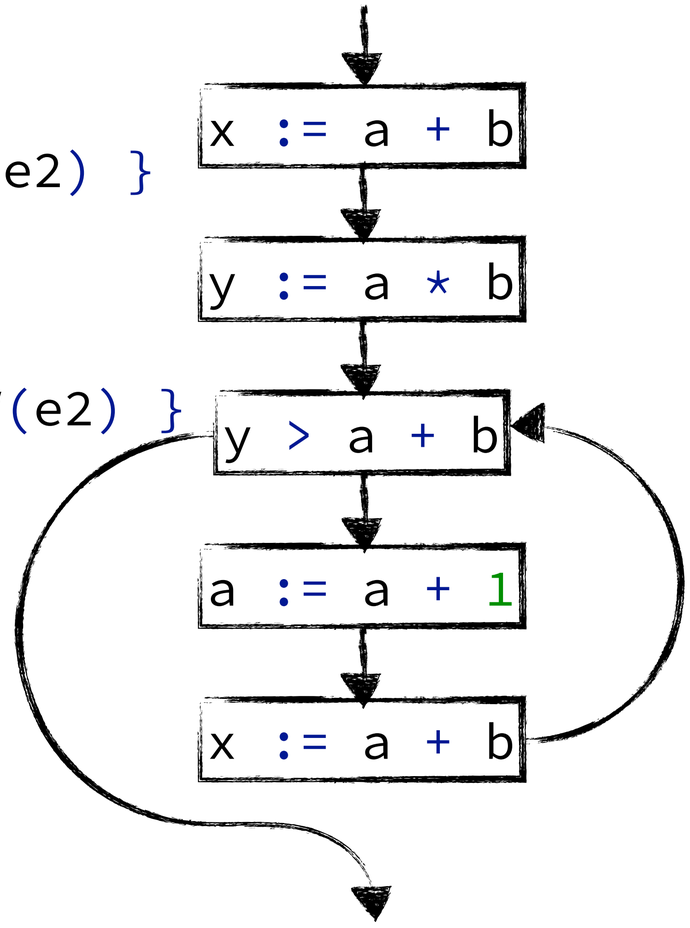

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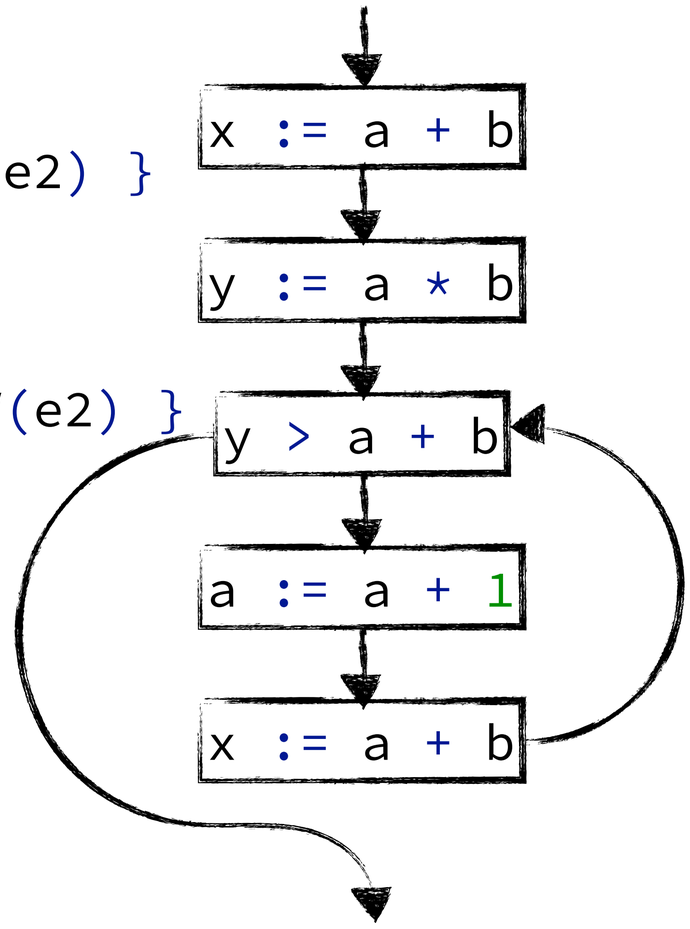


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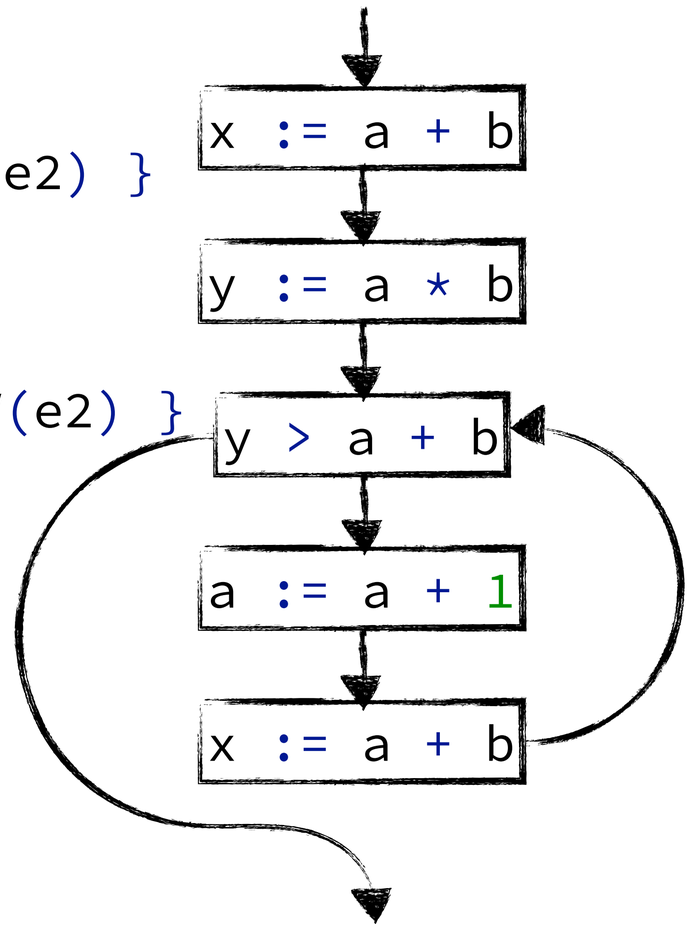


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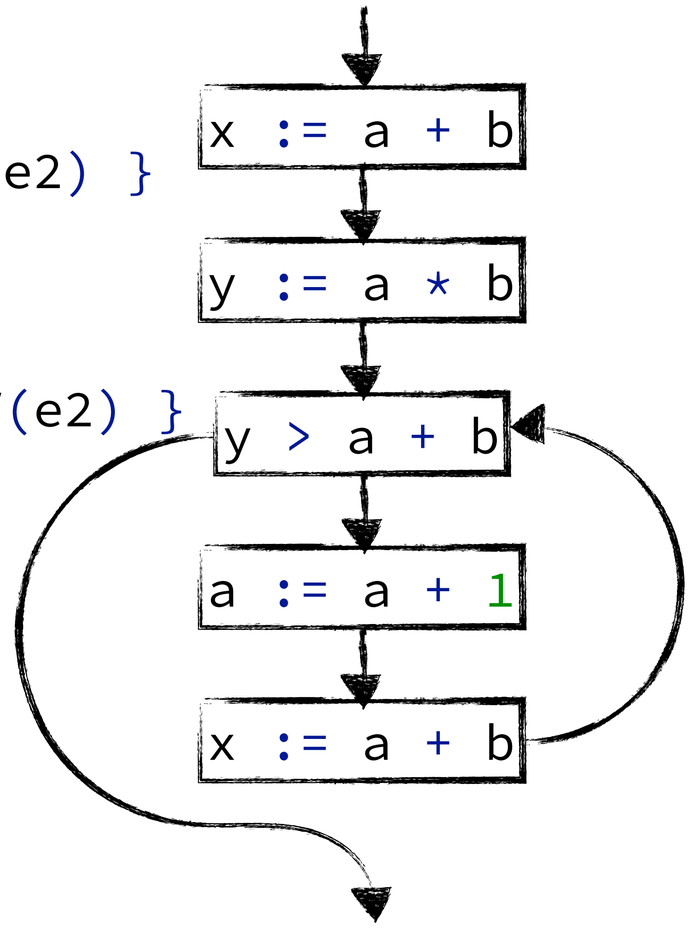


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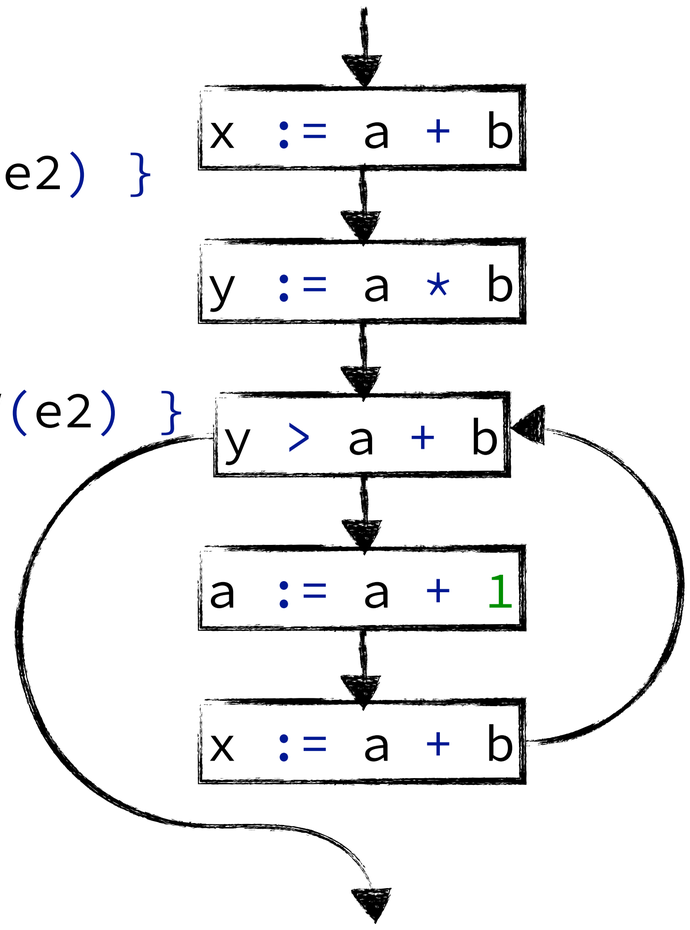


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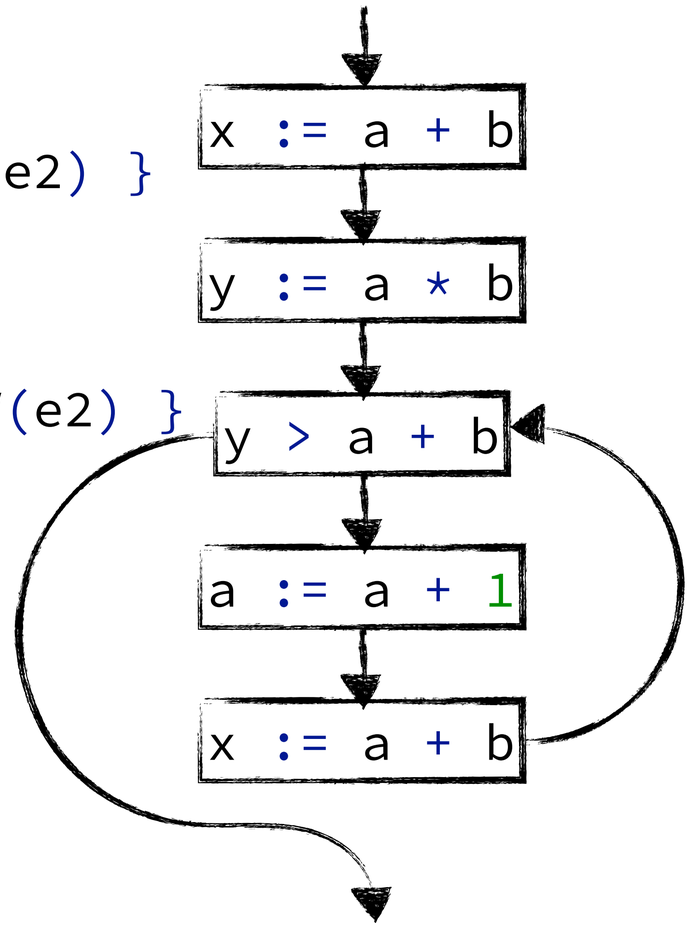


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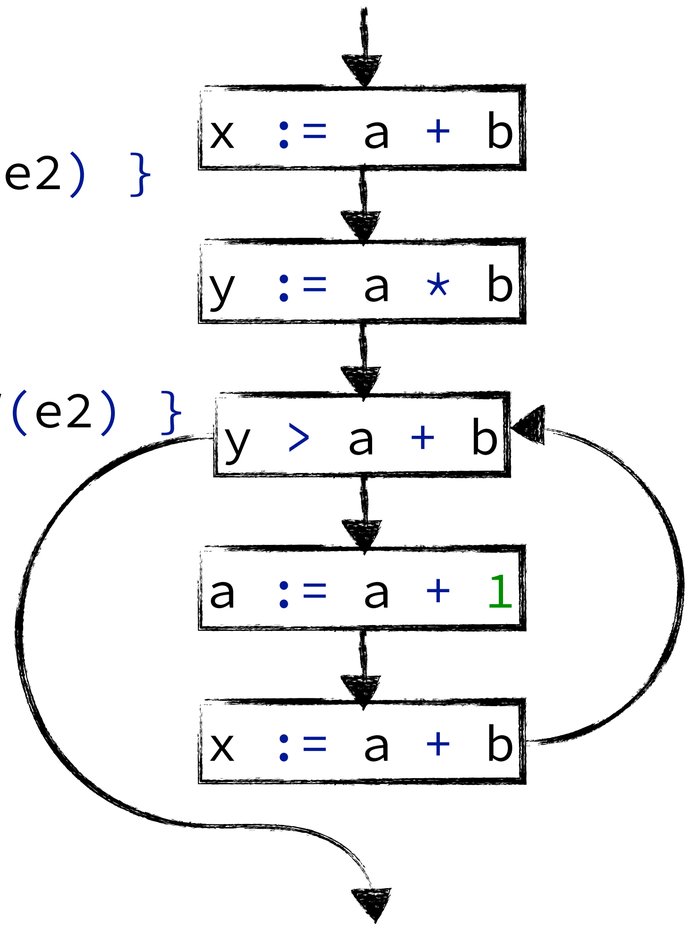


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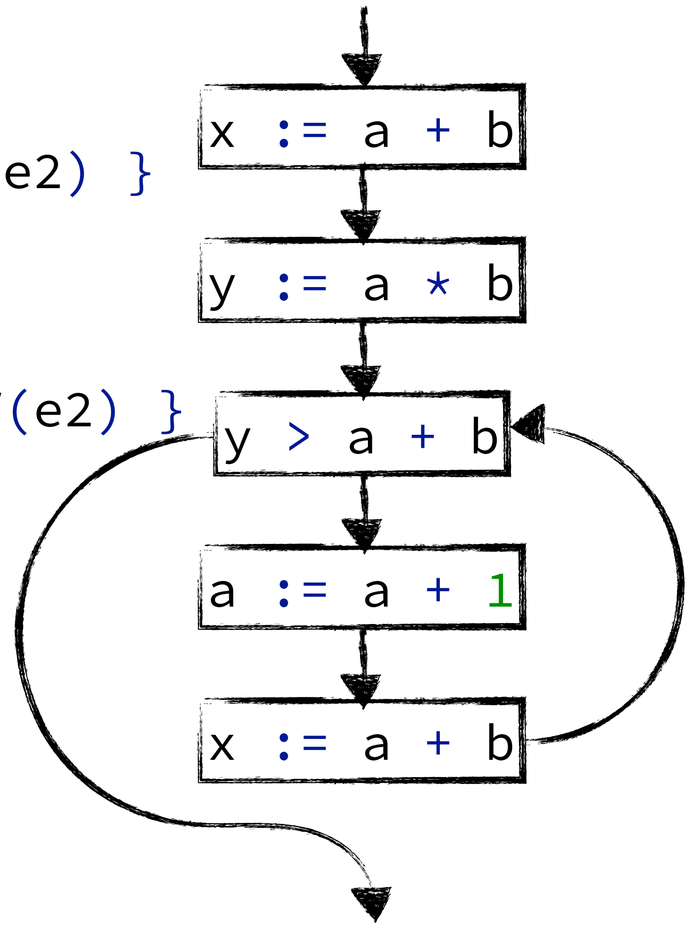


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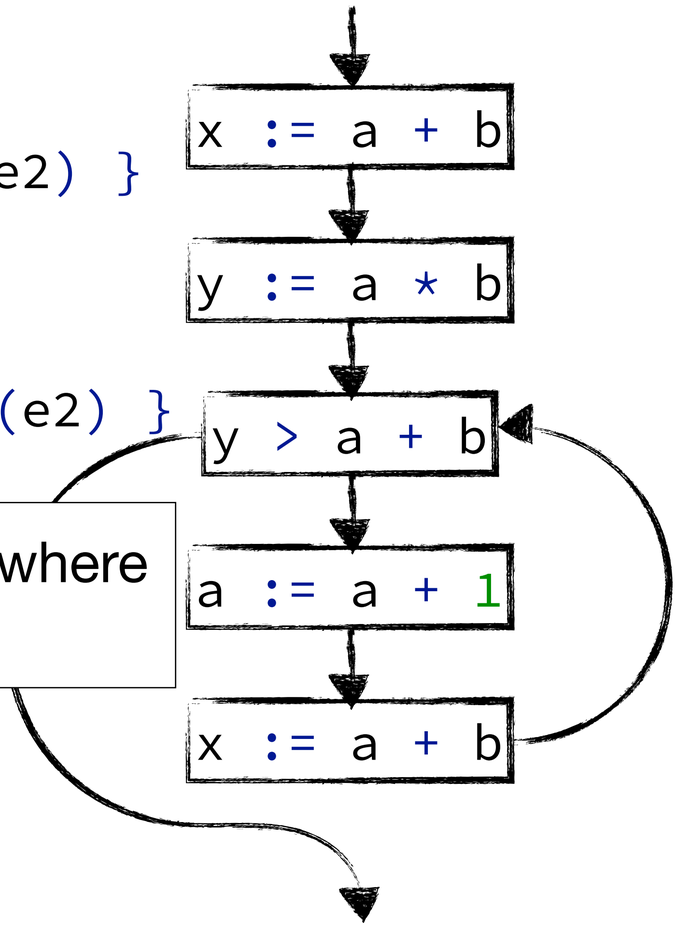
A *must* analysis intersects sets where control flow merges

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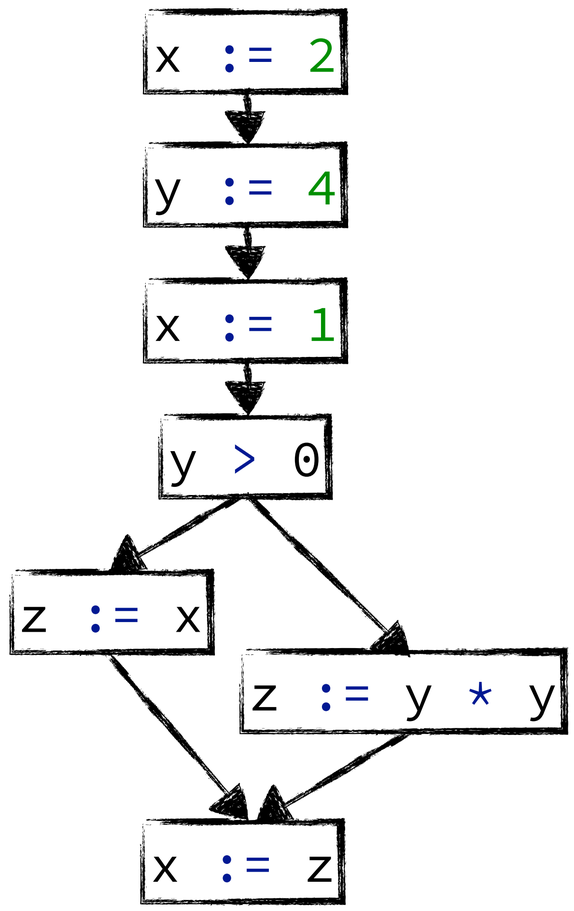

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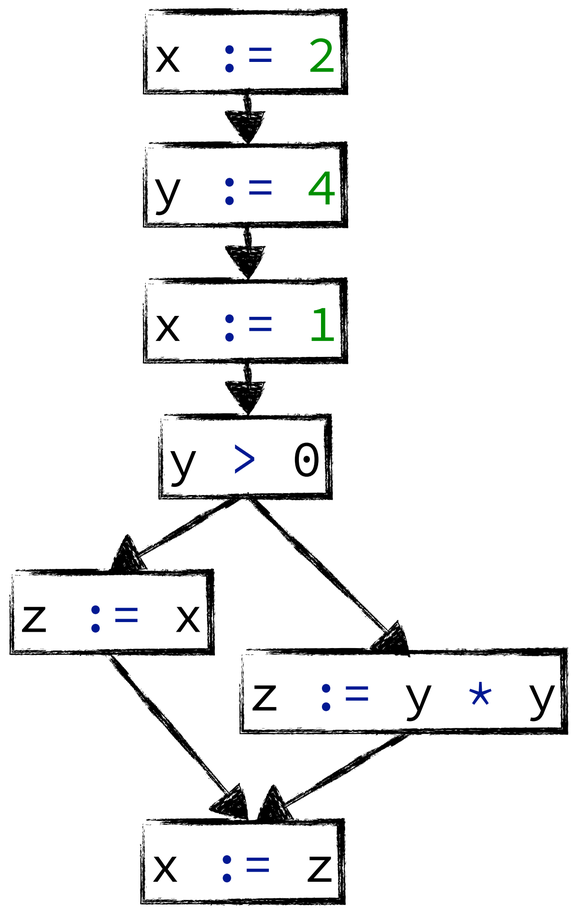

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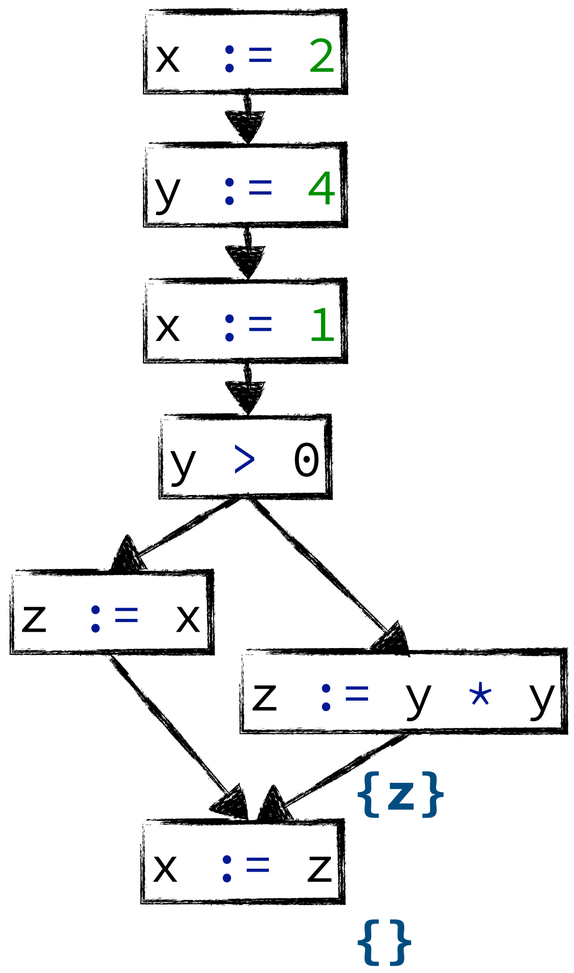

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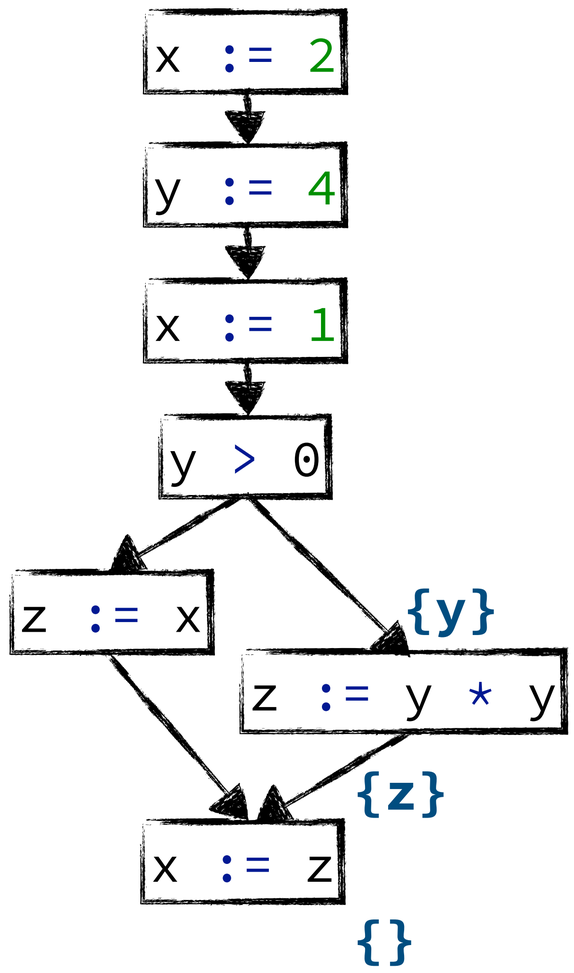

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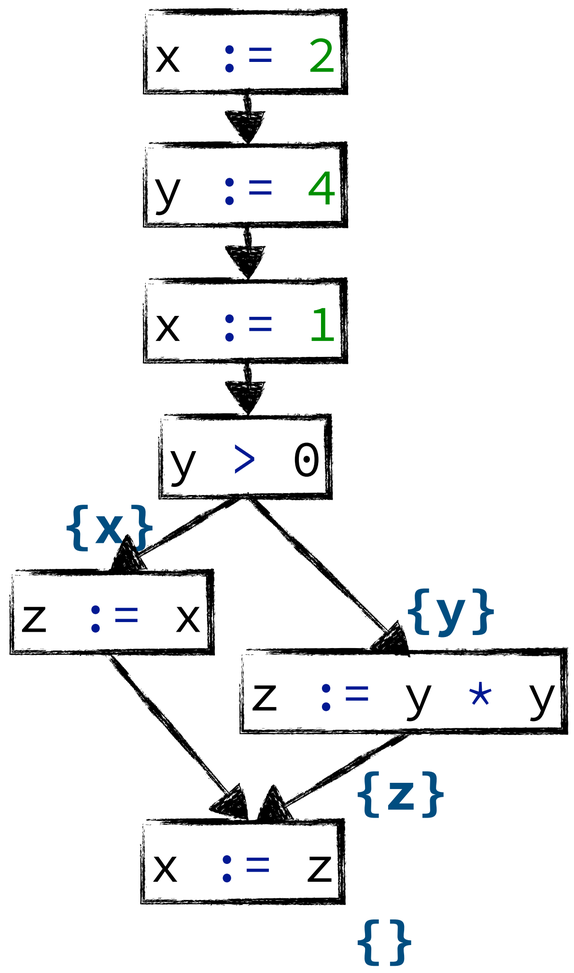

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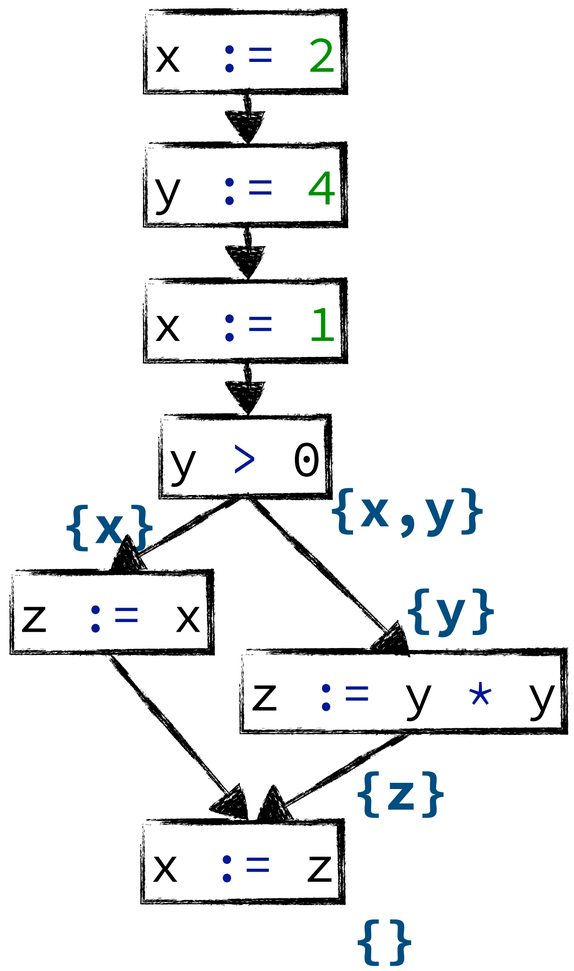

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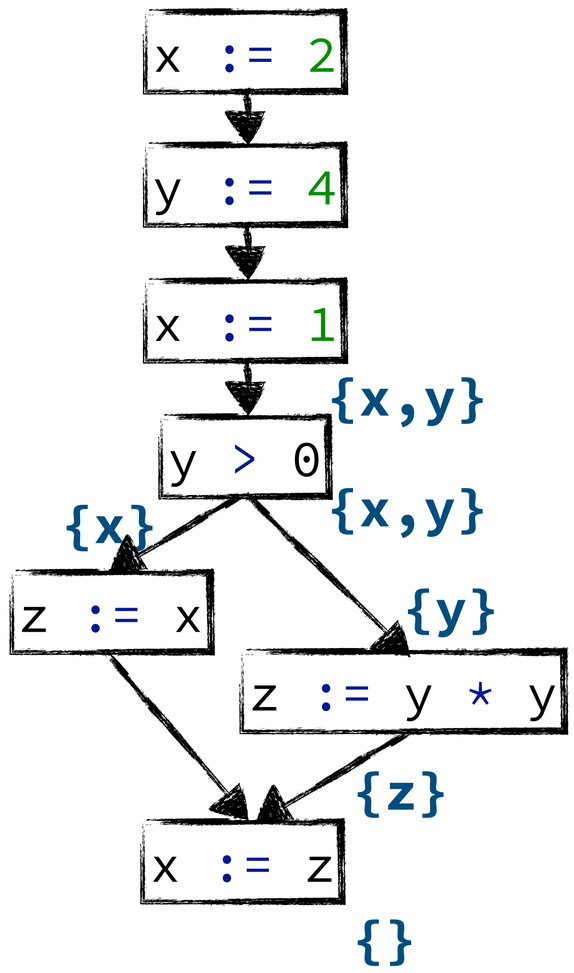

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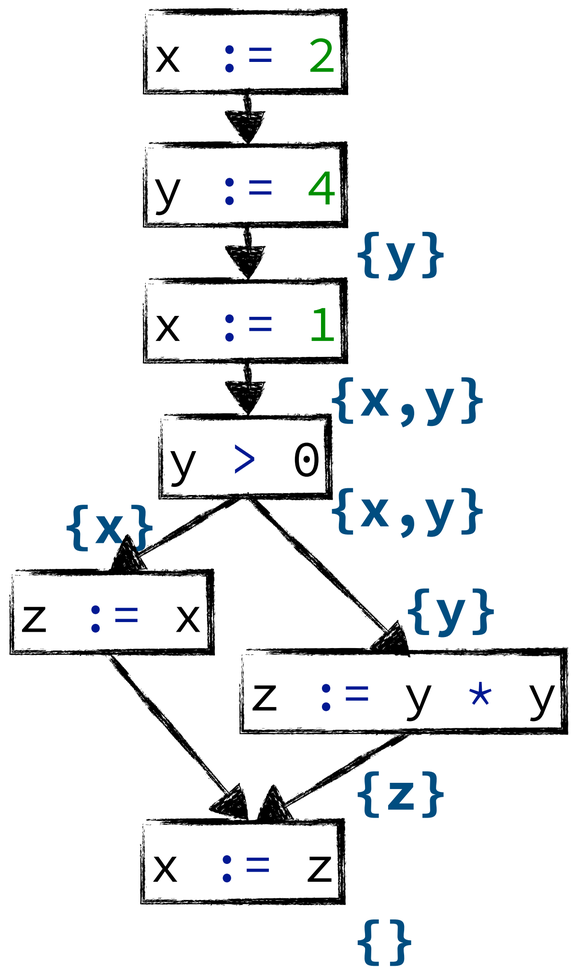

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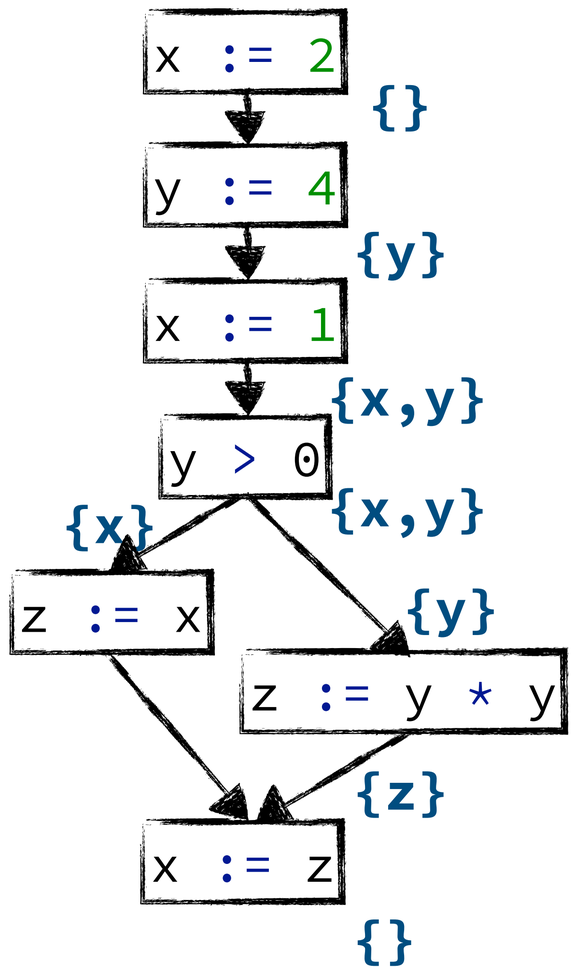

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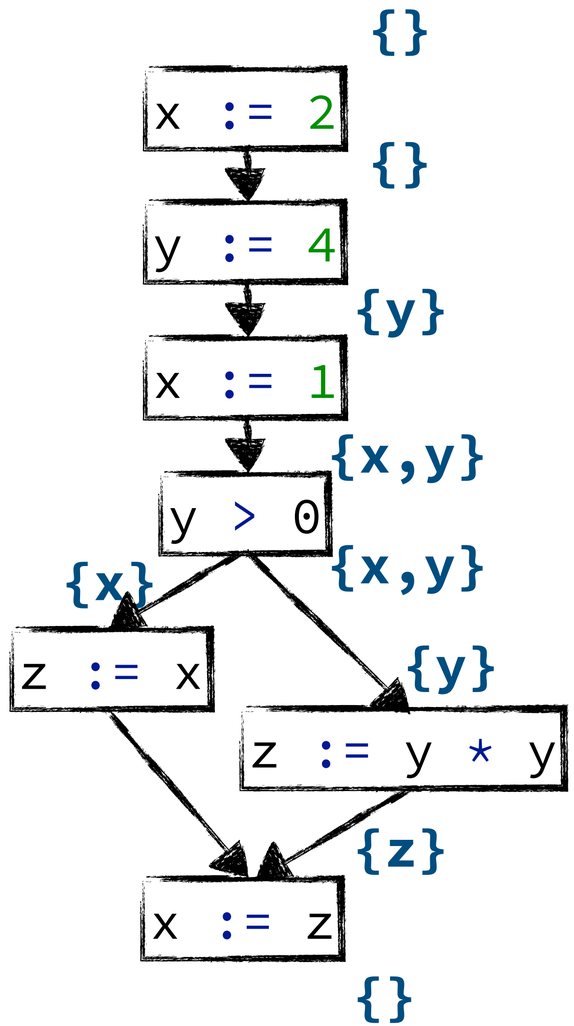

# Traditional set based analysis

**Sets** as analysis information

**Kill** and **gen** sets per control node type

- previousSet ∖ **kill**(currentNode) ∪ **gen**(currentNode)

Can propagate either **forward** or **backward**

Can merge information with either **union** or **intersection**

- Respectively called **may** and **must** analyses

# Beyond Sets

# Constant propagation and folding

```
let
  var a : int := 0
  var b : int := a + 1
 in
    c := c + b;
    a := 2 * b
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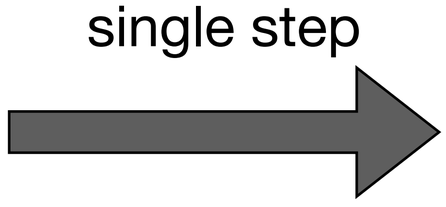

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full propagation

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# Constant propagation and folding

## The type of the analysis information

- Variables bound to either a particular *constant* or a *marker for non-constants*

## The transfer functions per control node

- Basically an interpreter implementation for constants
- Needs to propagate markers when found

# Monotone Frameworks

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- Because of loops

**To terminate, there needs to *be* a fixpoint**

- **And** we need to actually *get* to that fix point
- How can we check this?

# Lattice Theory

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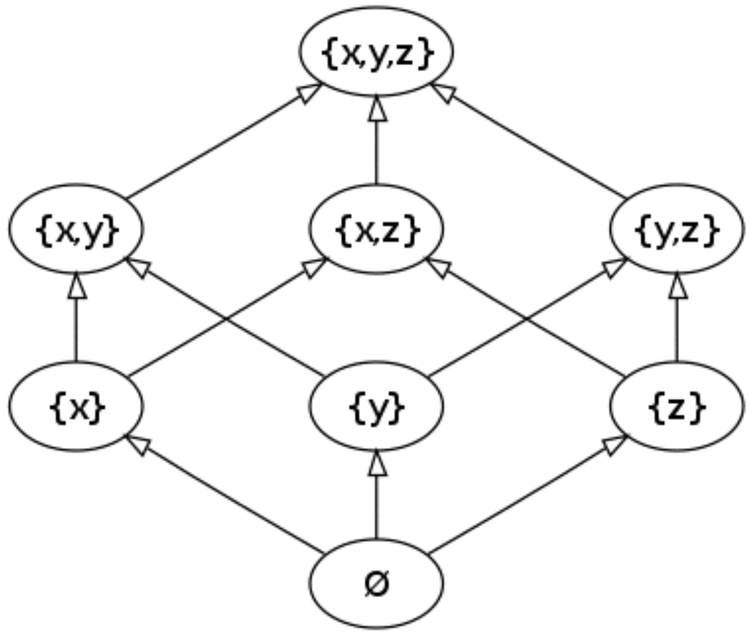

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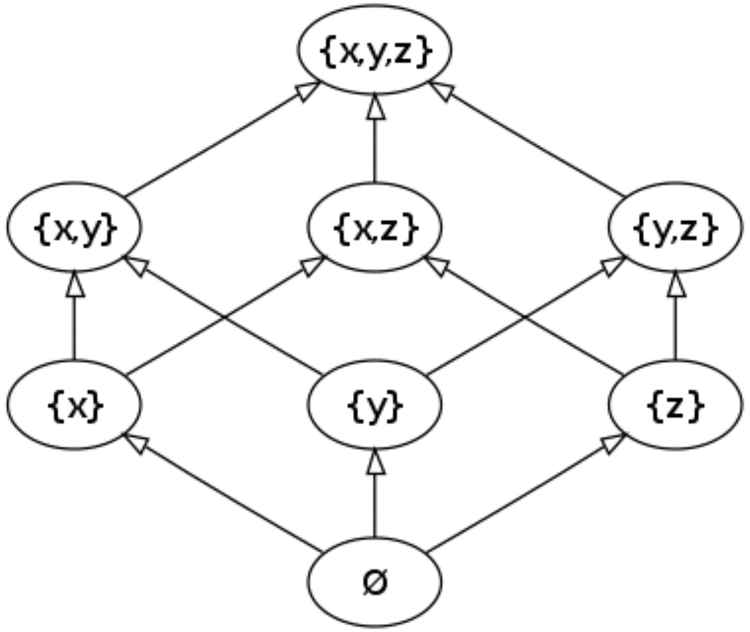

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- every two elements have a *unique* least upper bound (or supremum or join)
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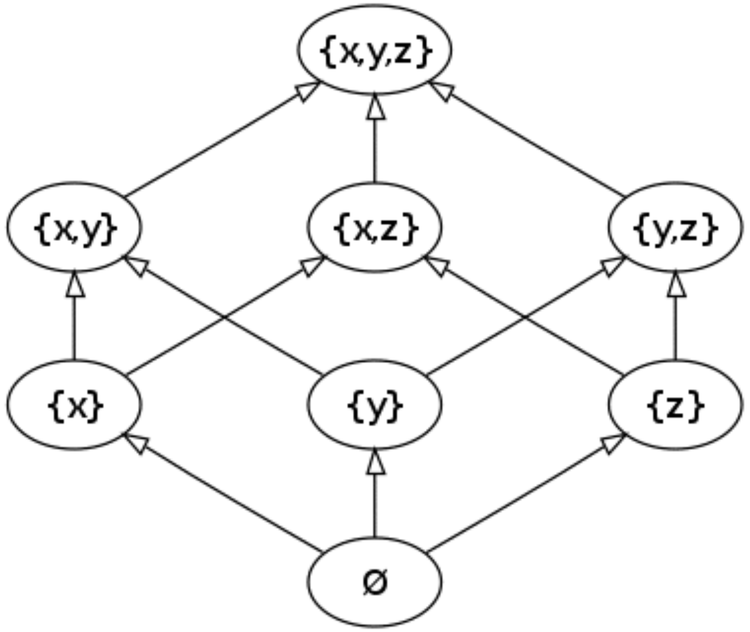

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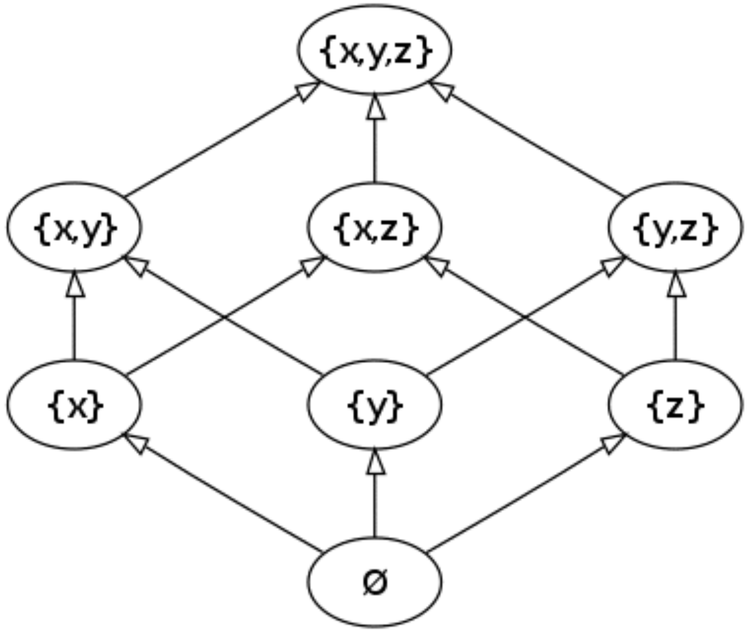

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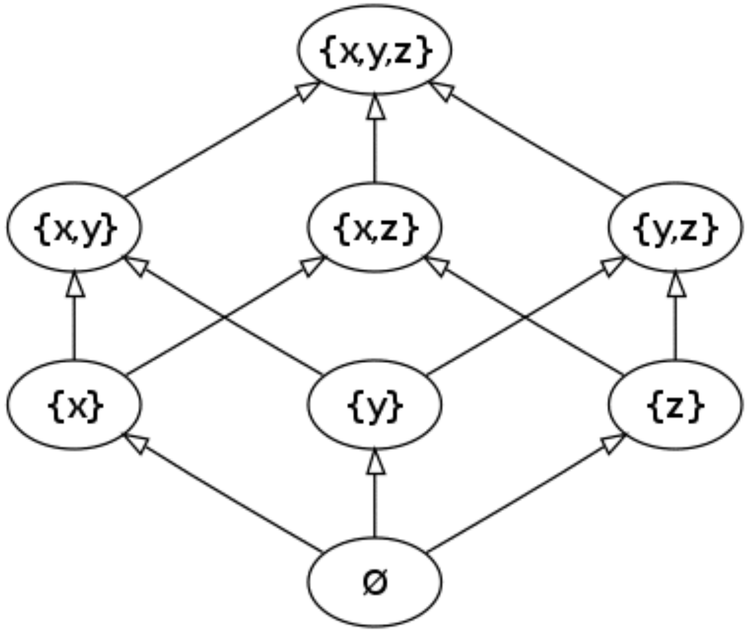

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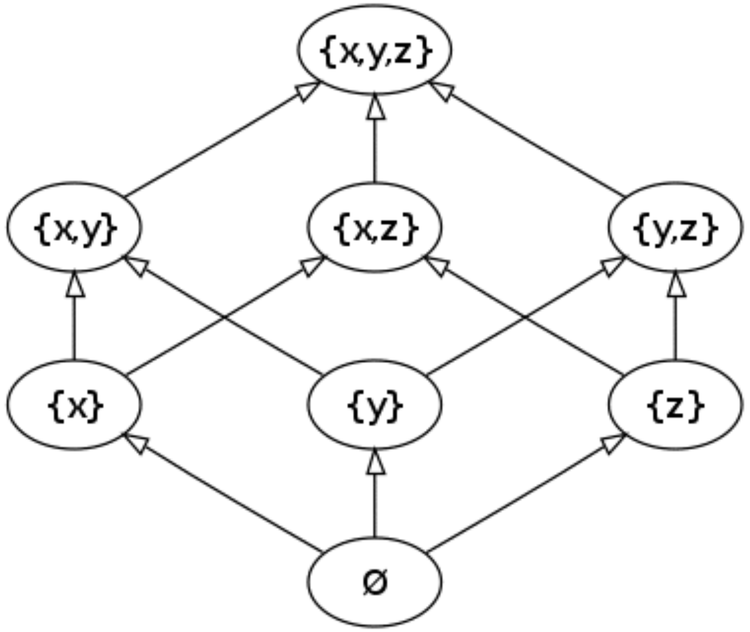


## A *bounded* lattice has a top and bottom

- These are $\top$ and $\bot$ respectively

# Lattices for data-flow analysis

**Consider $\top$ as the coarsest approximation**

- It's a safe approximation, because it says we're not sure of anything

**Then we can combine data-flow information with $\sqcup$**

- It is the most information preserving combination of information

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## General interval analysis has an infinite lattice

- $\top = [-\infty,\infty]$
- If a loop adds a finite number to a variable, you never get to $\infty$

# Recap

**An analysis consists of**

- The type of the analysis information
- The *transfer functions* that express the ‘effect’ of a control node
- The initial analysis information

# Recap

**An analysis consists of**

- The type of the analysis information, **and the lattice instance for that type**
- The *transfer functions* that express the ‘effect’ of a control node
  - **These should be monotone with respect to the lattice**
- The initial analysis information

# Data-Flow Languages

# How to define the data-flow rules of a language

?

# Data-Flow specification approaches

**Languages used for specifying data-flow analysis**

- Attribute grammars: JastAdd [Söderberg'13]
- Datalog [Smaragdakis'15]: Doop [Kasterinis'13], Flix [Madsen'16]
- $INCA_L$ / MPS-DF [Szabó'18 / '16]
- Temporal Logic: Silver [VanWyk'10]

# Separation of Concerns

## Representation

- **Control Flow Graphs**
- **Before/After data-flow information on CFG nodes**

## Declarative Rules

- To define control-flow rules of a language
- To define data-flow rules of a language

## Language-Independent Tooling

- Analysis
- Code completion
- Refactoring
- Optimisation
- …

# Control-flow graphs in FlowSpec

*FlowSpec*

*Example program*

```
x := 1;
if y > x then
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else
  z := y * y;
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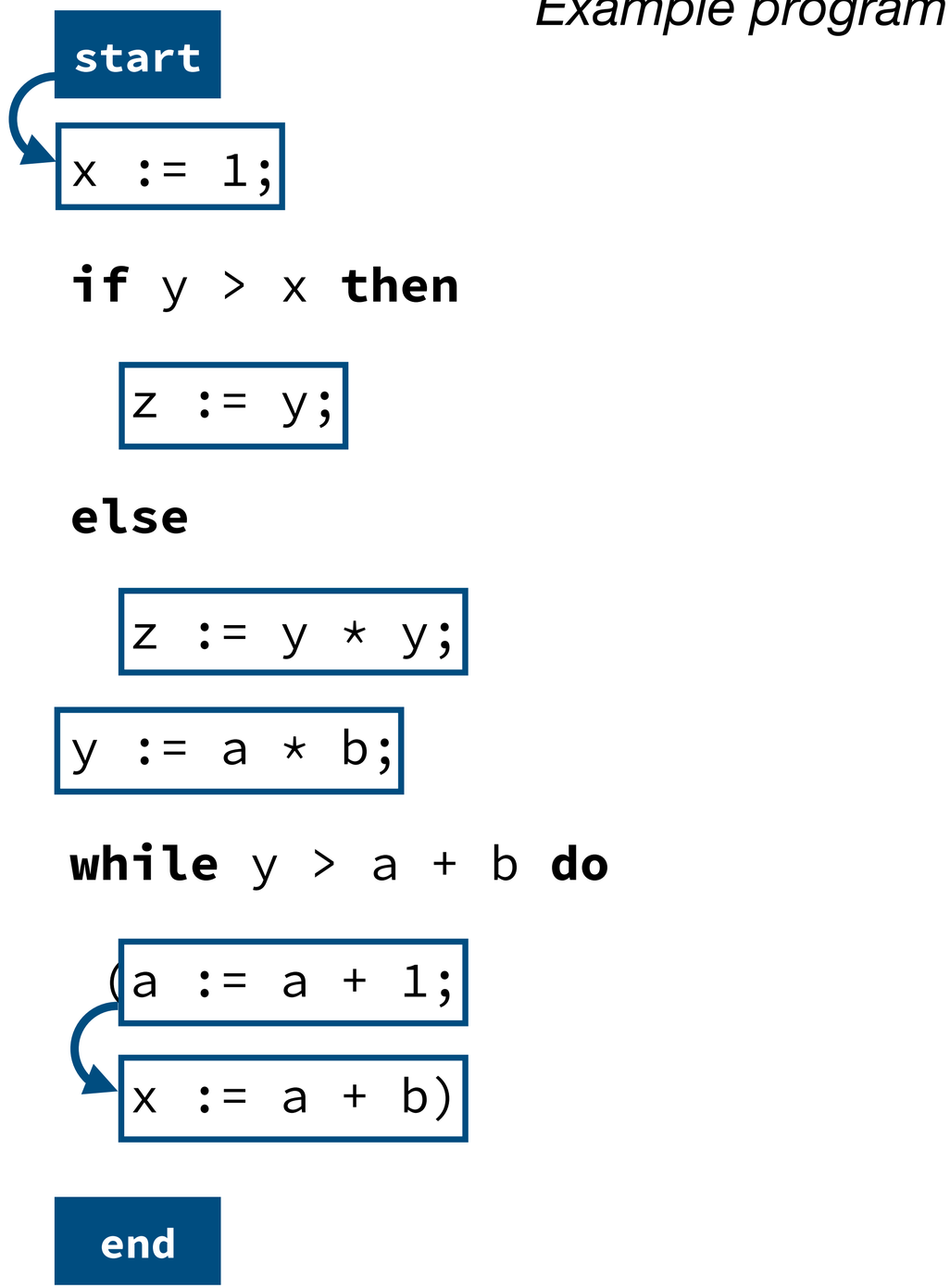

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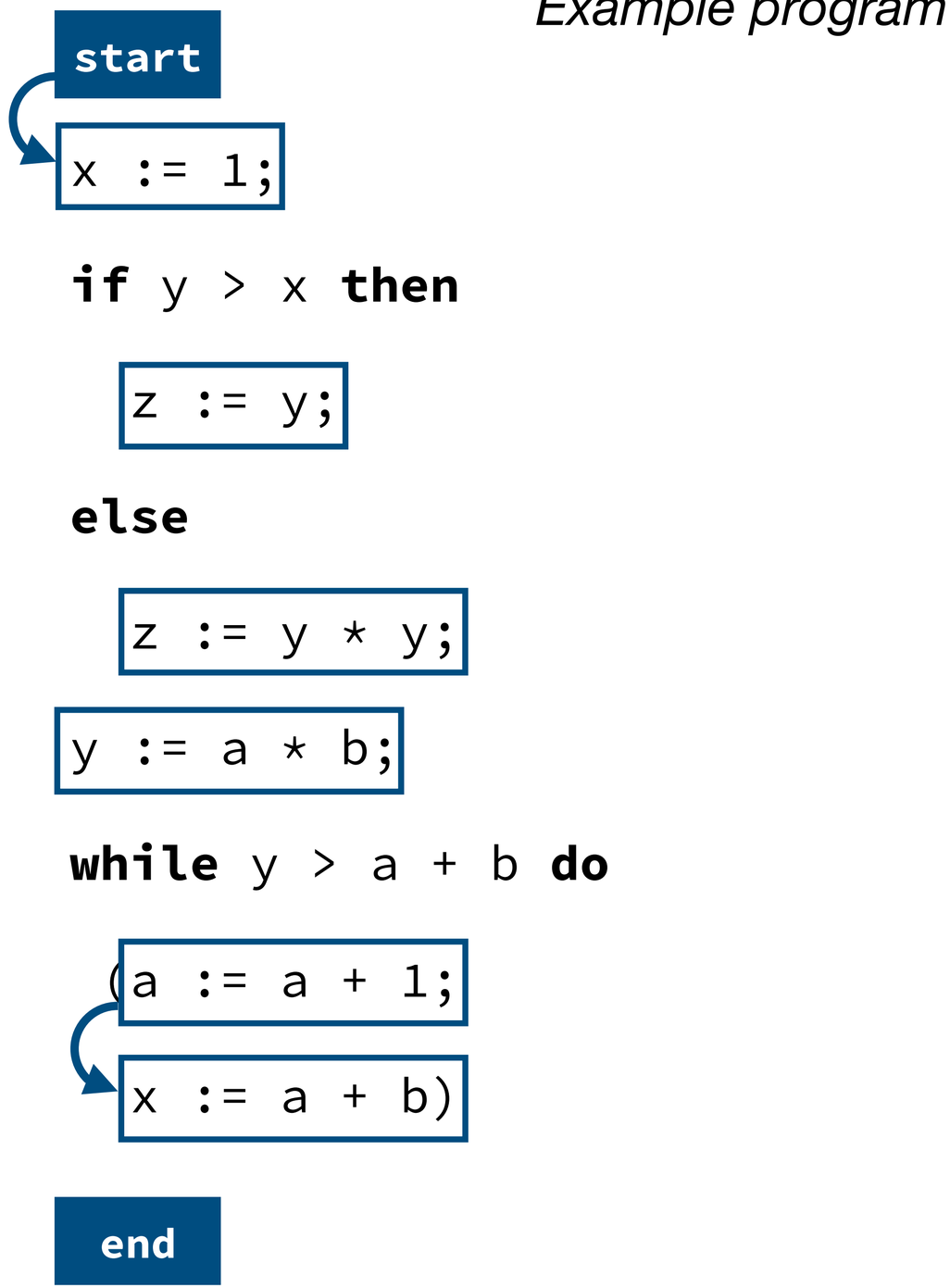

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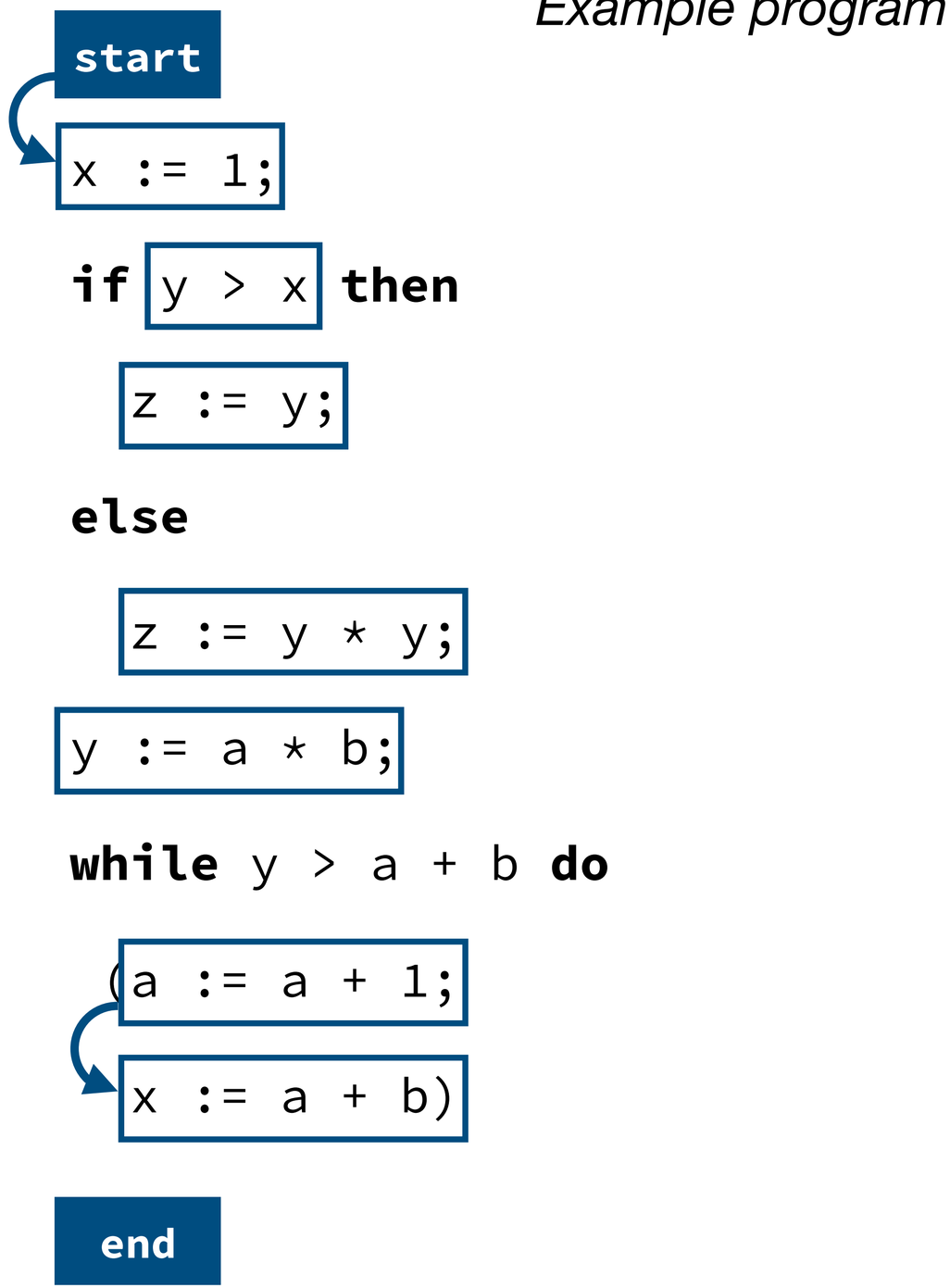

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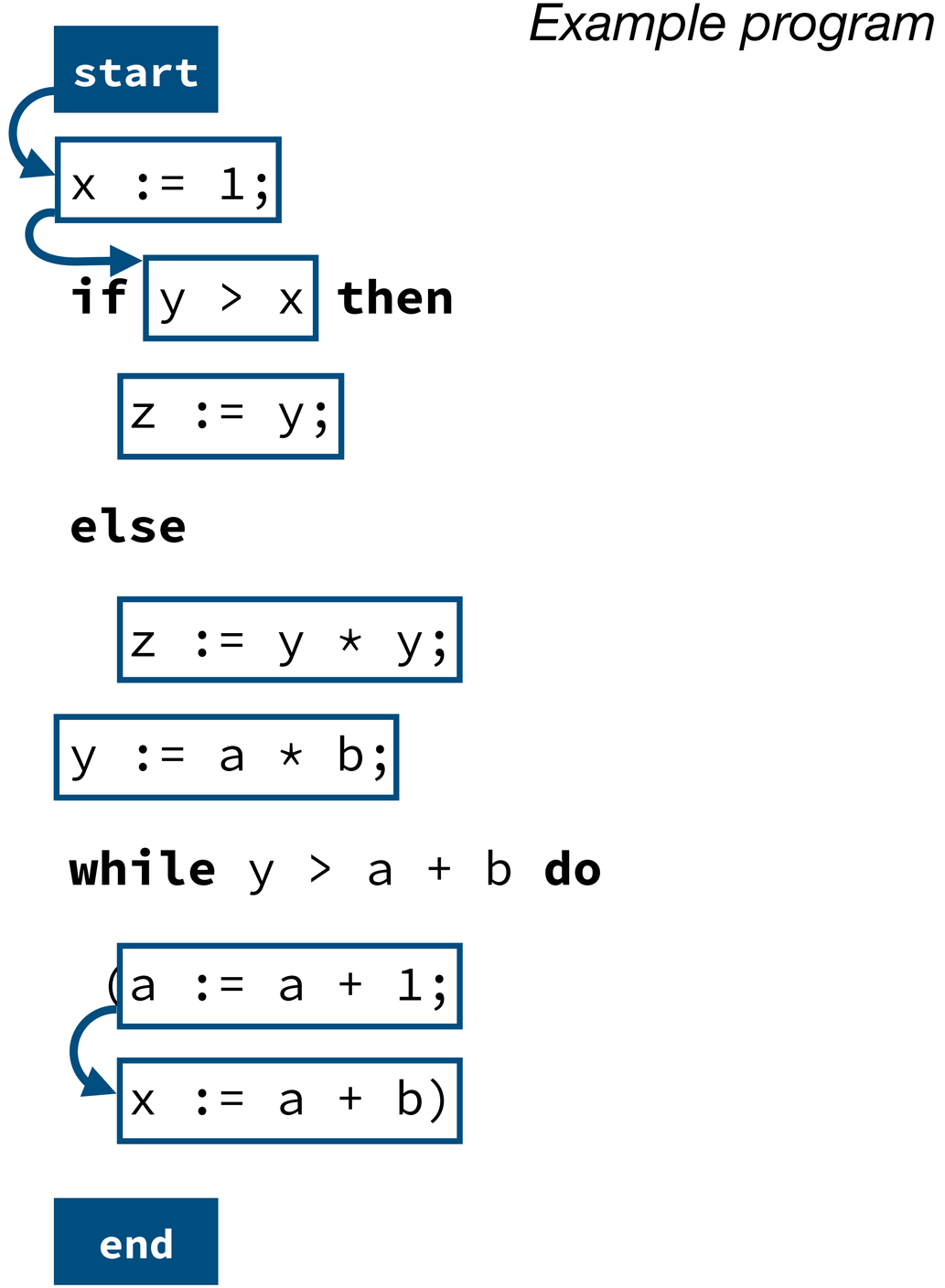

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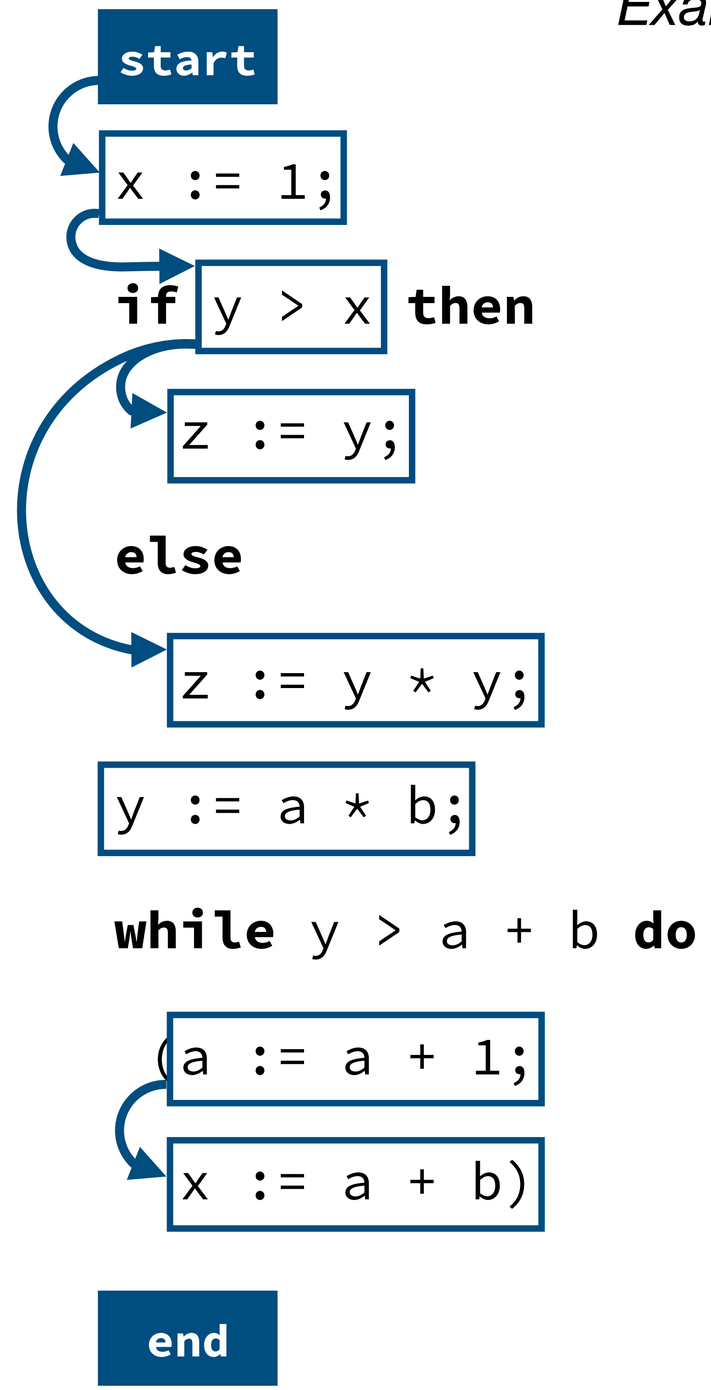

# Control-flow graphs in FlowSpec

*FlowSpec*

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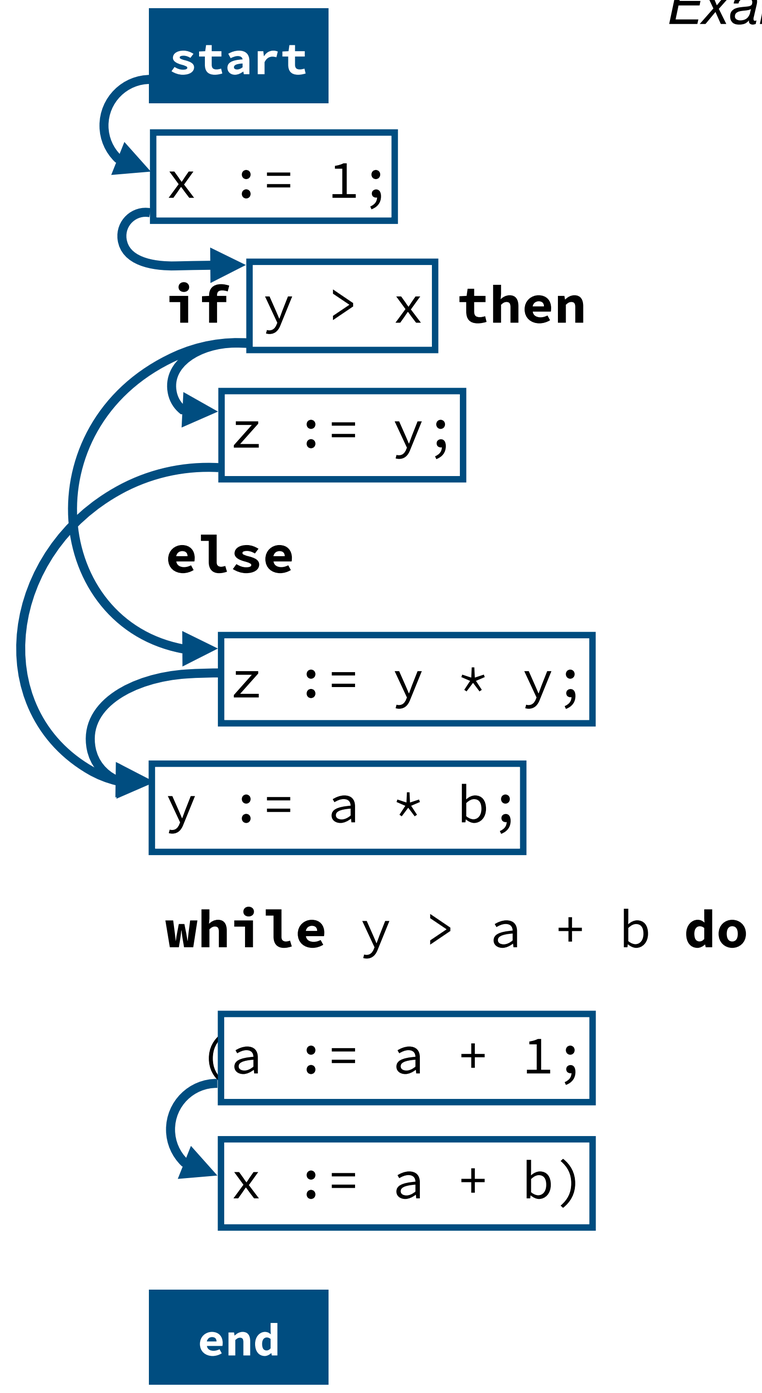

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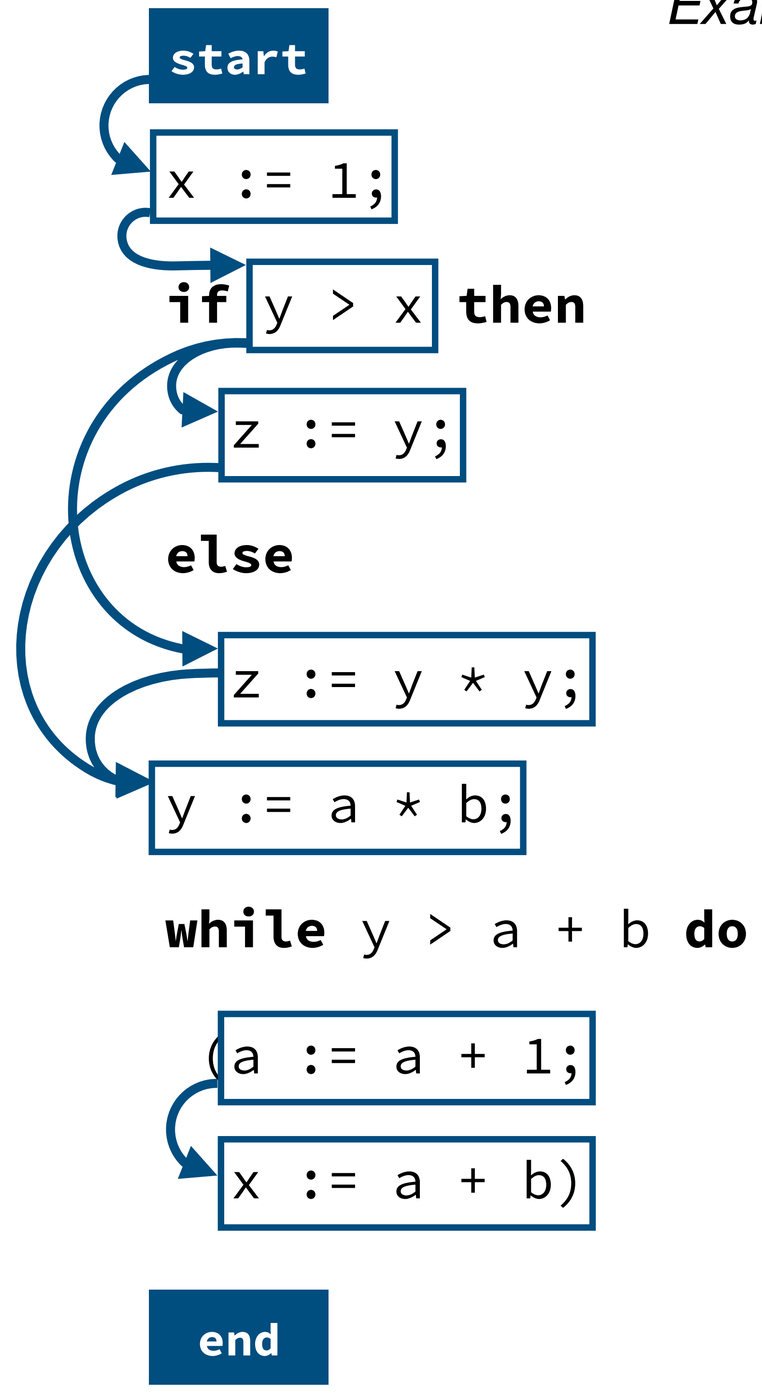

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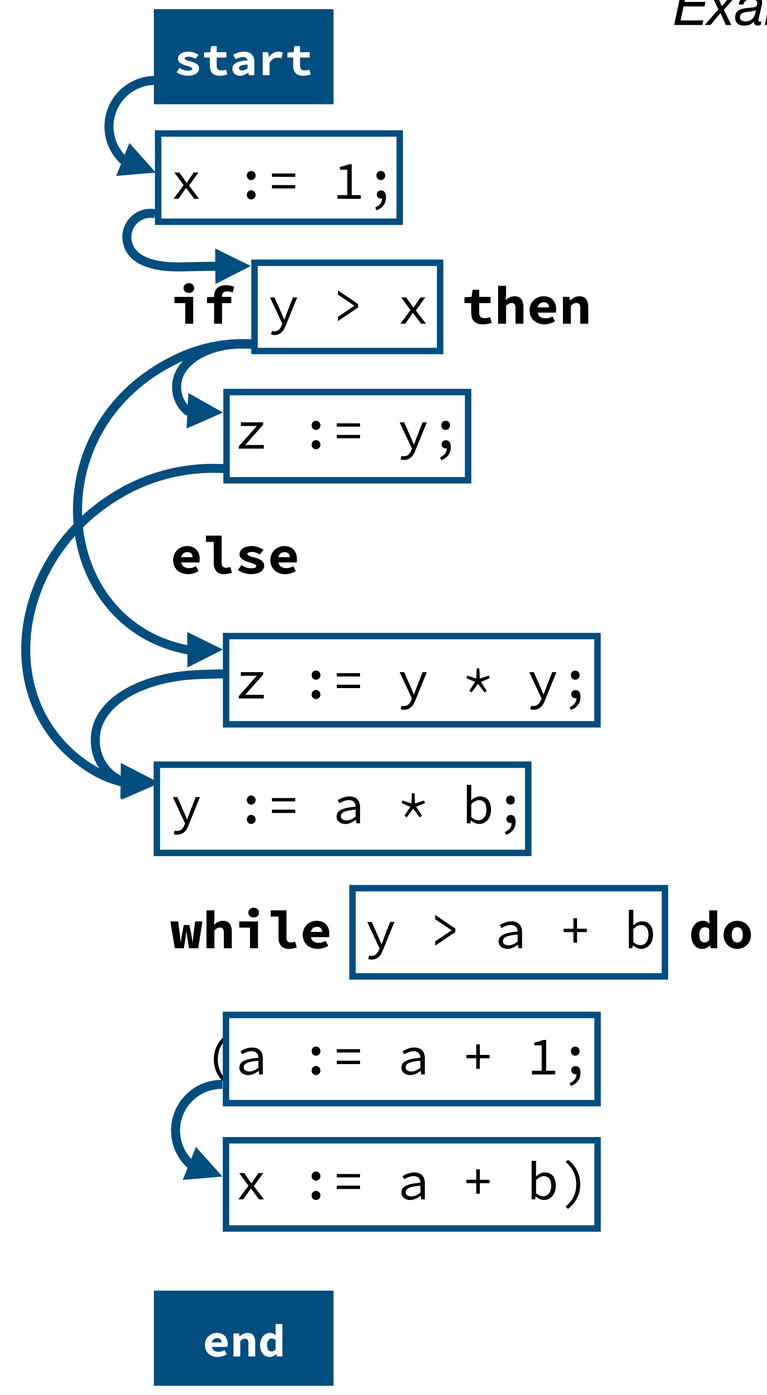

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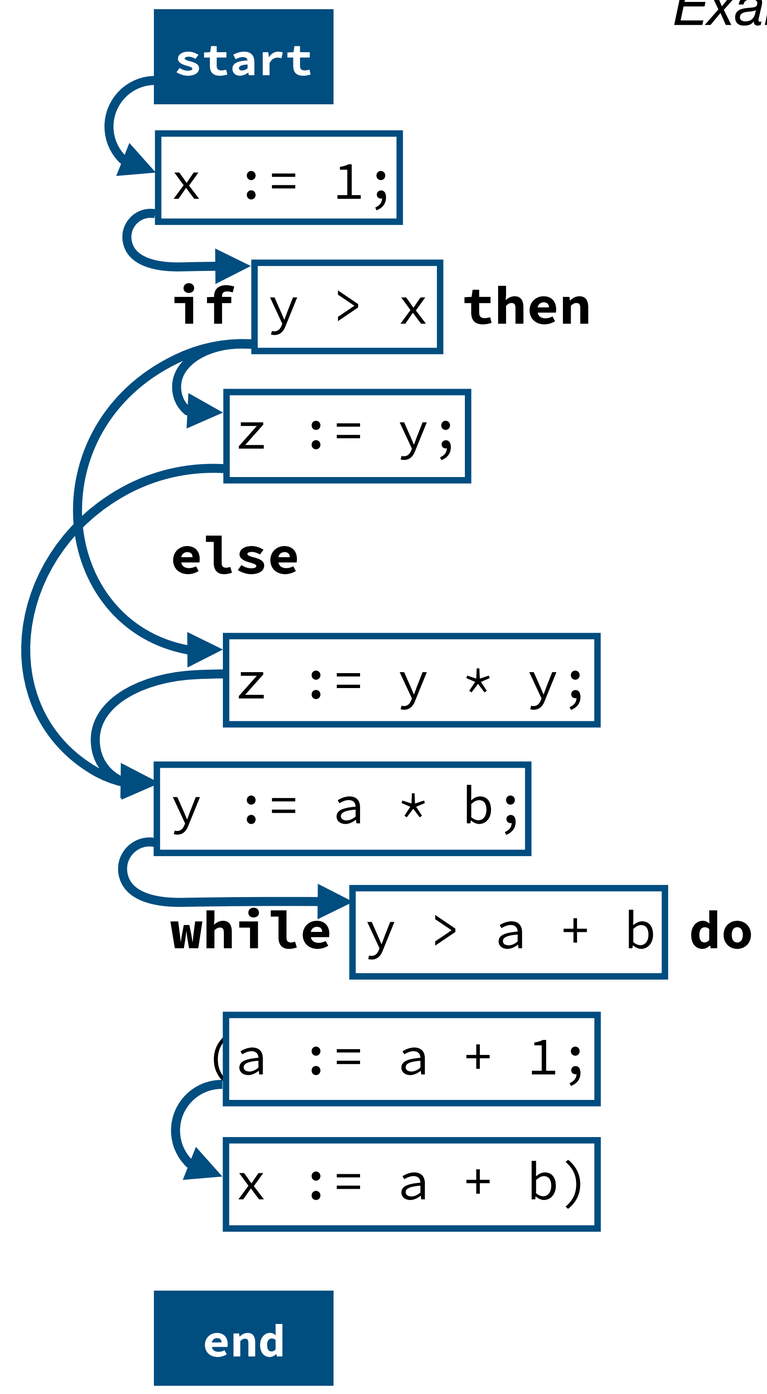

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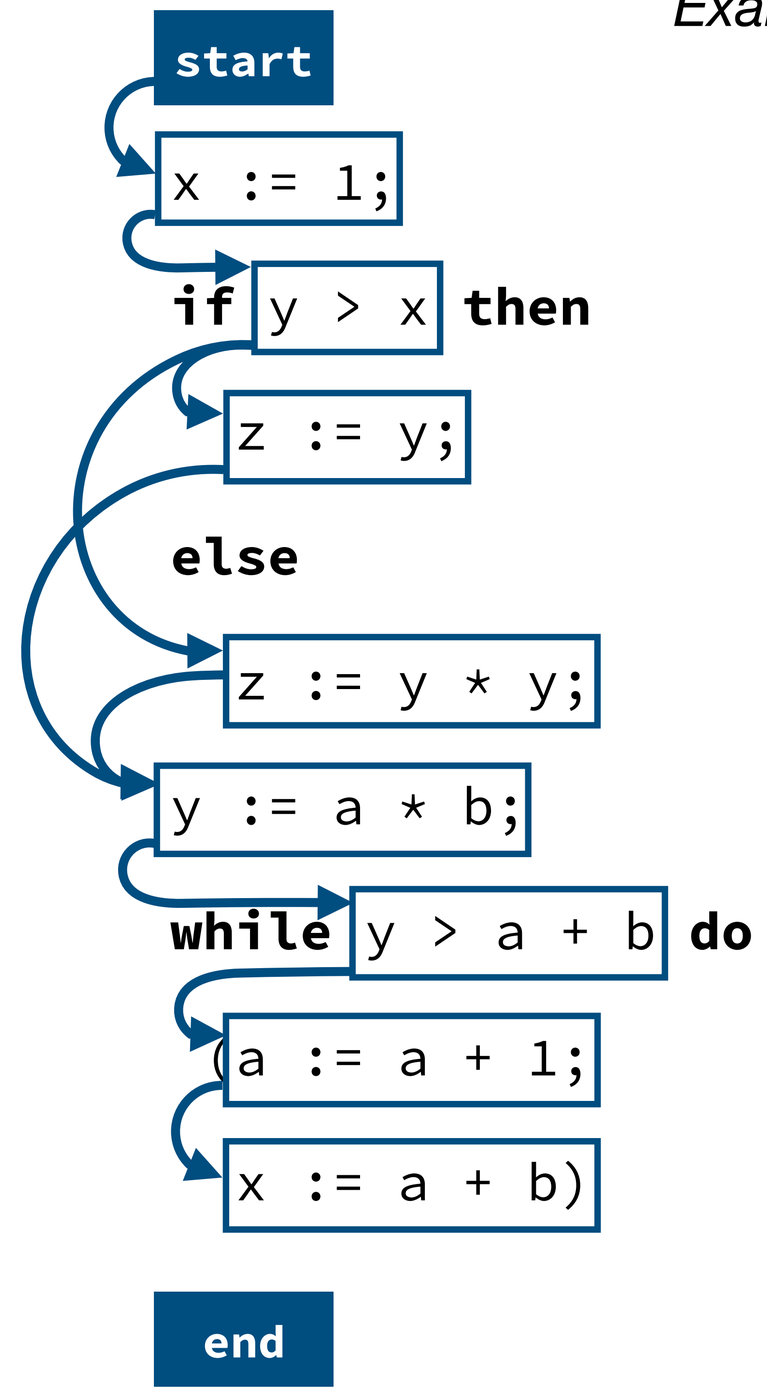

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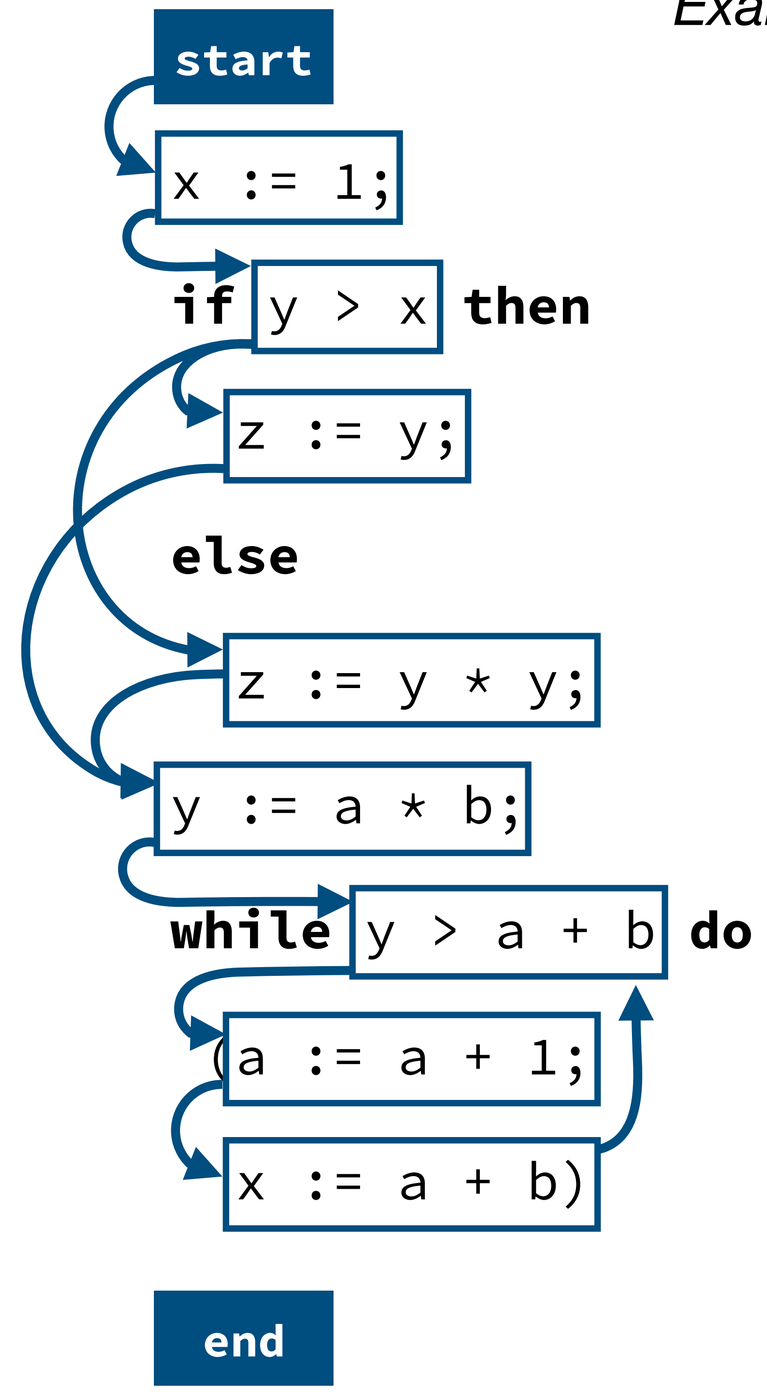

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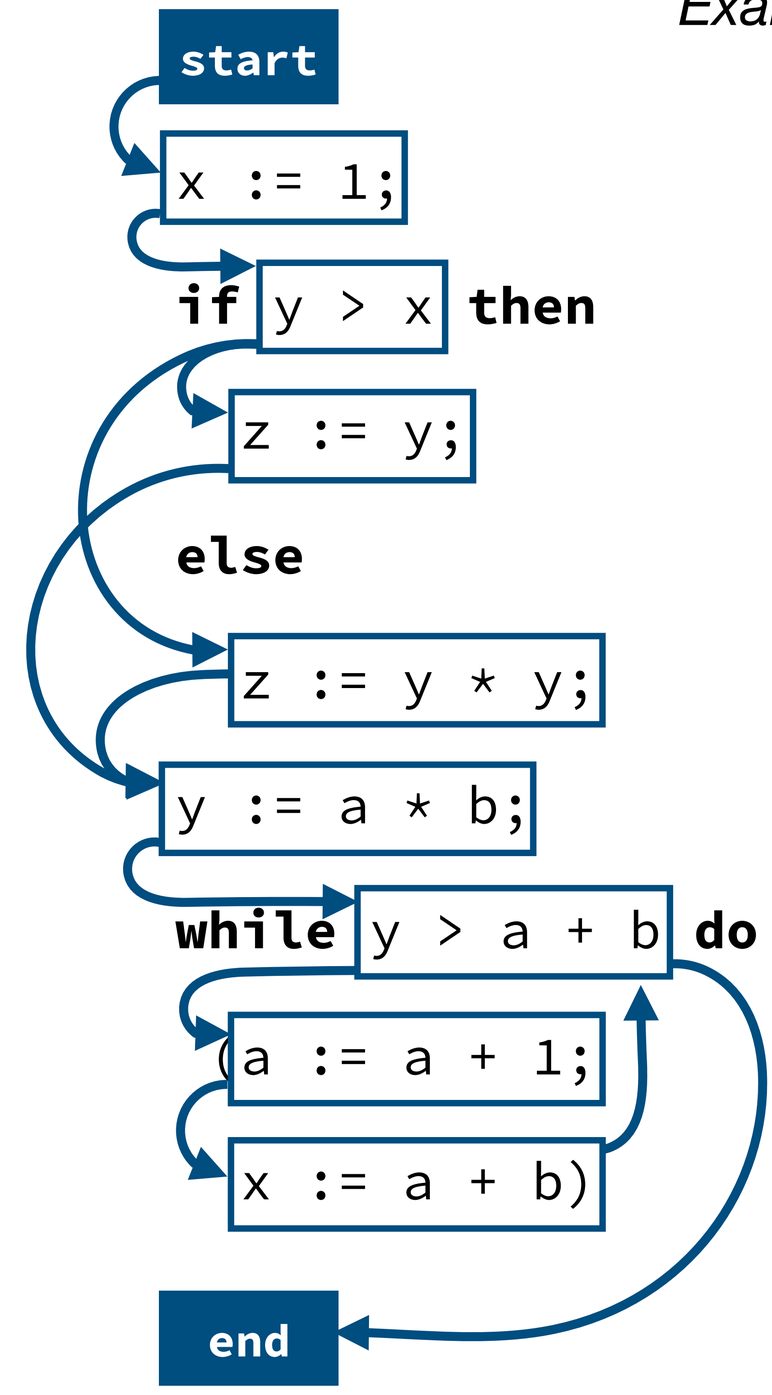

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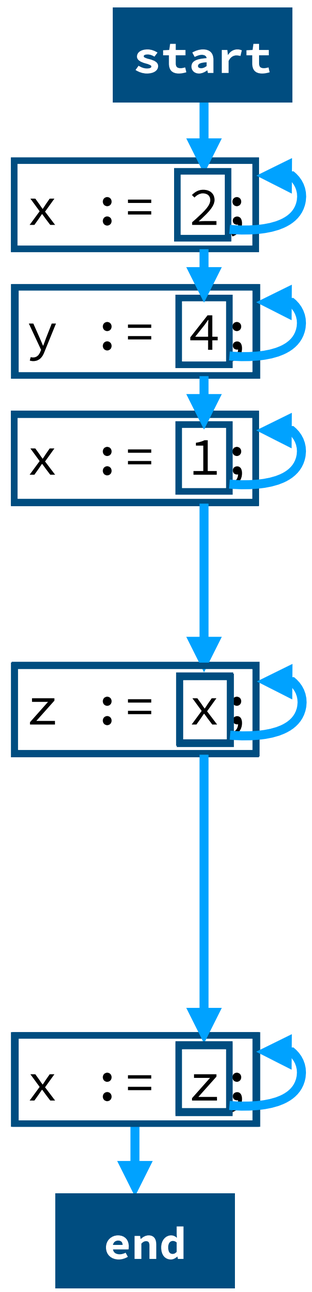

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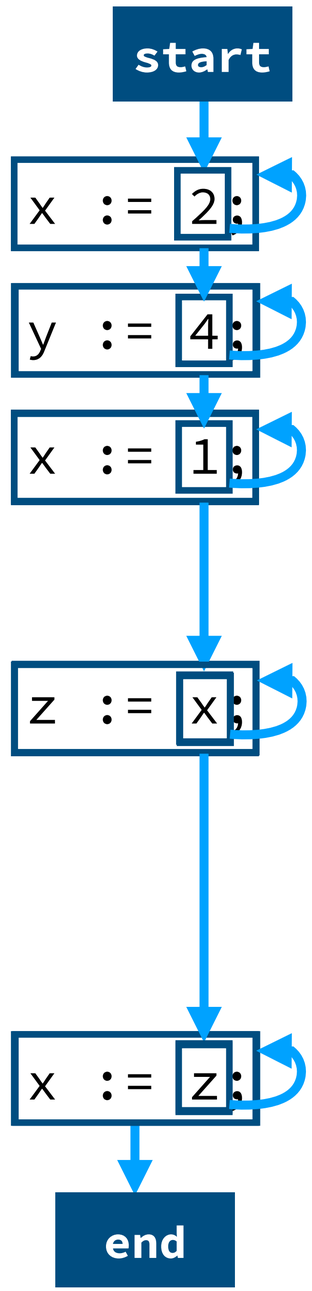

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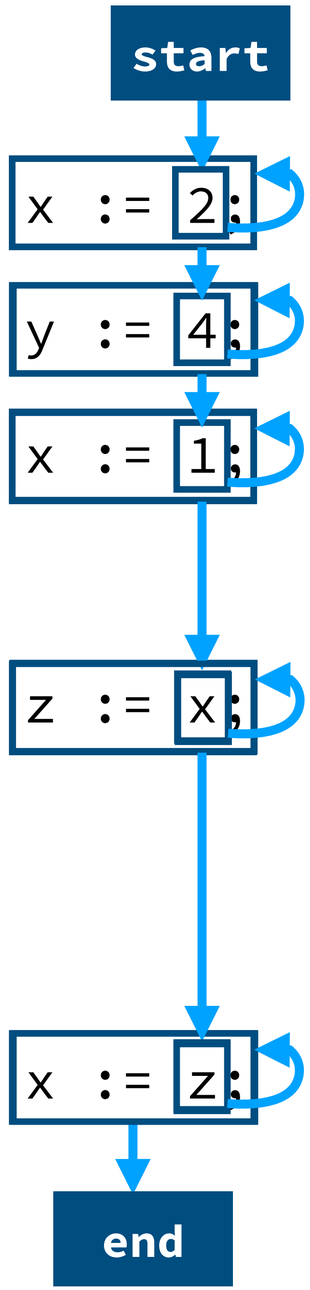

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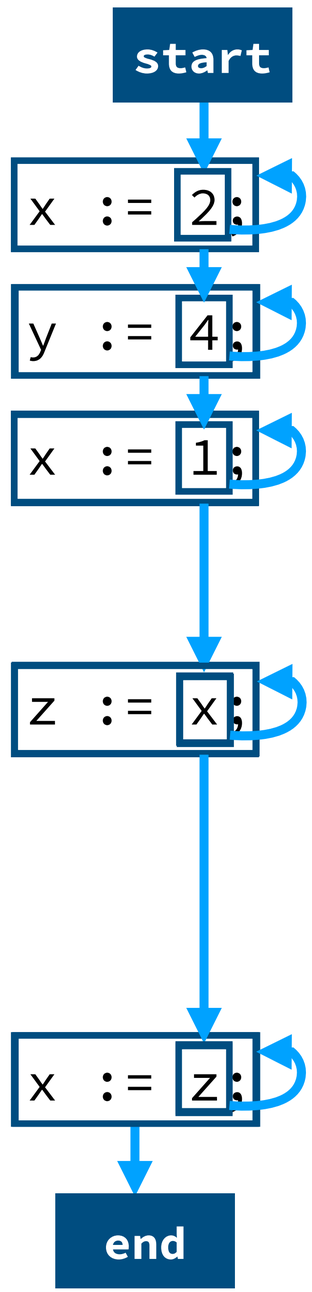


{}

{}

{}

{}

{}

{}

{}

{}

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```
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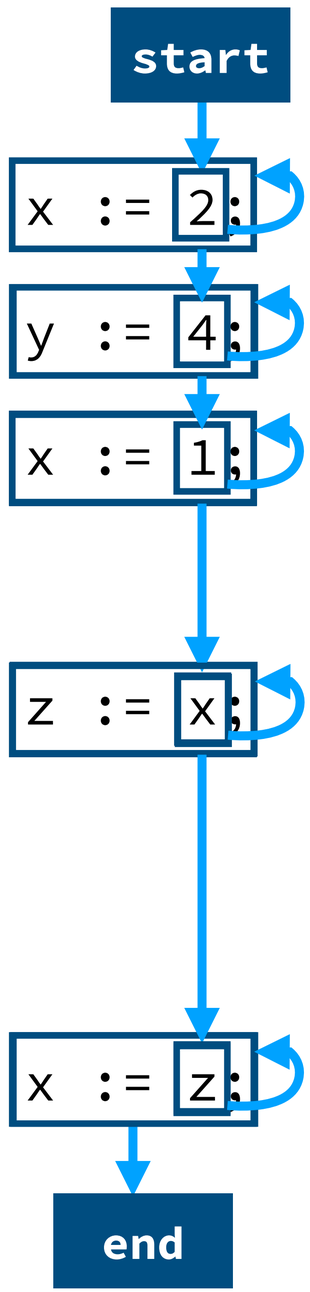


{}

{}

{}

{}

{}

{}

{}

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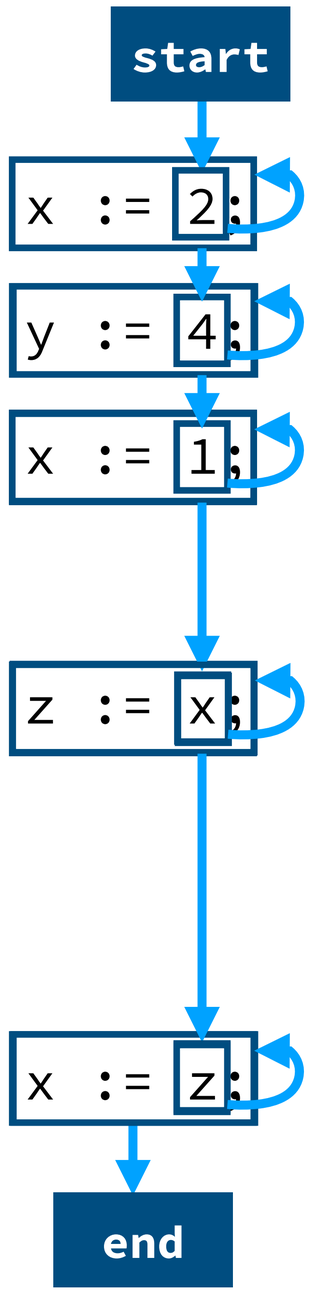

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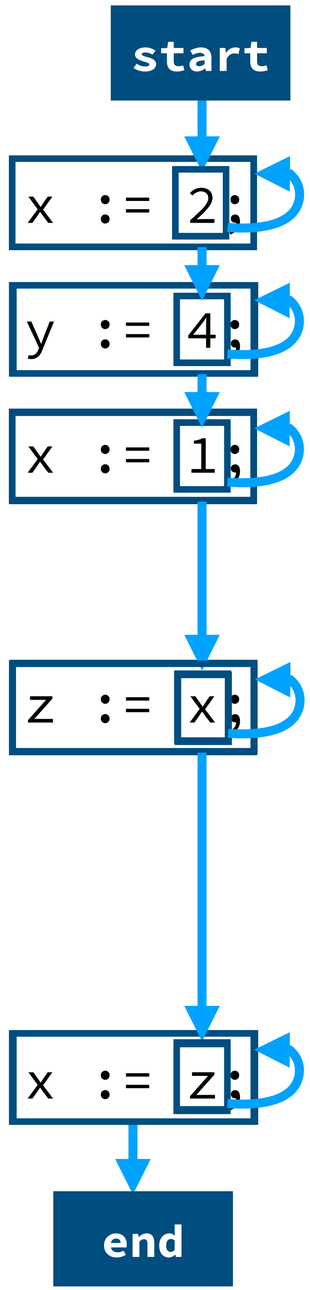


```
{z,x}
{z,x}
{z,x}
{z,x}
{z,x}
{z}
{}
{}
```

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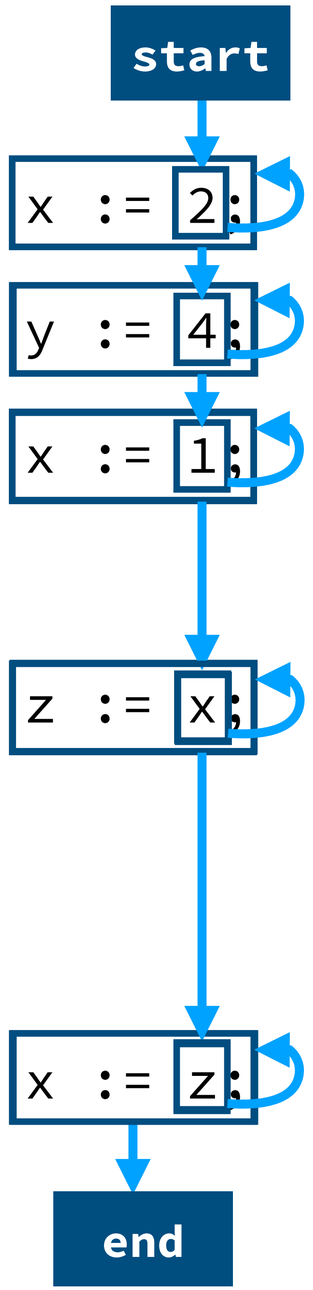


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{z}

{}

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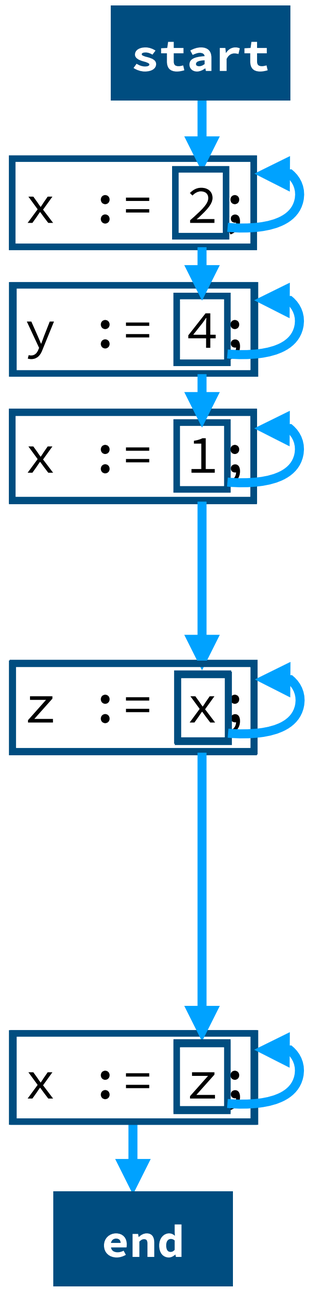

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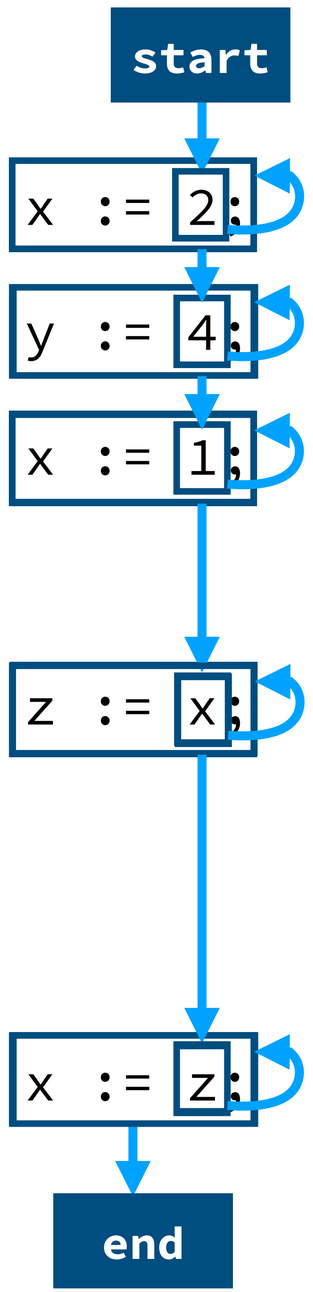


{}

{}

{}

{x}

{z}

{}

{}

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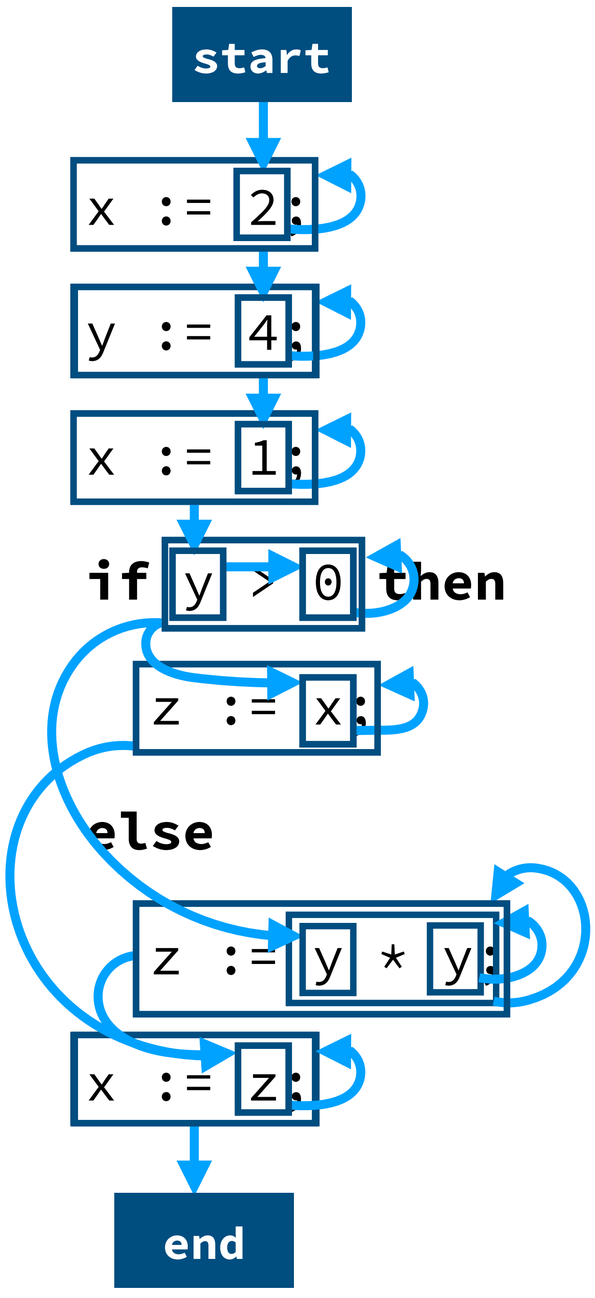

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```
x := 2;

y := 4;

x := 1;

if y > 0 then

  z := x;

else

  z := y * y;

x := z;
```

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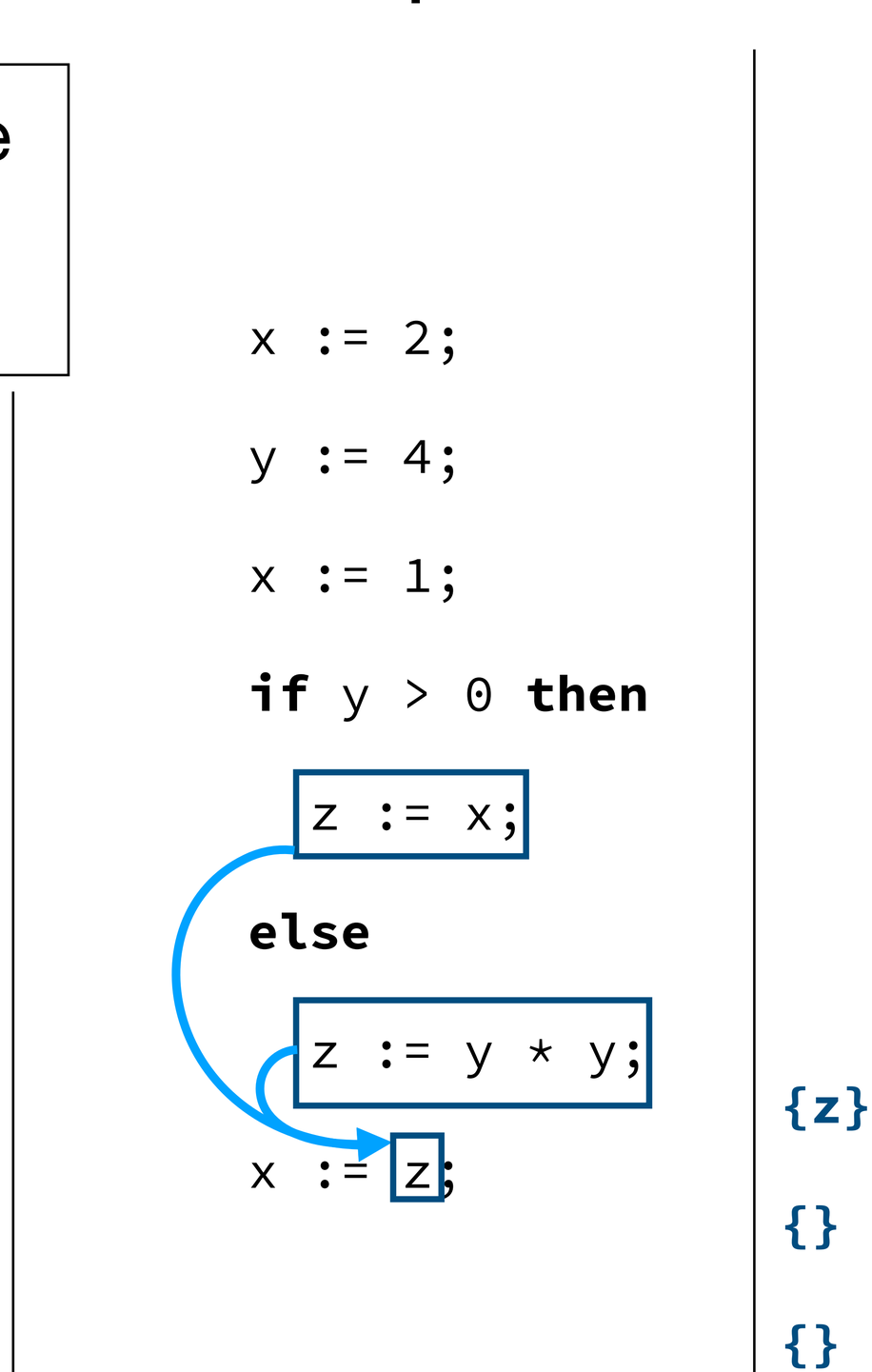

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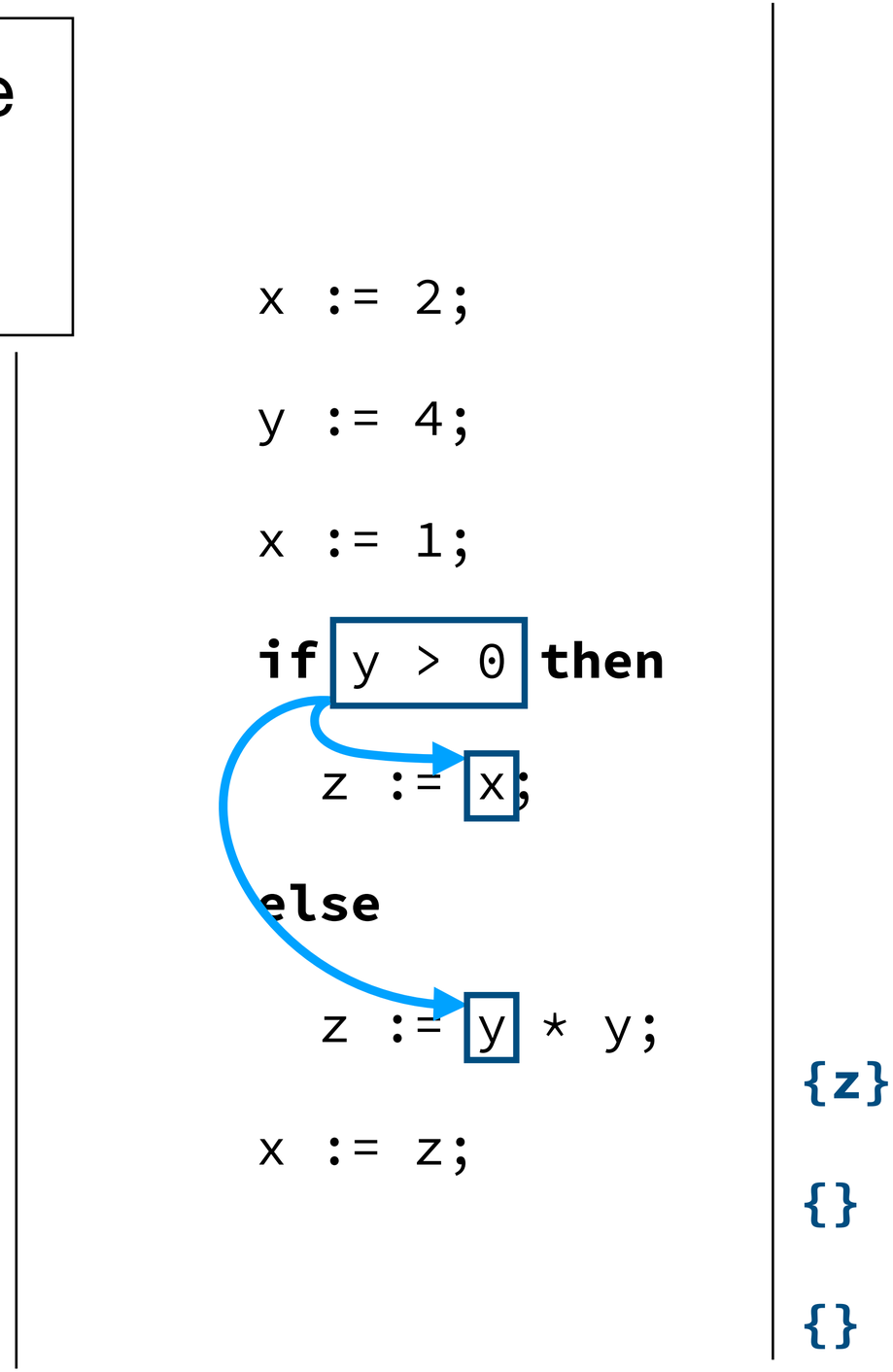

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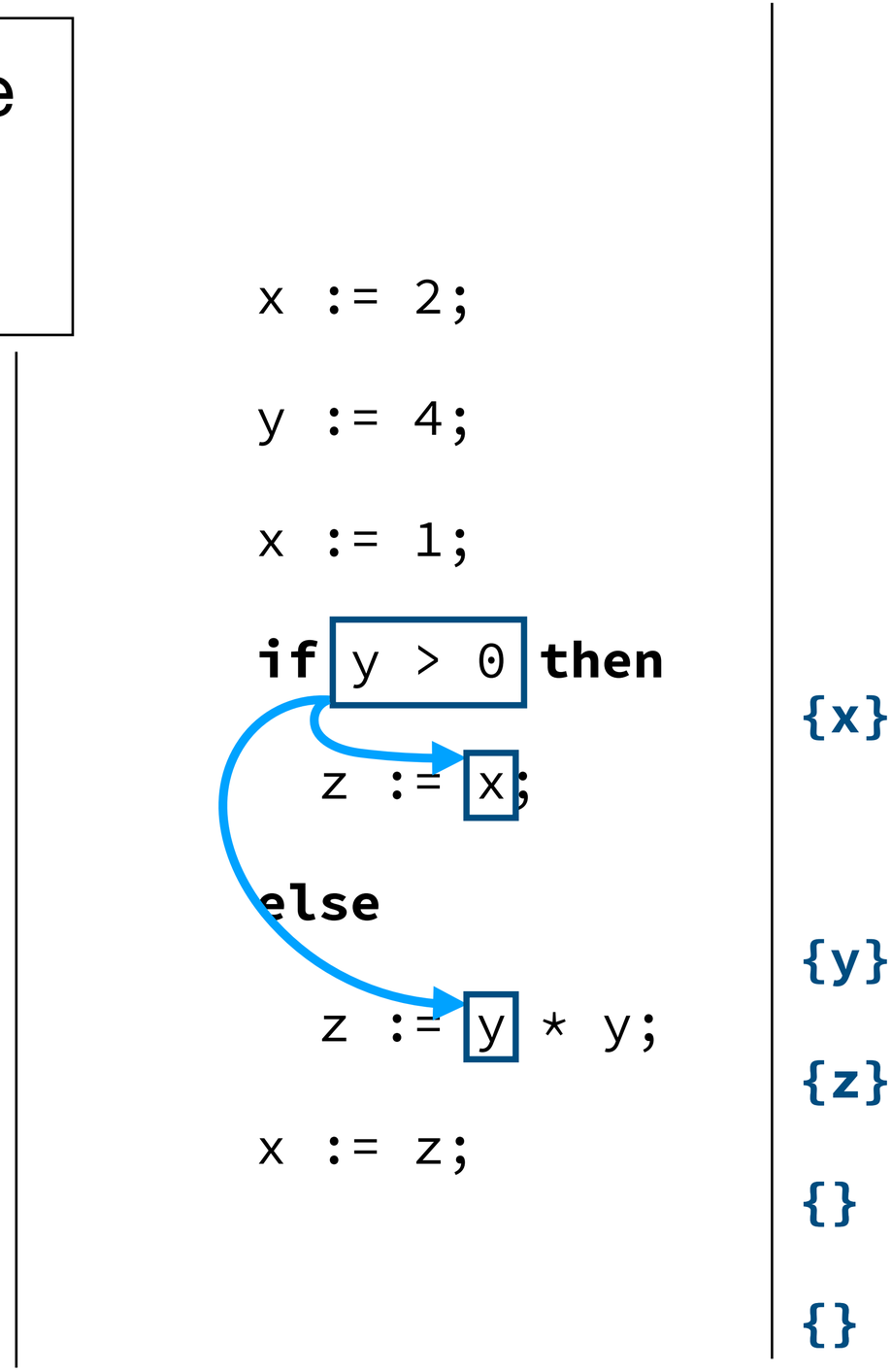

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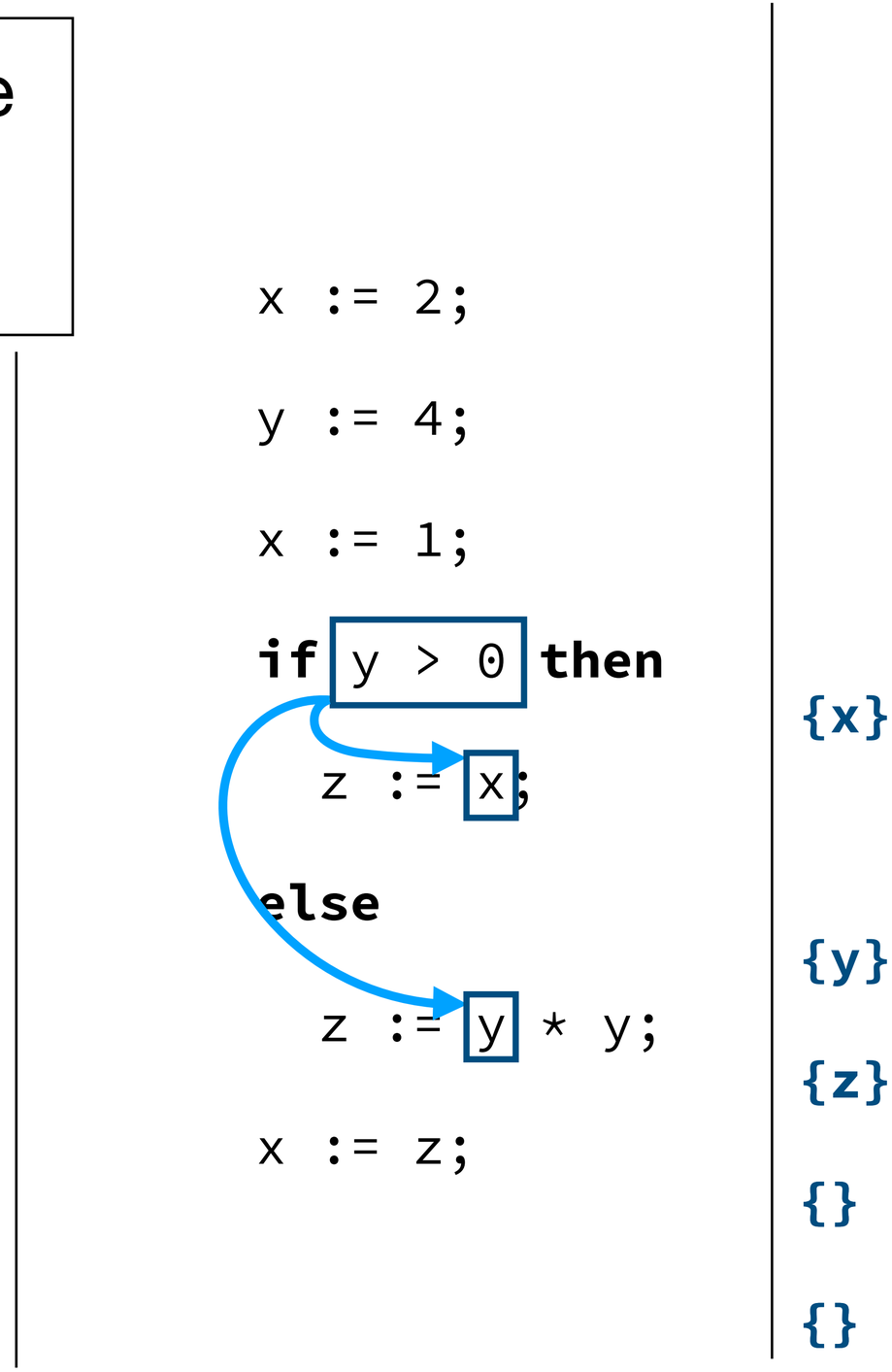

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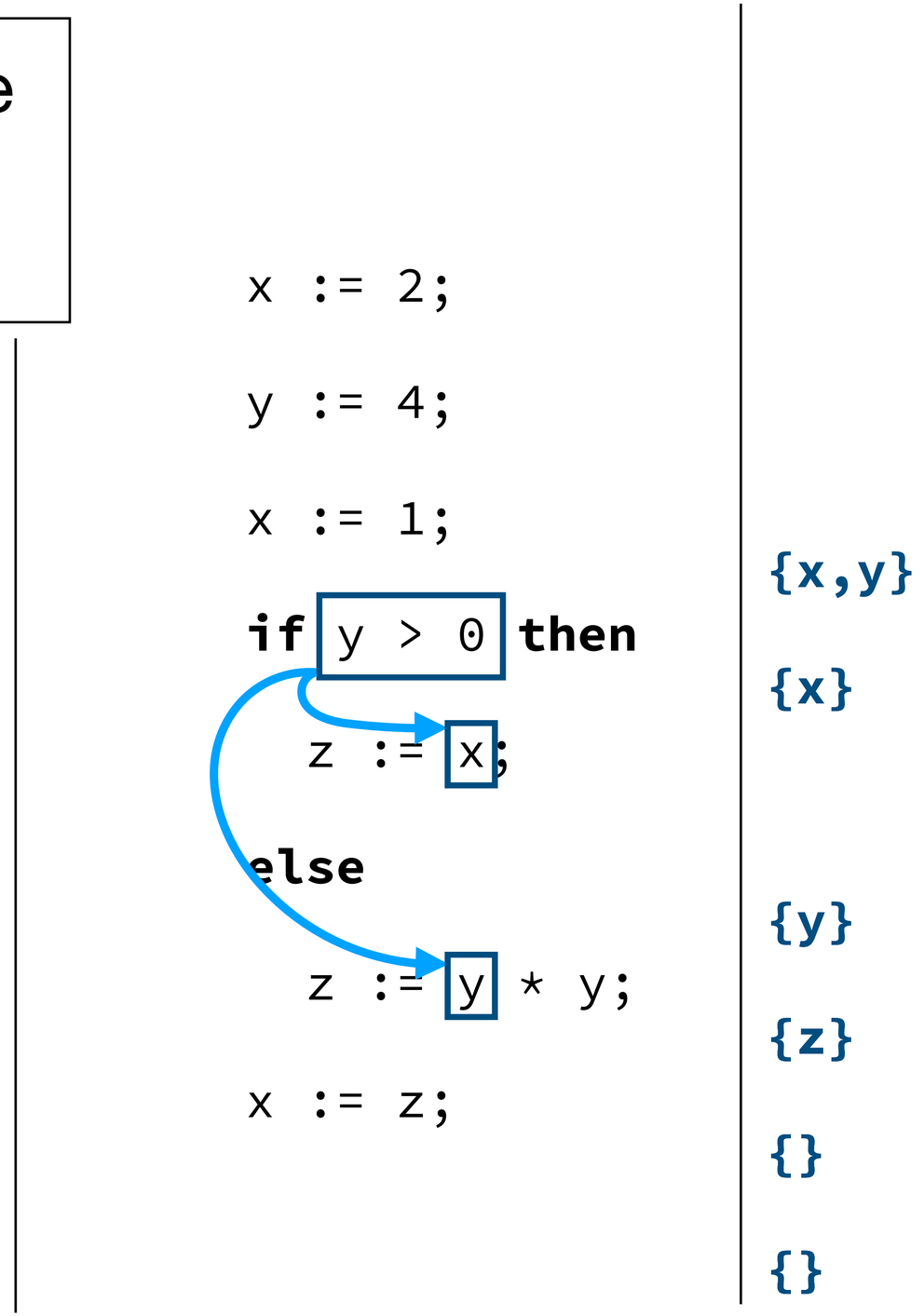

# Closing

# But wait! There’s more!

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## Incrementality

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- Follow function calls / where were we called from?
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- Optimisation: transform the program into a more efficient one

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External PhD candidate Tamás Szabó researches incremental static analysis under supervision of Sebastian Erdweg

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  - Galois connections

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PhD candidate Sven Keidel (HB08.260) researches abstract interpretation under supervision of Sebastian Erdweg

# But wait! There’s more!

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## Correctness (2)

- Are you sure your optimisations are correct?
- Are the results guaranteed to have the same semantics?
- Can you generate a proof to show this property?
  - Perhaps using parameterised program equivalence
  - You might leverage scope graphs in your model!

# But wait! There's more!

## Correctness (2)

- Are you sure your optimisations are correct?
- Are the results guaranteed to have the same semantics?
- Can you generate a proof to show this property?
  - Perhaps using parameterised program equivalence
  - You might leverage scope graphs in your model!

PhD candidate Arjen Rouvoet (HB08.260) researches optimisation correctness under supervision of Eelco Visser

# Future Work

## A running FlowSpec prototype

- So, no, you can't try out FlowSpec yet
- Almost done though, promise!

## Evaluation of FlowSpec

- Is it powerful enough to capture everything we want?

## Expand the control flow model

- Unordered control flow in expressions
- Parallel control flow for concurrent/parallel loops

## Path-sensitive data-flow analysis

- Learning facts about conditions in conditional control flow

## Supporting mechanised language meta-theory

- Relating static analysis and dynamic semantics

# Summary: Data-Flow Analysis

## Representation: Control Flow Graphs + Data Flow information

- Standardised representation for control flow
- Annotate with information from analysis

## Formalism: Lattices and Transfer Functions

- Captures the type of information
- How to combine that information
- How to check that the analysis terminates

## Limitations: Intra-procedural, context-insensitive

- So no function/method calls
- No tracking of objects or pointers for dynamic dispatch
- But at least we are *flow-sensitive*

# Separation of Concerns

## Representation

- **Control Flow Graphs**
- **Before/After data-flow information on CFG nodes**

## Declarative Rules

- To define control-flow rules of a language
- To define data-flow rules of a language

## Language-Independent Tooling

- Analysis
- Code completion
- Refactoring
- Optimisation
- …

# Separation of Concerns

## Representation

- Control Flow Graphs
- Before/After data-flow information on CFG nodes

## Declarative Rules

- FlowSpec

## Language-Independent Tooling

- Analysis
- Code completion
- Refactoring
- Optimisation
- …