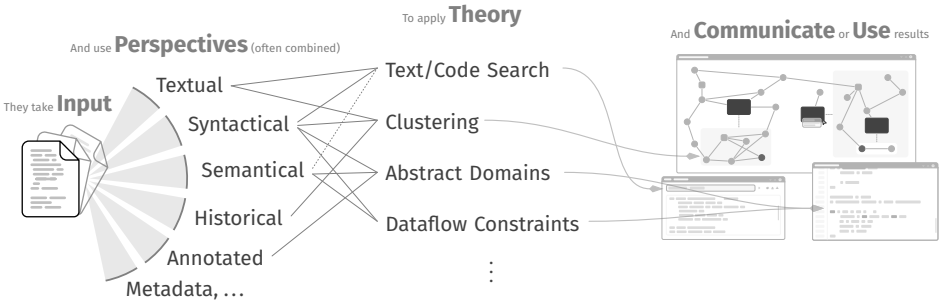


Static Analysis in the Real World

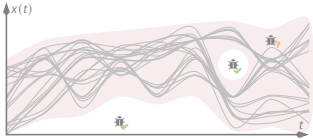
Software Engineering
Programming Languages

universität ulm

Outline

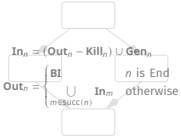
1. Introduction

What we have… **Theory**



Abstractions

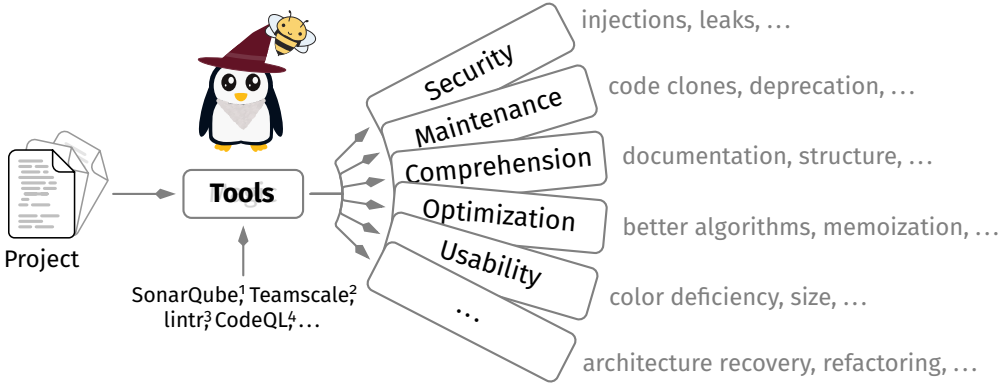
Abstractions



Data Flow Analysis

…

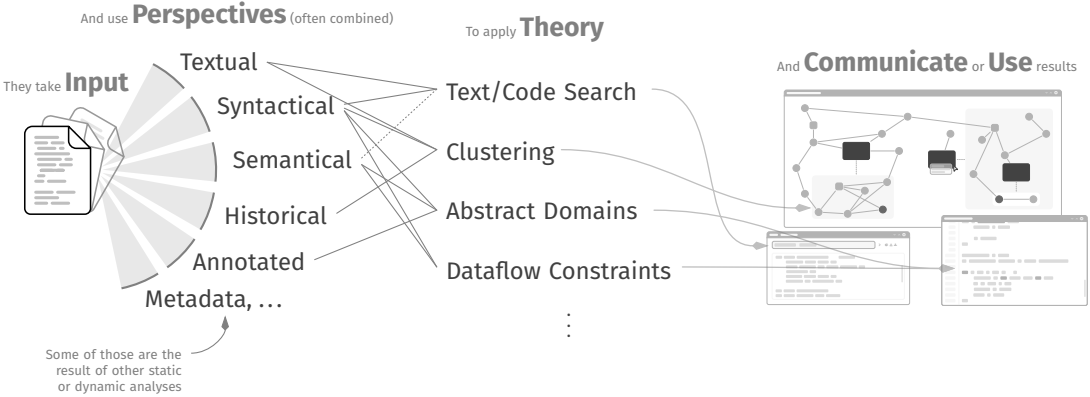
What we want… **Tools**



"Any sufficiently advanced technology is indistinguishable from magic." — Arthur C. Clarke

[1] sonarsource.com, [2] teamscale.com, [3] lintr.r-lib.org, [4] codeql.github.com

What do they… do?



2. Real-World Static Analyzers

Let's Look at Tools

SootUp

flowR

LiquidHaskell

AbsInt

lintr

Teamscale

Infer

LiSA

CodeQL

sonar

Clang

GCC

ESLint

MOPSA analyzer

frama C

There are countless…

github.com/analysis-tools-dev/static-analysis

Let's Look at Tools

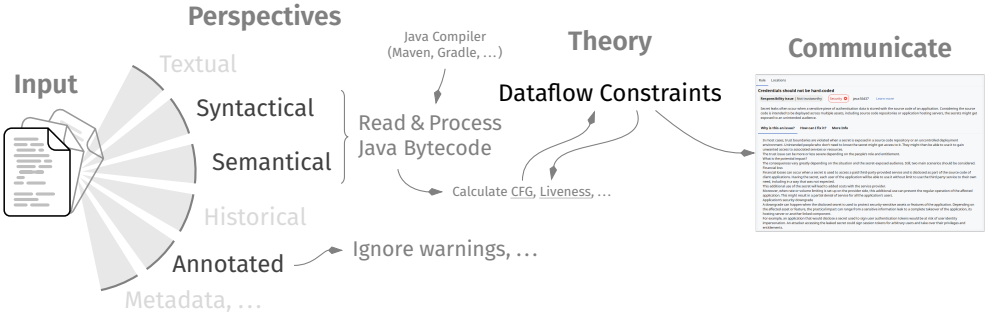
- **SonarLint**
- Astrée (sound!)
- LiSA
- Java Language Server
- lintr
- flowR

There are countless…

github.com/analysis-tools-dev/static-analysis

SonarLint

- Support for multiple languages (15+)
  - Widely varying support and rules
    Separate frontends and analyzers per language!
  - We focus on **sonar-java**
    704 rules!



github.com/SonarSource/sonar-java

SonarLint

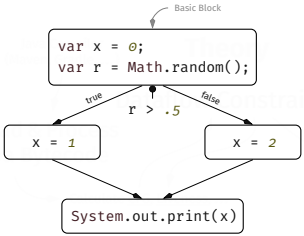
- Support for multiple languages (15+)
  - Widely varying support and rules
  - We focus on **sonar-java**

Separate frontends and analyzers per language!

704 rules!

```
var x = 0;
var r = Math.random();
if(r > .5) {
  x = 1;
} else {
  x = 2;
}
System.out.print(x);
```

Code

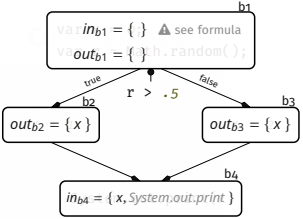


Control Flow Graph

$$\mathbf{In}_n = (\mathbf{Out}_n - \mathbf{Kill}_n) \cup \mathbf{Gen}_n$$

$$\mathbf{Out}_n = \begin{cases} \mathbf{BI} & n \text{ is End} \\ \bigcup_{m \in succ(n)} \mathbf{In}_m & \text{otherwise} \end{cases}$$

With fixpoint iteration



Liveness[KSK09, p. 26]

github.com/SonarSource/sonar-java

[KSK09] *Data Flow Analysis: Theory and Practice* (Khedker, Sanyal, and Karkare)

SonarLint — Unused Assignments

- Analyze "Dead Stores" (in 311 loc / 259 cloc):

```
int x = 0;
x = 42;
```

- Use liveness analysis to obtain out_n of each basic block in the CFG
- Check if assignments (`x =`, `x++`, ...) are in out_n and resolved
- Check overwrites in the same basic block
- Minor special handling for **`try-finally`** blocks, ...

Implementation of Rule S1854

SonarLint — Unused Assignments

- Analyze "Dead Stores" (in 311 loc / 259 cloc):

```
int x = 0;
x = 42;
```

- Use liveness analysis to obtain out_n of each basic block in the CFG
- Check if assignments (`x =`, `x++`, ...) are in out_n and resolved
- Check overwrites in the same basic block
- Minor special cases

```
LiveVariables liveVariables = LiveVariables.analyze(cfg);
// Liveness analysis provides information only for block boundaries,
    so we should do analysis between elements within blocks
for(CFG.Block block : cfg.blocks()) {
  checkElements(block, liveVariables.getOut(block), methodSymbol);
}
```

Implementation of Rule S1854

SonarLint — Hardcoded Credentials

- It does not always have to be that heavy! (116 loc / 87 cloc may suffice)
- For example, to identify hardcoded credentials:

```
new PasswordAuthentication("password", "secret".toCharArray());
```

- Traverse the Abstract Syntax Tree (AST)
- Check calls against a long list of signatures (currently 7664) with problematic indices
- Check if the arguments are “constant”
  visiting the dataflow links and checking for predefined “plain text”

Implementation of Rule S6437

SonarLint — Hardcoded Credentials

- It does not always have to be that heavy! (116 loc / 87 cloc may suffice)
- For example, to identify hardcoded credentials:

```
new PasswordAuthentication("password", "secret".toCharArray());
```

- Traverse the Abstract Syntax Tree (AST)
- Check calls against a long list of signatures (currently 7664) with problematic indices
- Cl
  vi

```
for (int targetArgumentIndex : method.indices) {
  ExpressionTree argument = arguments.get(targetArgumentIndex);
  var secondaryLocations = new ArrayList<JavaFileScannerContext.Location>();
  if (isExpressionDerivedFromPlainText(argument,
            secondaryLocations, new HashSet<>())) {
    reportIssue(argument, ISSUE_MESSAGE, secondaryLocations, null);
  }
}
```

Implementation of Rule S6437

Let's Look at Tools

- SonarLint
- **Astrée (sound!)**
- LiSA
- Java Language Server
- lintr
- flowR

There are countless…

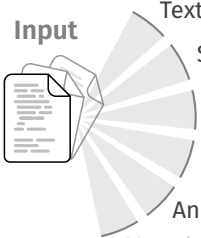
github.com/analysis-tools-dev/static-analysis

Astrée

- *Analyseur statique de logiciels temps-réel embarqués*
  Static analyzer for real-time embedded software
- Proprietary, sound*y* static analyzer for C/C++
  100+ directives and intrinsics, 140+ options
  250 kloc of Ocaml, 240 kloc C/C++
- Uses abstract domains for timing validation, buffer overflows, …

Perspectives

Input



- Textual
- Syntactical
- Semantical
- Historical
- Annotated
- Metadata, …

Build abstractions
handle undef. behavior

C/C++ Project

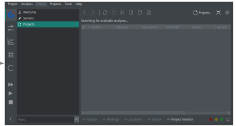
CFG, Data Races, …

Specifications, Configuration, …
for widening, assumptions, …

Theory

Abstract Domains
≈ 30

Communicate



Semantic Loop Unrolling
Local precision tuning
Interleaving Semantics

Analysis Time
from couple of hours to days

Let's Look at Tools

- SonarLint
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- Java Language Server
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- flowR

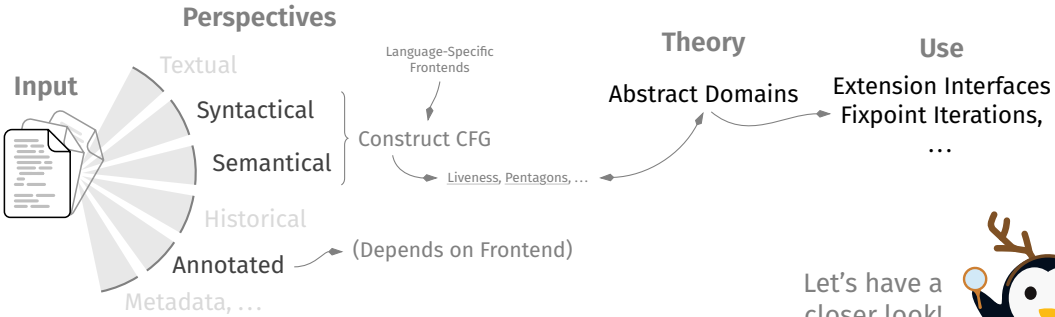
There are countless…

github.com/analysis-tools-dev/static-analysis

LiSA

- (Largely) Language Independent Library for Static Analysis
- Custom frontends for Rust, Go, Python, EVM, …

Similar to Mopsa or Apron



Let's have a closer look!

github.com/lisa-analyzer/lisa

LiSA — Interval Analysis[Cou21, p. 389]

lisa-analyses/src/main/java/it/unive/lisa/analysis/numeric/Interval.java (simplified)

```
Interval TOP = new Interval(IntInterval.INFINITY);
Interval BOTTOM = new Interval(null);

public Interval lubAux(Interval other) {
  var newL = getLow().min(other.getLow());
  var newH = getHigh().max(other.getHigh());
  return new Interval(newLow, newHigh);
}

public Interval glbAux(Interval other) {
  var newL = getLow().max(other.getLow());
  var newH = getHigh().min(other.getHigh());
  if(newLow.compareTo(newHigh) > 0) return bottom();
  return new Interval(newLow, newHigh);
}
```

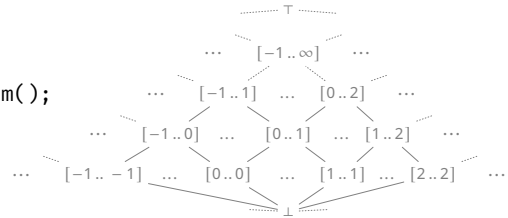
Widening, Narrowing, Assume, Satisfies, …

$$\top = [-\infty \,..\, \infty] \qquad \text{Top}$$

$$\bot = \varnothing \qquad \text{Bottom}$$

$$\bigsqcup_k [\ell_k \,..\, h_k] = [\min(\ell_k) \,..\, \max(h_k)] \qquad \text{Join}$$

$$\bigsqcap_k [\ell_k \,..\, h_k] = [\max(\ell_k) \,..\, \min(h_k)] \qquad \text{Meet}$$



[Cou21] "Principles of Abstract Interpretation" (Cousot)

LiSA — Interval Analysis[Cou21, p. 389]

Semantics

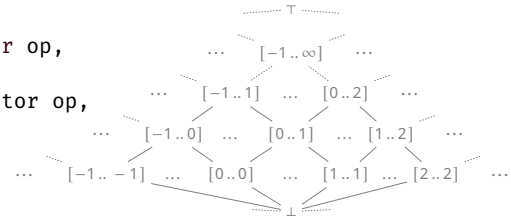
When to create which interval?

lisa-analyses/src/main/java/it/unive/lisa/analysis/numeric/Interval.java (simplified)

```
public Interval evalNonNullConstant(Constant constant,
    ProgramPoint pp, SemanticOracle oracle) {
  if(constant.getValue() instanceof Integer) {
    var i = (Integer) constant.getValue();
    return new Interval(i, i);
  }
  return top();
}

public Interval evalUnaryExpression(UnaryOperator op,
   Interval arg, ...) { ... }
public Interval evalBinaryExpression(BinaryOperator op,
   Interval left, Interval right, ...) { ... }
```

Fold-like Evaluation



[Cou21] "Principles of Abstract Interpretation" (Cousot)

Let's Look at Tools

- SonarLint
- Astrée (sound!)
- LiSA

- **Java Language Server**
- lintr
- flowR

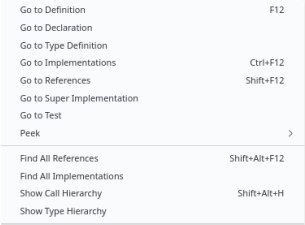
There are countless…

github.com/analysis-tools-dev/static-analysis

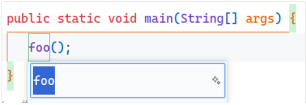
Java Language Server

- Uses the Language Server Protocol to provide static analysis for Java

Code Actions



...



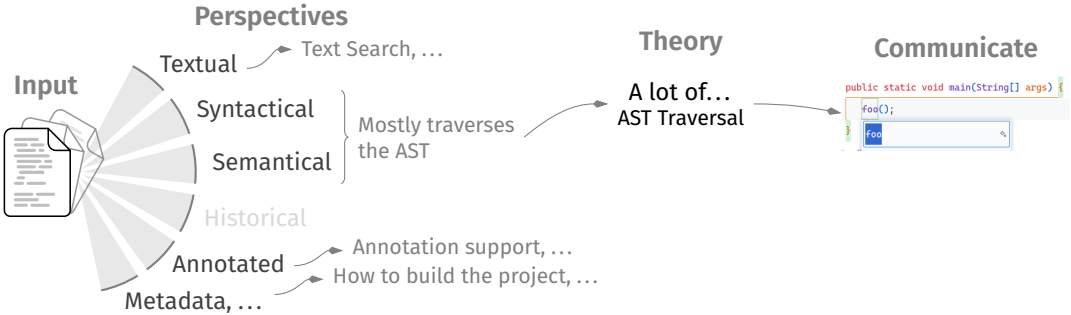
Rename Refactoring

- Relies on the Eclipse JDT Language Server

github.com/eclipse-jdtls/eclipse.jdt.ls

Java Language Server

- Uses the Language Server Protocol to provide static analysis for Java
  Renaming, Code Actions, …
- Relies on the Eclipse JDT Language Server



github.com/eclipse-jdtls/eclipse.jdt.ls

Let's Look at Tools

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There are countless…

github.com/analysis-tools-dev/static-analysis

lintr

Why is this… special?

- A linter for the R programming language

```
x <- 4
f <- function() x
body(f) <- quote(y)
y <- 42
f() # 42
```

```
`if` <- function(...) 42
if(TRUE) print(3) # 42
```

```
x <- 2
`<-` <- `*`
x <- 21 # 42
```

- Common static analysis strategies have their… problems with R
- Most of R's users are no computer scientists (just a small set of existing work)
- So… how does *lintr* do it?
  - ~~Dataflow Constraints?~~
  - ~~Abstract Domains?~~
  - ~~Control Flow Graphs?~~
  - AST ~~Traversal?~~ (mostly) Pattern Matching and Evaluation!

github.com/r-lib/lintr

[Flü+19] "R melts brains: an IR for first-class environments and lazy effectful arguments" (Flückiger et al.)

lintr — Under the Hood

≈ 100 rules

R/object_usage_linter.R

```
magic <- "
   expr[LEFT_ASSIGN or EQ_ASSIGN]/expr[2][FUNCTION or OP-LAMBDA]
   | expr_or_assign_or_help[EQ_ASSIGN]/expr[2][FUNCTION or OP-LAMBDA]
   | equal_assign[EQ_ASSIGN]/expr[2][FUNCTION or OP-LAMBDA]
   | //SYMBOL_FUNCTION_CALL[text() = 'assign']/parent::expr/following-sibling::
       expr[2][FUNCTION or OP-LAMBDA]
   | //SYMBOL_FUNCTION_CALL[text() = 'setMethod']/parent::expr/following-sibling::
       expr[3][FUNCTION or OP-LAMBDA]"
```

- What does this do?
  This XPATH expression matches assignments to functions
- It is very rigid (no alias tracking, flow sensitivity, …)
- And it… cheats:
  `try_silently(eval(envir = env,parse(text = code, keep.source = TRUE)))`
  It simply runs (parts of) the program (including side-effects), …

Let's Look at Tools

- SonarLint
- Astrée (sound!)
- LiSA
- Java Language Server
- lintr
- **flowR**

There are countless…

github.com/analysis-tools-dev/static-analysis

Existing Work

		references	op. assignments	dyn. assignments	value trace	control flow	non-std. eval.	special operators	function calls	libraries	reflection	side effects	static scope	dynamic scope	type inference	pointer analysis	external files	pre-processors	hooks	FFI	expose info.	goal	method
	flowR	●	●	○	○	●	○	●	●	○	○	○	●	○		○					●	static analysis	AST visitor
[Cha23]	{checkglobals}	●	●	○			○	○	○	○			○						○			missing libs.	AST visitor
[Lan+23]	{CodeAnalysis}	●	●	○	○	●	○	○	○	○			●		○		○				●	static analysis	AST visitor
[Lan+18]	{CodeDepends}	●	●	○			○	○	○	○		○	●								●	static analysis	AST visitor
[Tie23]	{codetools}	●	●	○	○	○	○	○	○				●								●	static analysis	AST visitor
[Csa23]	{cyclocomp}					○							●									static analysis	AST visitor
[Rob16]	{DependenciesGraphs}								○	○											○	visualize	regex
[Kar21]	{dfgraph}	●	○			○			○												○	static analysis	AST visitor
[Fab23]	{flow}	●	○			●		○		○					○						○	vis., debug	AST visitor
[App24]	{foodwebr}								○												○	visualize	regex
[Ben22]	{globals}	●	●		○	○	○	○	○				●									distributed env.	AST visitor
[Lai23]	{languageserver}	●	●	○					○	○			●								○	editor support	XPath, visitor
[Hes+23]	{lintr}	●	●	○		○		○		○			●									linting	XPath, visitor
[Bra18]	{mvbutils}								○													utility	regex
[van23]	{PaRe}		○			○			○													code review	regex
[Pad21]	{pkgstats}	●	○					○	○				○									pkg. insights	ctags & gtags
[Lau22]	{Rclean}	●	●	○			○	○	○	○			●									debug/refactor	PDG traversal
[Rod21]	{rco}	●	●		●	○							●									optimization	AST visitor
[Pat19]	{rflowgraph}	●							○	○											○	call graph	AST visitor
[UT19]	{rstatic}	●	●		○	●		○					●								●	static analysis	AST visitor
[UT21]	{RTypeInference}	●	●		○	●		○					●			●					○	type inference	AST visitor
[BG20]	{SimilaR}	●	○			○			○				●									plagiarism	PDG, visitor
[Kal+14]	FastR	●	●		○			○	○	○			●									execute R	AST visitor
[R C23]	GNU R	●	●	○	●	○	○	●	○				●									execute R	bytecode
[19]	MRO	●	●	○	○	○																execute R	bytecode
[Nea14]	pqR	●	●	○	●	○	○	●	○				●									execute R	bytecode
[AS12]	Random	●	○	○	○	○				○			○									abstract int.	trace & visitor
[Gar04]	RCC	●	●		●	○	○		○		○		●									transpile to C	CFG, bytecode
[Ber13]	renjin	●	●	○	○	●		○	○		○		●			●						execute R	SSA, CFG
[Flü+20]	R̃	●	●	○	●	●	○	●	○				●	○		●						execute R	SSA, bytecode
[Sen+17]	ROSA	●	●			○			○			○	●			●	○					optimization	visitor
[Pos23]	RStudio	●	●	○					○	○			●									editor support	AST visitor

flowR

- A static analysis framework for R
- Developed here, at Ulm University
  Florian Sihler, Julian Schubert, Lars Pfrenger, Johanna Scheck, Lukas Pietzschmann, Ruben Dunkel, Felix Schlegel, Pascal Deusch, ...
- Let's get back to R:

```
x <- 4
f <- function() x
body(f) <- quote(y)
y <- 42
f() # 42
```

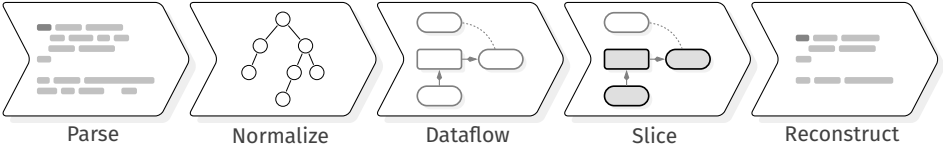
```
`if` <- function(...) 42
if(TRUE) print(3) # 42
```

```
x <- 2
`<-` <- `*`
x <- 21 # 42
```

- We have to intertwine dataflow- and control-flow analysis...

github.com/flowr-analysis/flowr

flowR — Architecture




```
sum  <- 0
prod <- 1
n    <- 10

for (i in 1:(n-1)) {
   sum  <- sum + i
   prod <- prod * i
}

cat("Sum:", sum, "\n")
cat("Product:", prod, "\n")
```

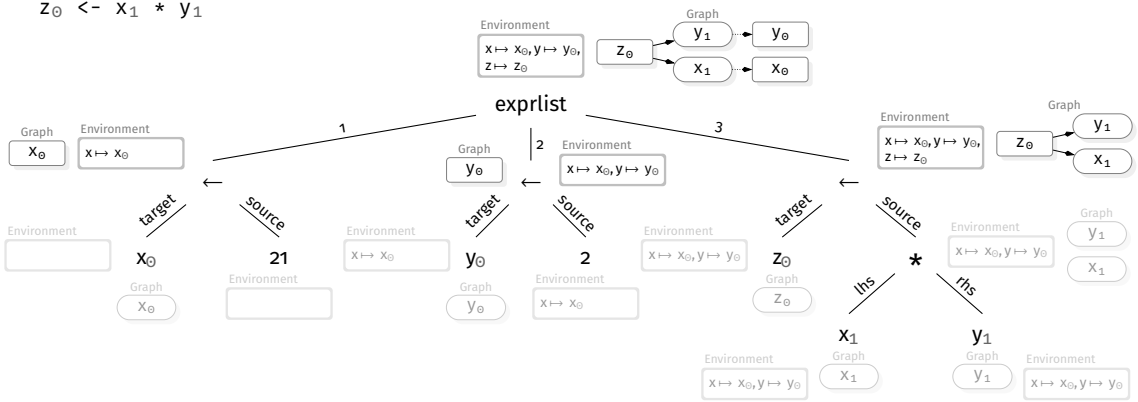
slice(10, **sum**) →

```
sum  <- 0
prod <- 1
n    <- 10

for (i in 1:(n-1)) {
   sum  <- sum + i
   prod <- prod * i
}

cat("Sum:", sum, "\n")
cat("Product:", prod, "\n")
```

github.com/flowr-analysis/flowr/tree/main/src/dataflow

flowr — Dataflow

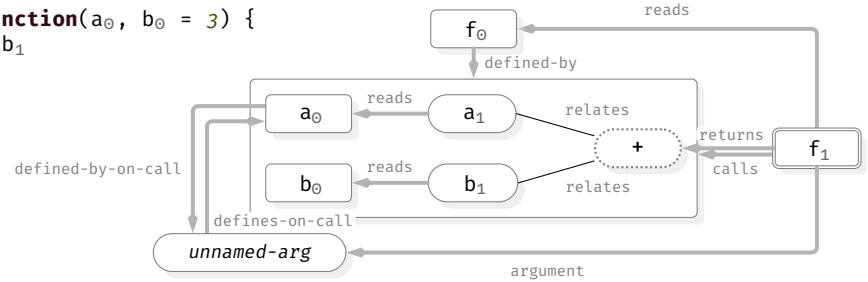
```
x0 <- 21
y0 <- 2
z0 <- x1 * y1
```



Without Value tracking

flowR — There Is More…

```
f₀ <- function(a₀, b₀ = 3) {
   a₁ + b₁
}
f₁(39)
```



3. Conclusion

Soundness and Completeness Revisited

- We want to prove properties of programs (e.g., no overflow, shapes, ...)
- However, thanks to Rice [Ric53] we know:

  Rice's theorem states that all nontrivial semantic properties of programs are undecidable. [Cou21, p. 100]

Soundness

- All properties we derive are true (but we may miss some)
- If we report bugs for violated properties, we produce no false negative

Completeness

- We are able to infer all interesting properties in the program
- If we report bugs for violated properties, we produce no false positive

Handling Errors

- Analyzers tend to **favor soundyness over completeness**
  Better to report a false positive than to miss a bug
- Yet many cases are hard to handle (e.g., `eval` with *any* possible effect)
- Issues are usually ranked by severity (and sometimes confidence)
- Cutoffs may be applied if there are too many alarms
- These is still a lot of research required [EN08; Cou21, p. 705]

Oh There Are so Many Tools…

LiquidHaskell Verify Properties at Compile Time

Oh There Are so Many Tools…

Use inference rules for linting

Oh There Are so Many Tools…

Determine Registers, Scheduling, …

Clang

And There Are Many More Strategies

- Static Analysis
  analyzing the code without executing it, for all possible runtime scenarios
- Dynamic Analysis
  executing the program with specific input(s) to observe its behavior
- Hybrid Analysis
  combining both strategies

Program Analysis is important. Additionally and combined with testing.

References I

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