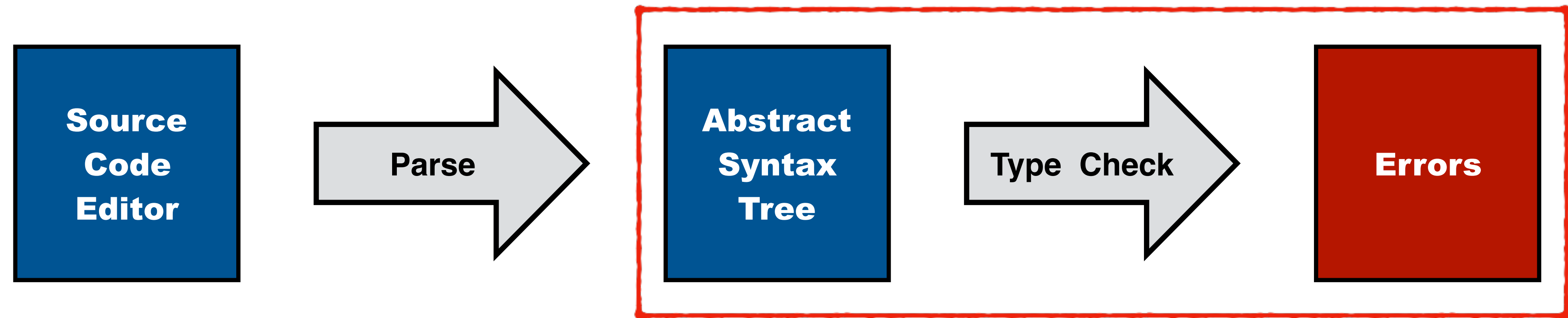# Lecture 10: Data-Flow Analysis

Jeff Smits

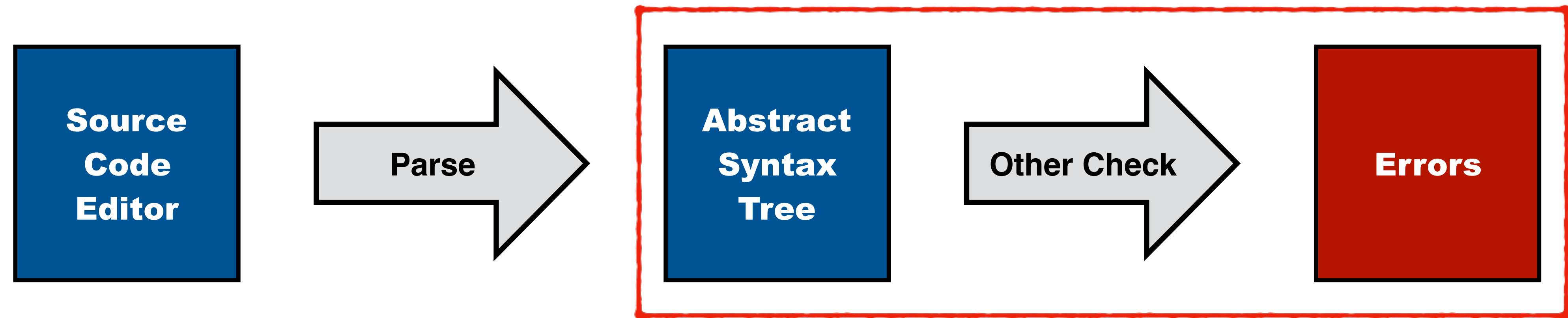**CS4200 Compiler Construction**
TU Delft
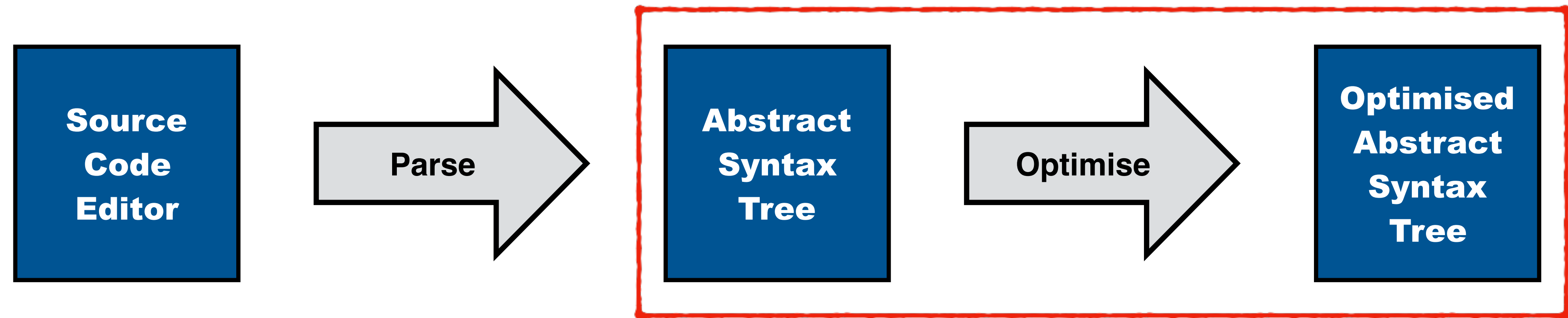**October 2018**

Earlier Lecture

Check that names are used correctly and that expressions are well-typed

This Lecture

Check that variables are initialised, statements are reached, etc.

This Lecture

| Source Code Editor | → Parse → | Abstract Syntax Tree | → Optimise → | Optimised Abstract Syntax Tree |

Eliminate common subexpressions, reduce loop strength, etc.

Reading Material

The following papers add background, conceptual exposition, and examples to the material from the slides. Some notation and technical details have been changed; check the documentation.

This paper introduces FlowSpec, the declarative data-flow analysis specification language in Spoofax. Although the design of the language described in this paper is still current, the syntax used is already dated, i.e. the current FlowSpec syntax in Spoofax is slightly different.

SLE 2017

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FlowSpec: Declarative Dataflow Analysis Specification

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Abstract

We present FlowSpec, a declarative specification language for the domain of dataflow analysis. FlowSpec has declarative support for the specification of control flow graphs of programming languages, and dataflow analyses on these control flow graphs. We define the formal semantics of FlowSpec, which is rooted in Monotone Frameworks. We also discuss implementation techniques for the language, partly used in the prototype implementation built in the Spoofax Language Workbench. Finally, we evaluate the expressiveness and conciseness of the language with two case studies. These case studies are analyses for Green-Marl, an industrial, domain-specific language for graph processing. The first case study is a classical dataflow analysis, scaled to this full language. The second case study is a domain-specific analysis of Green-Marl.

CCS Concepts • **Software and its engineering → Domain specific languages;**
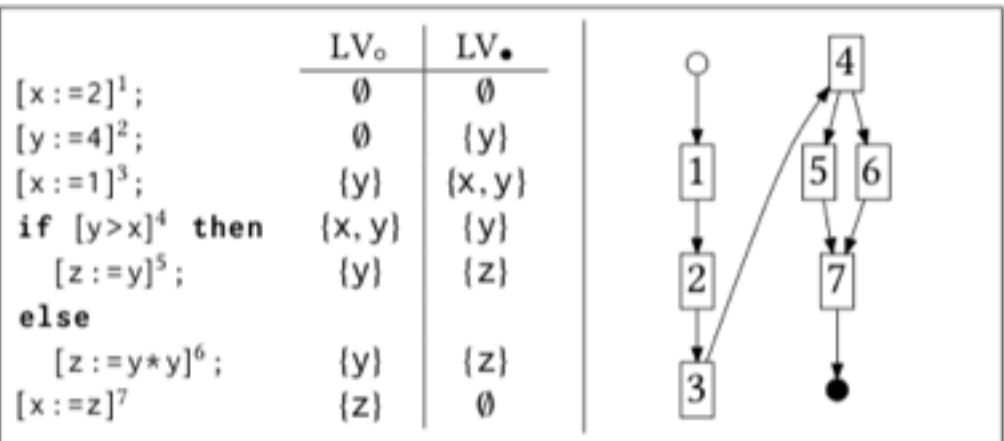
Keywords control flow graph, dataflow analysis

1 Introduction

Dataflow analysis is a static analysis that answers questions on what *may* or *must* happen before or after a certain point in a program's execution. With dataflow analysis we can answer whether a value written to a variable *here* may be

Figure 1. Classical dataflow analysis Live Variables (LV). On the left is an example program in the WHILE language, with added brackets to number program fragments. On the right is the control flow graph (CFG) of the program. In the centre is the analysis result. The $LV_\circ$ and $LV_\bullet$ are before and after the CFG node's variables accesses respectively.

read *later*. Such dataflow analyses can be used to inform optimisations.

For example, consider Live Variables analysis, illustrated in Figure 1. This type of dataflow analysis can identify dead code, which can be removed as an optimisation. In the example this would be statement 1 since it writes x which is overwritten by statement 3 without being read in between. The Live Variables analysis provides a set of variables which are read before being written after each statement in $LV_\bullet$. The figure shows this in the $LV_\bullet$ set of statement 1, which does not contain x.

Dataflow may also be part of a language's static semantics. For example, in Java a final field in a class must be initialised by the end of construction of an object of that class. Since constructor code can have conditional control flow, a dataflow analysis is necessary to check that all possible execution paths through constructors actually assign a value to the final field [Gosling et al. 2005, sect. 16.9].

Dataflow analyses are often operationally encoded, whether in a general purpose language, an attribute grammar system or a logic programming language. This encoding is both an overhead for the engineer implementing it, as well as an overhead in decoding for anyone who wishes to understand the analysis.

In formal, mathematical descriptions of a dataflow analysis, the common patterns are often factored out. This shows commonalities between different analyses, allows the study of those commonalities and differences, as well as general

Documentation for FlowSpec at the metaborg.org website.

Spoofax
latest

Search docs

The Spoofax Language Workbench
Examples
Publications

TUTORIALS
Installing Spoofax
Creating a Language Project
Using the API
Getting Support

REFERENCE MANUAL
Language Definition with Spoofax
Abstract Syntax with ATerms
Syntax Definition with SDF3
Static Semantics with NaBL2
Data-Flow Analysis with FlowSpec

1. Introduction
2. Language Reference
3. Stratego API
4. Configuration
5. Examples (under construction)
6. Bibliography

Transformation with Stratego
Dynamic Semantics with DynSem
Editor Services with ESV
Language Testing with SPT
                    Command-
line
Programmatic API

Read the Docs   v: latest ▼

Docs » Data Flow Analysis Definition with FlowSpec   ○ Edit on GitHub

Data Flow Analysis Definition with FlowSpec

Programs that are syntactically well-formed are not necessarily valid programs. Programming languages typically impose additional *context-sensitive* requirements on programs that cannot be captured in a syntax definition. Languages use data and control flow to check certain extra properties that fall outside of names and type systems. The FlowSpec 'Flow Analysis Specification Language' supports the specification of rules to define the static control flow of a language, and data flow analysis over that control flow. FlowSpec supports flow-sensitive intra-procedural data flow analysis.

Table of Contents

Control-Flow

What is Control-Flow?

- "Order of evaluation"

Discuss a series of example programs

- What is the control flow?
- What constructs in the program determine that?

What is Control-Flow?

```
function id(x) { return x; }
id(4); id(true);
```

Function calls

- Calling a function passes control to that function
- A **return** passes control back to the caller

What is Control-Flow?

```
if (c) { a = 5 } else { a = "four" }
```

Branching

- Control is passed to one of the two branches
- This is dependent on the value of the condition

What is Control-Flow?

```
while (c) { a = 5 }
```

Looping

- Control is passed to the loop body depending on the condition
- After the body we start over

What is Control-Flow?

```
float distance = 12.0;
float velocity = time / distance;
```

Sequence

- No conditions or anything complicated
- But still order of execution

What is Control-Flow?

```
distance = distance + 1;
```

Writes and reads

- The expression needs to be evaluated,
                                before we can save its result

What is Control-Flow?

```
counter.next() / counter.next()
```

Expressions & side-effects

- Order in sub-expressions is usually undefined
- Side-effects make sub-expression order relevant

What kind of Control-Flow?

- Sequential   statements
- Conditional   if / switch / case
- Looping   while / do while / for / foreach / loop
- Exceptions   throw / try / catch / finally
- Continuations   call/cc
- Async-await   threading
- Coroutines / Generators   yield
- Dispatch   function calls / method calls
- Loop jumps   break / continue
- ... many more ...

Why Control-Flow?

Shorter code

- No need to repeat the same statement 10 times

Parametric code

- Extract reusable patterns

- Let user decide repetition amount

Expressive power

- Playing with the Turing Machines

Reason about program execution

- What happens when?

- In what order?

Control-Flow and language design

Imperative programming

- Explicit control-flow constructs

Declarative programming

- What, not how

- Less explicit control-flow

- More options for compilers to choose order

- Great if your compiler is often smarter than the programmer

Separation of Concerns in Data-Flow Analysis

Representation

- Represent control-flow of a program

- Conduct and represent results of data-flow analysis

Declarative Rules

- To define control-flow of a language

- To define data-flow of a language

Language-Independent Tooling

- Data-Flow Analysis

- Code completion

- Refactoring

- Optimisation

- …

Control-Flow Graphs

What is a Control-Flow Graph?

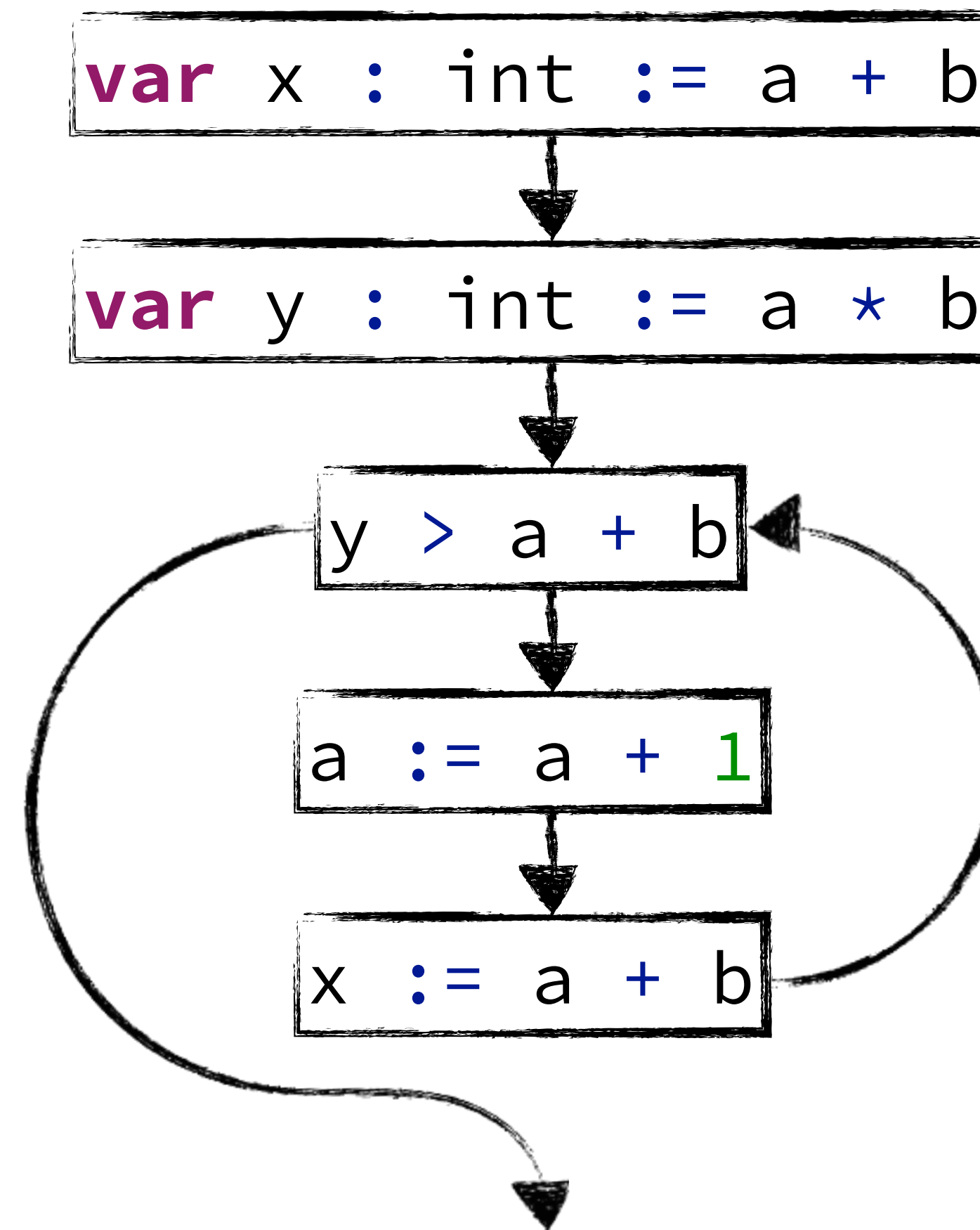A **control flow graph** (**CFG**) in computer science is a representation, using graph notation, of all paths that might be traversed through a program during its execution.

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

Control-Flow Graph example

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

Control-Flow Graph example

Basic blocks

```
var x : int := a + b
var y : int := a * b
```

```
y > a + b
```

```
a := a + 1
x := a + b
```
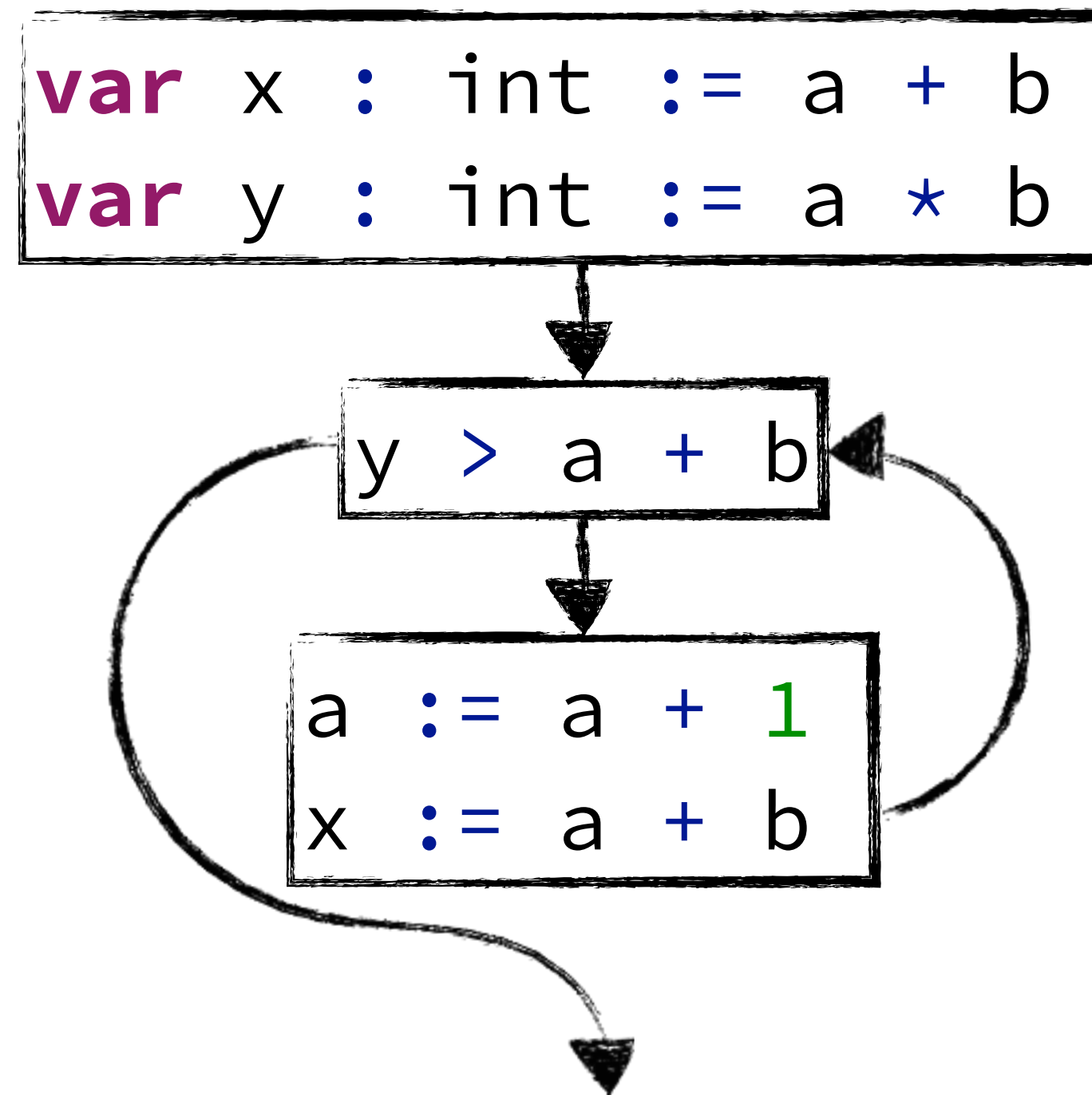
Control Flow Graphs
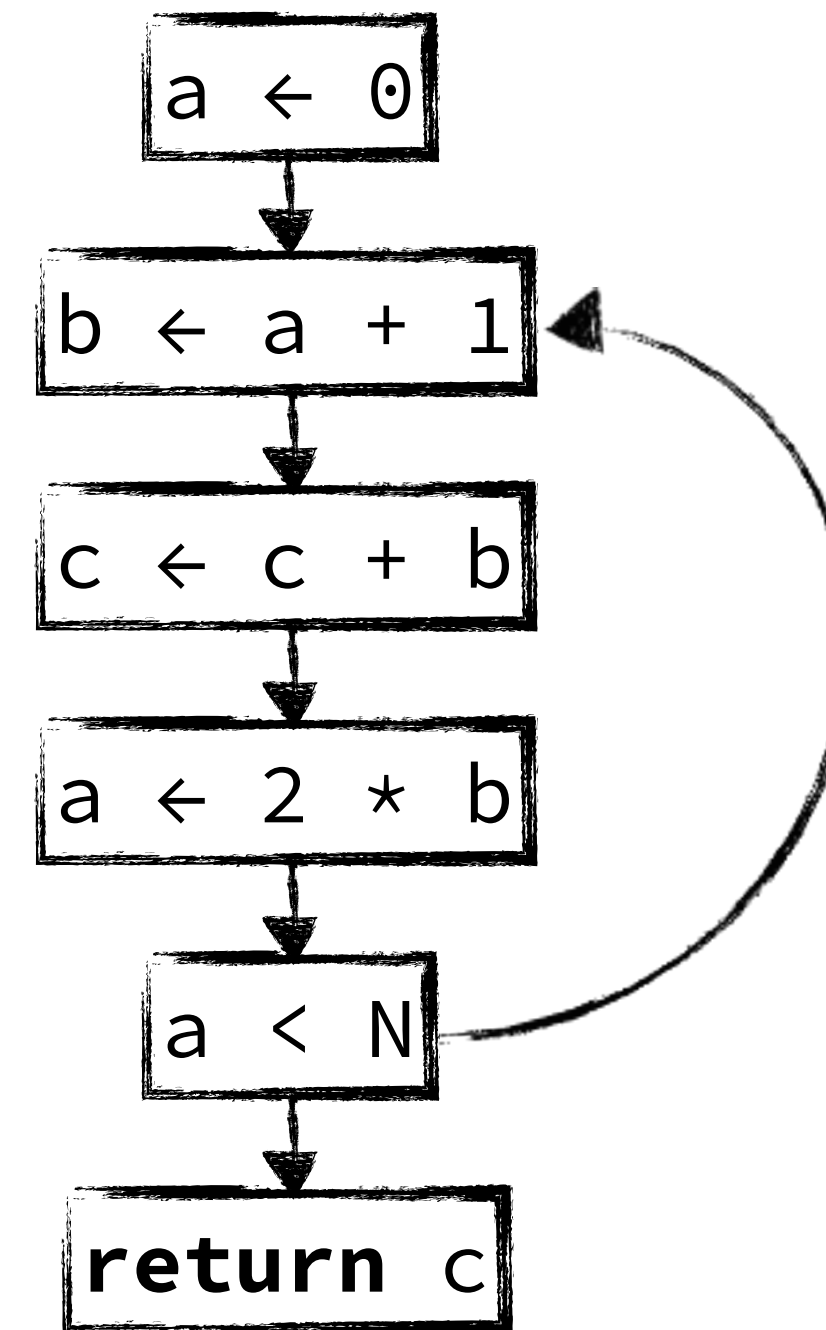
Nodes

- Usually innermost statements and expressions
- Or blocks for consecutive statements (basic blocks)

Edges

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

Equivalent to 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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Representation

- **Control Flow Graphs**
- Conduct and represent results of data-flow analysis

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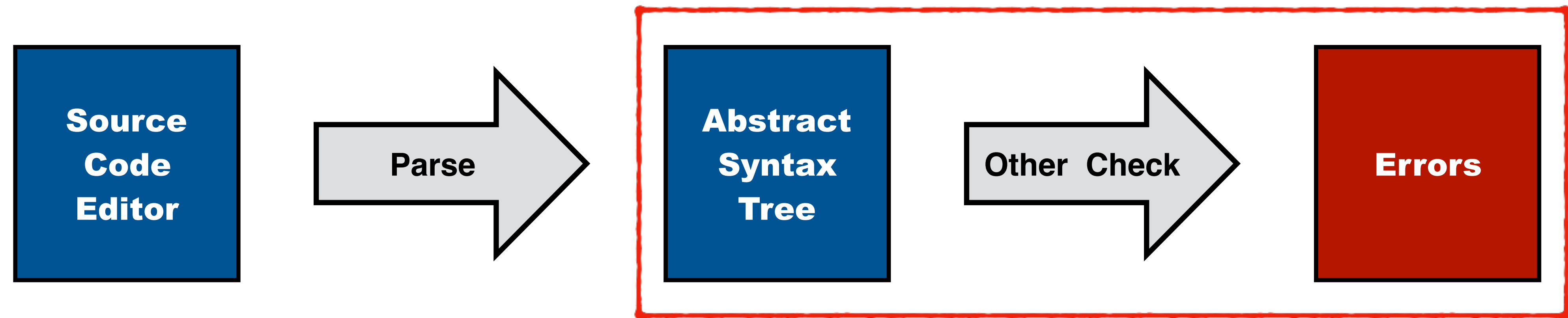- …

Data-Flow

Data-Flow

What is Data-Flow?

- Possible values (data) that flow through the program

- Relations between that data (data dependence)

Discuss a series of example programs

- What is wrong or can be optimised?

- What is the flow we can use for this?

Source Code Editor → Parse → Abstract Syntax Tree → Other Check → Errors

Check that code is reachable or observable

What is wrong here?

```
public int ComputeFac(int num) {
    return num;
    int num_aux;
    if (num < 1)
        num_aux = 1;
    else
        num_aux = num * this.ComputeFac(num-1);
    return num_aux;
}
```

Dead code (control-flow)

- Most of the code is never reached because of the early return
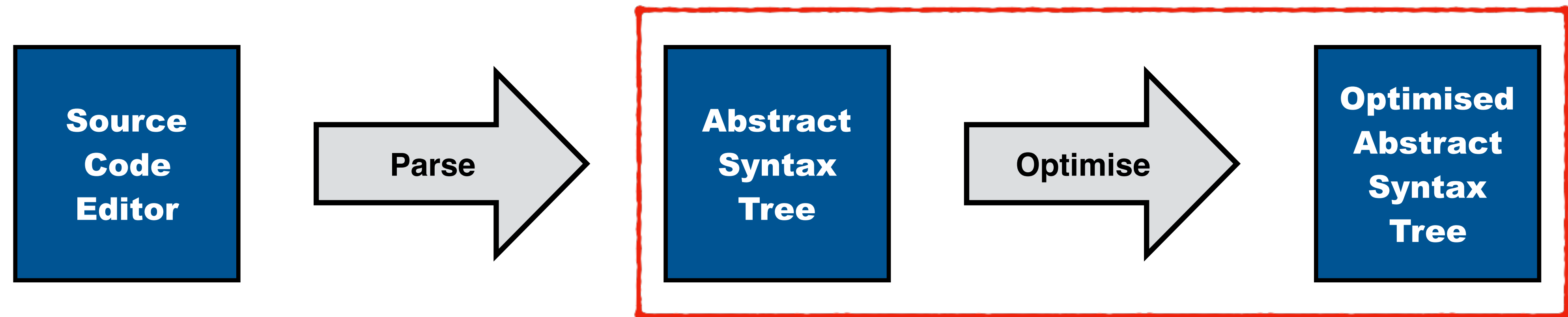- This is usually considered an error by compilers

What is "wrong" here?

```
x := 2;
y := 4;
x := 1;
// x and y used later
```

Dead code (data-flow)

Live variable analysis

- The first value of x is never observed
- This is sometimes warned about by compilers

```
┌──────────┐              ┌──────────┐              ┌──────────┐
│  Source  │    Parse     │ Abstract │   Optimise   │ Optimised│
│   Code   │  ────────▶   │  Syntax  │  ────────▶   │ Abstract │
│  Editor  │              │   Tree   │              │  Syntax  │
│          │              │          │              │   Tree   │
└──────────┘              └──────────┘              └──────────┘
```

Eliminate common subexpressions, reduce loop strength, etc.

What is suboptimal here?

```
let
  var x : int := a + b
  var y : int := a * b
 in
  if y > a + b then
    (
      a := a + 1;
      x := a + b
    )
end
```

Common subexpression elimination

Available expression analysis

- a + b is already computed when you get to the condition
- There is no need to compute it again

What is suboptimal here?

```
for i := 1 to 100 do
  (
    x[i] := y[i];
    if w > 0 then
      y[i] := 0
  )
```

Loop unswitching

Data-dependence analysis

- The if condition is not dependent on i, x or y
- Still it is checked in the loop, which is slowing the loop

Tiger in FlowSpec

Separation of Concerns in Data-Flow Analysis

Representation

- **Control Flow Graphs**
- Conduct and represent results of data-flow analysis

Declarative Rules

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

Language-Independent Tooling

- Data-Flow Analysis
- Code completion
- Refactoring
- Optimisation
- …

Separation of Concerns in Data-Flow Analysis

Representation

- **Control Flow Graphs**
- **Data-flow information on CFG nodes**

Declarative Rules

- To define control-flow of a language

- To define data-flow of a language

Language-Independent Tooling

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- Code completion

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- Optimisation

- …

Control-Flow rules

Map abstract syntax to control-flow (sub)graphs

- Match an AST pattern
- List all edges of that AST
- Use special "context" nodes to connect a subgraph to the outside graph

Control-flow graphs in FlowSpec

FlowSpec

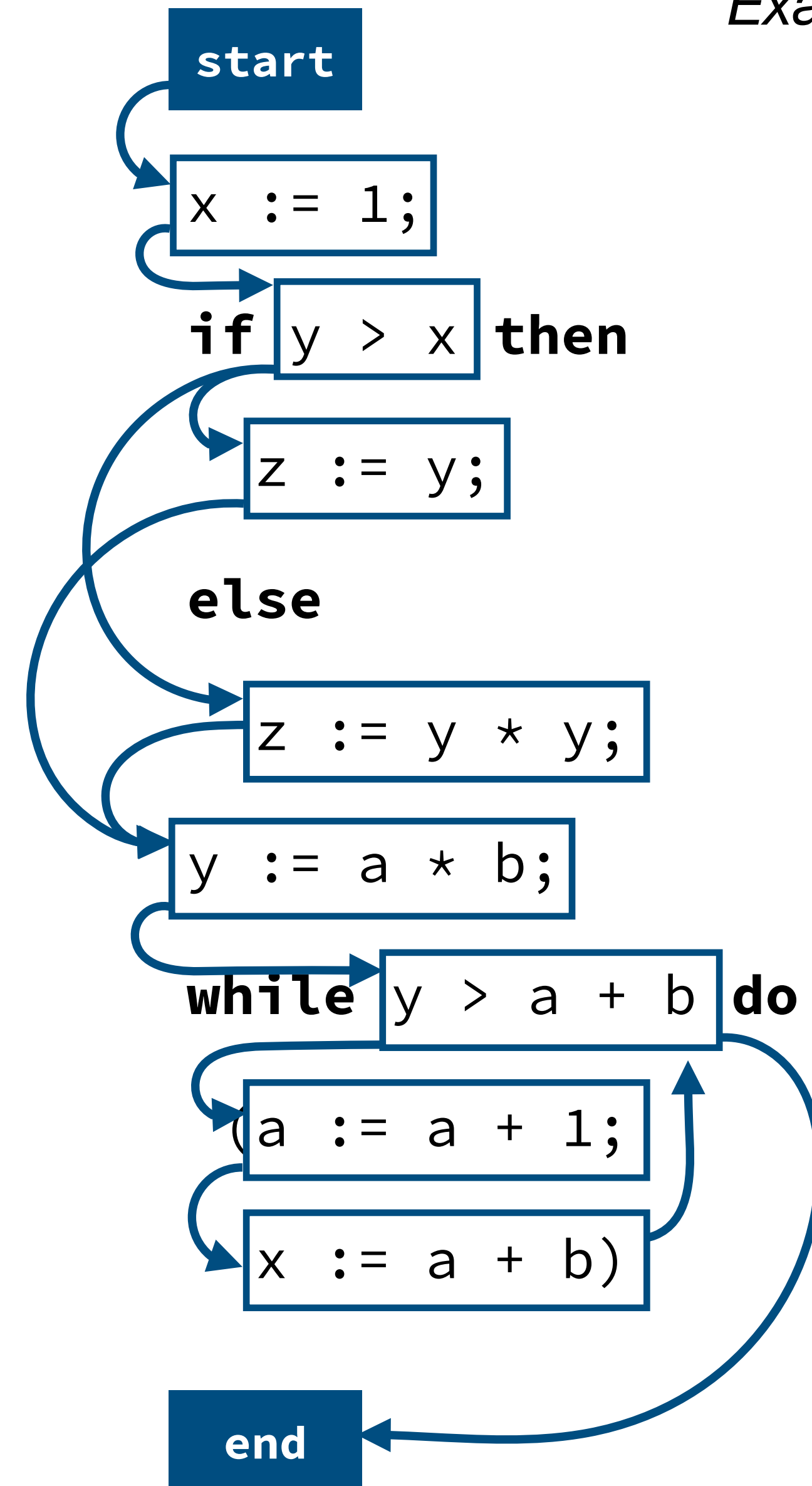*Example program*

```
root Mod(s) =
    start -> s -> end


node Assign(_, _)



Seq(s1, s2) =
    entry -> s1 -> s2 -> exit


IfThenElse(c, t, e) =
    entry -> node c -> t -> exit,
             node c -> e -> exit


While(c, b) =
    entry -> node c -> b -> node c -> exit
```

Data-Flow rules

Define effect of control-flow nodes

- Match an AST pattern on one side of a CFG edge
- Propagate the information from the other side of the edge
- Adapt that information as the effect of the matched CFG node
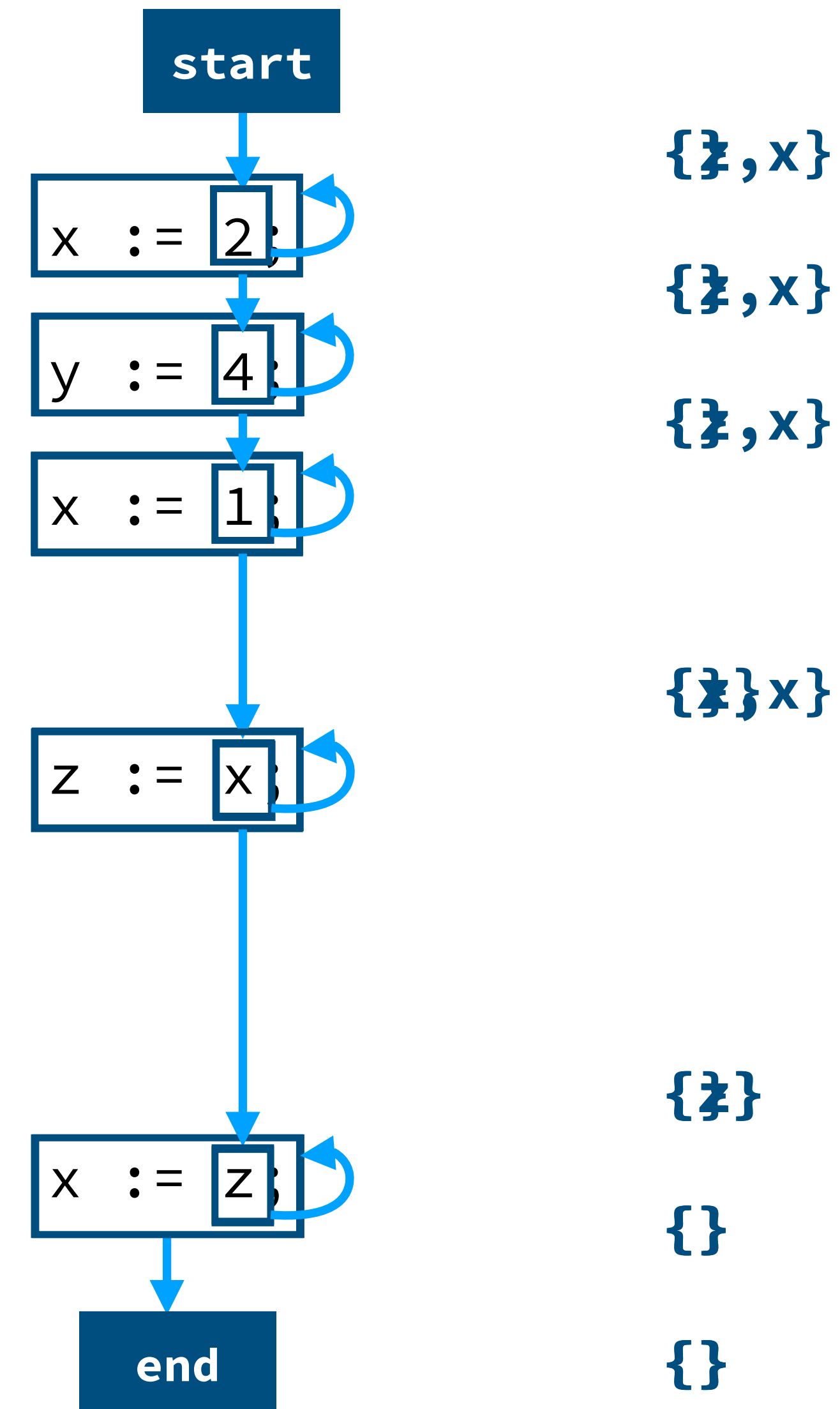
Live Variables in FlowSpec

A variable is *live* if the current value of the variable *may* be read further along in the program

```
prop live:     Set(name)

live(Ref(n) -> next) =
  live(next) \/ {n}

live(Assign(n, _) -> next) =
  { m | m <- live(next), n != m }

live(end) =
  {}
```

start

x := 2;   {z,x}

y := 4;   {z,x}

x := 1;   {z,x}

z := x;   {x}x}

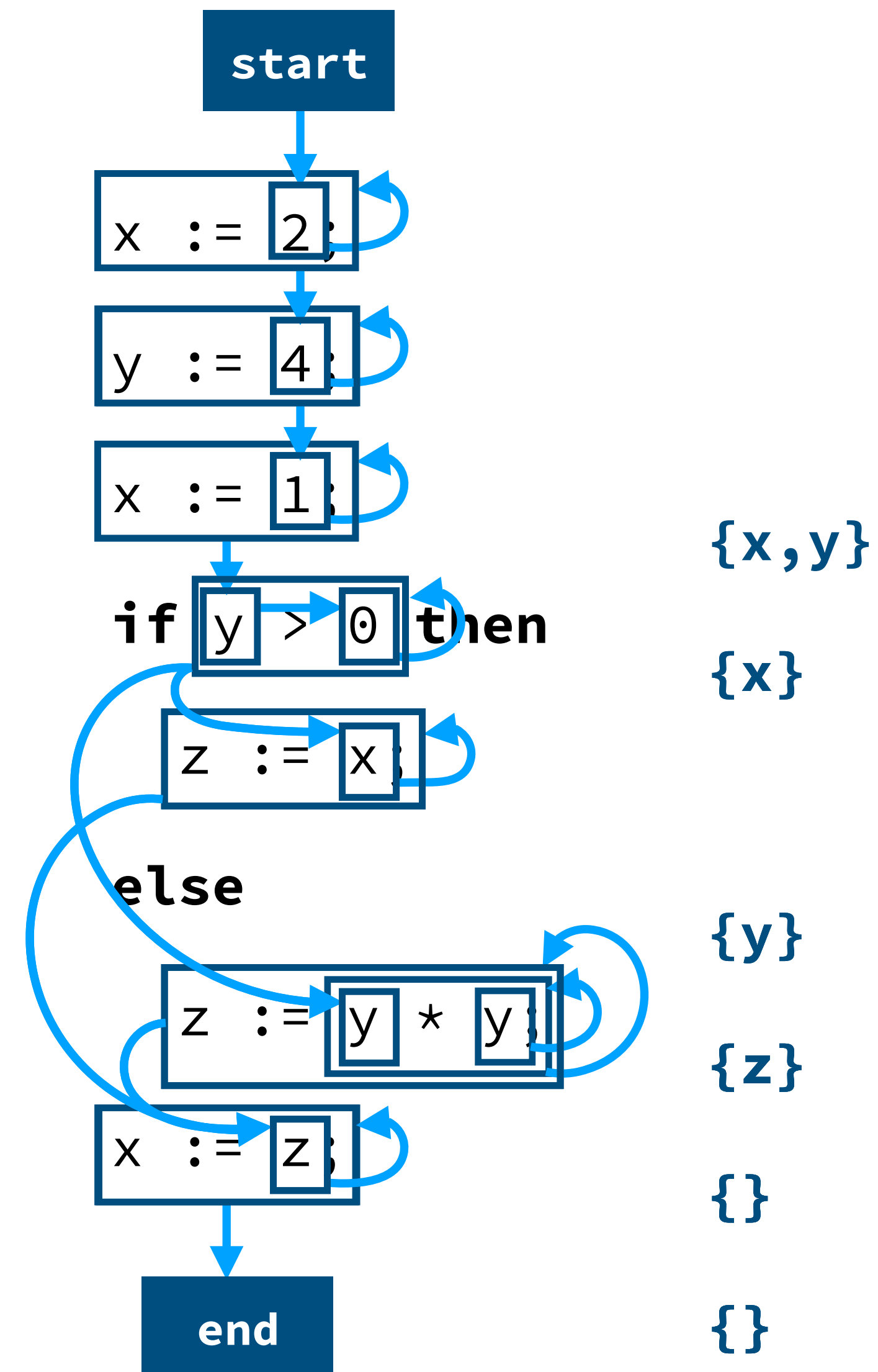x := z;   {z}

end   {}

{}

Live Variables in FlowSpec

A variable is *live* if the current value of the variable *may* be read further along in the program

```
prop live:     Set(name)

live(Ref(n) -> next) =
    live(next) \/ {n}

live(Assign(n, _) -> next) =
    { m | m <- live(next), n != m }

live(end) =
    {}
```

Conclusion

Summary

Control-Flow

- Order of execution

- Reasoning about what is reachable

Data-Flow

- Flow of data through a program

- Reasoning about data, and dependencies between data

FlowSpec

- Control-Flow rules to construct the graph

- Annotate with information from analysis by Data-Flow rules

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