Lecture 5: Transformation by Term Rewriting

Eelco Visser

CS4200 Compiler Construction
TU Delft
September 2019

TU Delft

#spoofax-users

Channel on research group Slack

Where many Spoofax users hang out

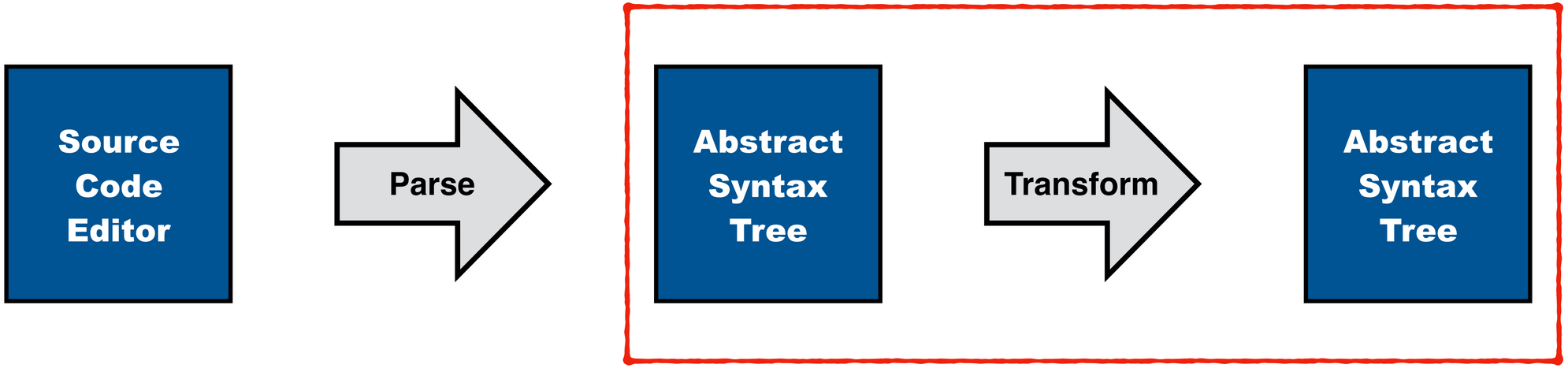
Ask questions about Spoofax

(Not answers to assignments)

No guarantee to quick response, or answer at all

Send me an email if you want an invitation

This Lecture



Define transformations on abstract syntax trees (terms) using rewrite rules

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.

Term rewrite rules define transformations on (abstract syntax) trees. Traditional rewrite systems apply rules exhaustively. This paper introduces programmable rewriting strategies to control the application of rules, the core of the design of the Stratego transformation language.

Note that the notation for contextual rules is no longer supported by Stratego. However, the technique to implement contextual rules still applies.

ICFP 1998

https://doi.org/10.1145/291251.289425

Building Program Optimizers with Rewriting Strategies*

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Abstract

We describe a language for defining term rewriting strategies, and its application to the production of program optimizers. Valid transformations on program terms can be described by a set of rewrite rules; rewriting strategies are used to describe when and how the various rules should be applied in order to obtain the desired optimization effects. Separating rules from strategies in this fashion makes it easier to reason about the behavior of the optimizer as a whole, compared to traditional monolithic optimizer implementations. We illustrate the expressiveness of our language by using it to describe a simple optimizer for an ML-like intermediate representation.

The basic strategy language uses operators such as sequential composition, choice, and recursion to build transformers from a set of labeled unconditional rewrite rules. We also define an extended language in which the side-conditions and contextual rules that arise in realistic optimizer specifications can themselves be expressed as strategy-driven rewrites. We show that the features of the basic and extended languages can be expressed by breaking down the rewrite rules into their primitive building blocks, namely matching and building terms in variable binding environments. This gives us a low-level core language which has a clear semantics, can be implemented straightforwardly and can itself be optimized. The current implementation generates C code from a strategy specification.

1 Introduction

Compiler components such as parsers, pretty-printers and code generators are routinely produced using program generators. The component is specified in a high-level language from which the program generator produces its implementation. Program optimizers are difficult labor-intensive components that are usually still developed manually, despite many attempts at producing optimizer generators (e.g., [19, 12, 28, 25, 18, 11]).

*This work was supported, in part, by the US Air Force Materiel Command under contract F19628-93-C-0069 and by the National Science Foundation under grant CCR-9503383.

A program optimizer transforms the source code of a program into a program that has the same meaning, but is more efficient. On the level of specification and documentation, optimizers are often presented as a set of correctness-preserving *rewrite rules* that transform code fragments into equivalent more efficient code fragments (e.g., see Table 5). This is particularly attractive for functional language compilers (e.g., [3, 4, 24]) that operate via successive small transformations, and don't rely on analyses requiring significant auxiliary data structures. The paradigm provided by conventional rewrite engines is to compute the normal form of a program with respect to a set of rewrite rules. However, optimizers are usually not implemented in this way. Instead, an algorithm is produced that implements a *strategy* for applying the optimization rules. Such a strategy contains meta-knowledge about the set of rewrite rules and the programming language they are applied to in order to (1) control the application of rules; (2) guarantee termination of optimization; (3) make optimization more efficient.

Such an ad-hoc implementation of a rewriting system has several drawbacks, even when implemented in a language with good support for pattern matching, such as ML or Haskell. First of all, the transformation rules are embedded in the code of the optimizer, making them hard to understand, to maintain, and to reuse individual rules in other transformations. Secondly, the strategy is not specified at the same level of abstraction as the transformation rules, making it hard to reason about the correctness of the optimizer even if the individual rules are correct. Finally, the host language has no awareness of the transformation domain underlying the implementation and can therefore not use this domain knowledge to optimize the optimizer itself.

It would be desirable to apply term rewriting technology directly to produce program optimizers. However, the standard approach to rewriting is to provide a fixed strategy (e.g., innermost or outermost) for normalizing a term with respect to a set of user-defined rewrite rules. This is not satisfactory when—as is usually the case for optimizers—the rewrite rules are neither confluent nor terminating. A common work-around is to encode a strategy into the rules themselves, e.g., by using an explicit function symbol that controls where rewrites are allowed. But this approach has the same disadvantages as the ad-hoc implementation of rewriting described above: the rules are hard to read, and the strategies are still expressed at a low level of abstraction.

In this paper we argue that a better solution is to use explicit specification of *rewriting strategies*. We show how

Stratego/XT combines SDF2 and Stratego into toolset for program transformation.

This paper gives a high-level overview of the concepts.

The StrategoXT.jar is still part of the Spoofax distribution.

Lecture Notes in Computer Science 2003

https://doi.org/10.1007/978-3-540-25935-0_13

Program Transformation with Stratego/XT

Rules, Strategies, Tools, and Systems in Stratego/XT 0.9

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Abstract. Stratego/XT is a framework for the development of transformation systems aiming to support a wide range of program transformations. The framework consists of the transformation language Stratego and the XT collection of transformation tools. Stratego is based on the paradigm of rewriting under the control of programmable rewriting strategies. The XT tools provide facilities for the infrastructure of transformation systems including parsing and pretty-printing. The framework addresses the entire range of the development process; from the specification of transformations to their composition into transformation systems. This chapter gives an overview of the main ingredients involved in the composition of transformation systems with Stratego/XT, where we distinguish the abstraction levels of rules, strategies, tools, and systems.

1 Introduction

Program transformation, the automatic manipulation of source programs, emerged in the context of compilation for the implementation of components such as optimizers [28]. While compilers are rather specialized tools developed by few, transformation systems are becoming widespread. In the paradigm of generative programming [13], the generation of programs from specifications forms a key part of the software engineering process. In refactoring [21], transformations are used to restructure a program in order to improve its design. Other applications of program transformation include migration and reverse engineering. The common goal of these transformations is to increase programmer productivity by automating programming tasks.

With the advent of XML, transformation techniques are spreading beyond the area of programming language processing, making transformation a necessary operation in any scenario where structured data play a role. Techniques from program transformation are applicable in document processing. In turn, applications such as Active Server Pages (ASP) for the generation of web-pages in dynamic HTML has inspired the creation of program generators such as Jostraca [31], where code templates specified in the concrete syntax of the object language are instantiated with application data.

Stratego/XT is a framework for the development of transformation systems aiming to support a wide range of program transformations. The framework consists of the transformation language Stratego and the XT collection of transformation tools. Stratego is based on the paradigm of rewriting under the control of programmable rewriting strategies. The XT tools provide facilities for the infrastructure of transformation

C. Lengauer et al. (Eds.): Domain-Specific Program Generation, LNCS 3016, pp. 216–238, 2004.

Spoofax combines SDF2 and Stratego into a language workbench, i.e. an IDE for creating language definition from which IDEs for the defined languages can be generated.

A distinctive feature of Spoofax is live language development, which supports developing a language definition and programs in the defined language in the same IDE instance.

Spoofax was developed for Eclipse, which is still the main development platform. However, Spoofax Core is now independent of any IDE.

Note that the since the publication of this paper, we have introduced more declarative approaches to name and type analysis, which will be the topic of the next lectures.

OOPSLA 2010

https://doi.org/10.1145/1932682.1869497

The Spoofax Language Workbench

Rules for Declarative Specification of Languages and IDEs

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Abstract

Spoofax is a language workbench for efficient, agile development of textual domain-specific languages with state-of-the-art IDE support. Spoofax integrates language processing techniques for parser generation, meta-programming, and IDE development into a single environment. It uses concise, declarative specifications for languages and IDE services. In this paper we describe the architecture of Spoofax and introduce idioms for high-level specifications of language semantics using rewrite rules, showing how analyses can be reused for transformations, code generation, and editor services such as error marking, reference resolving, and content completion. The implementation of these services is supported by language-parametric editor service classes that can be dynamically loaded by the Eclipse IDE, allowing new languages to be developed and used side-by-side in the same Eclipse environment.

Categories and Subject Descriptors D.2.3 [*Software Engineering*]: Coding Tools and Techniques; D.2.6 [*Software Engineering*]: Programming Environments

General Terms Languages

1. Introduction

Domain-specific languages (DSLs) provide high expressive power focused on a particular problem domain [38, 47]. They provide linguistic abstractions over common tasks within a domain, so that developers can concentrate on application logic rather than the accidental complexity of low-level implementation details. DSLs have a concise, domain-specific notation for common tasks in a domain, and allow reasoning at the level of these constructs. This allows them to be used for automated, domain-specific analysis, verification, optimization, parallelization, and transformation (AVOPT) [38].

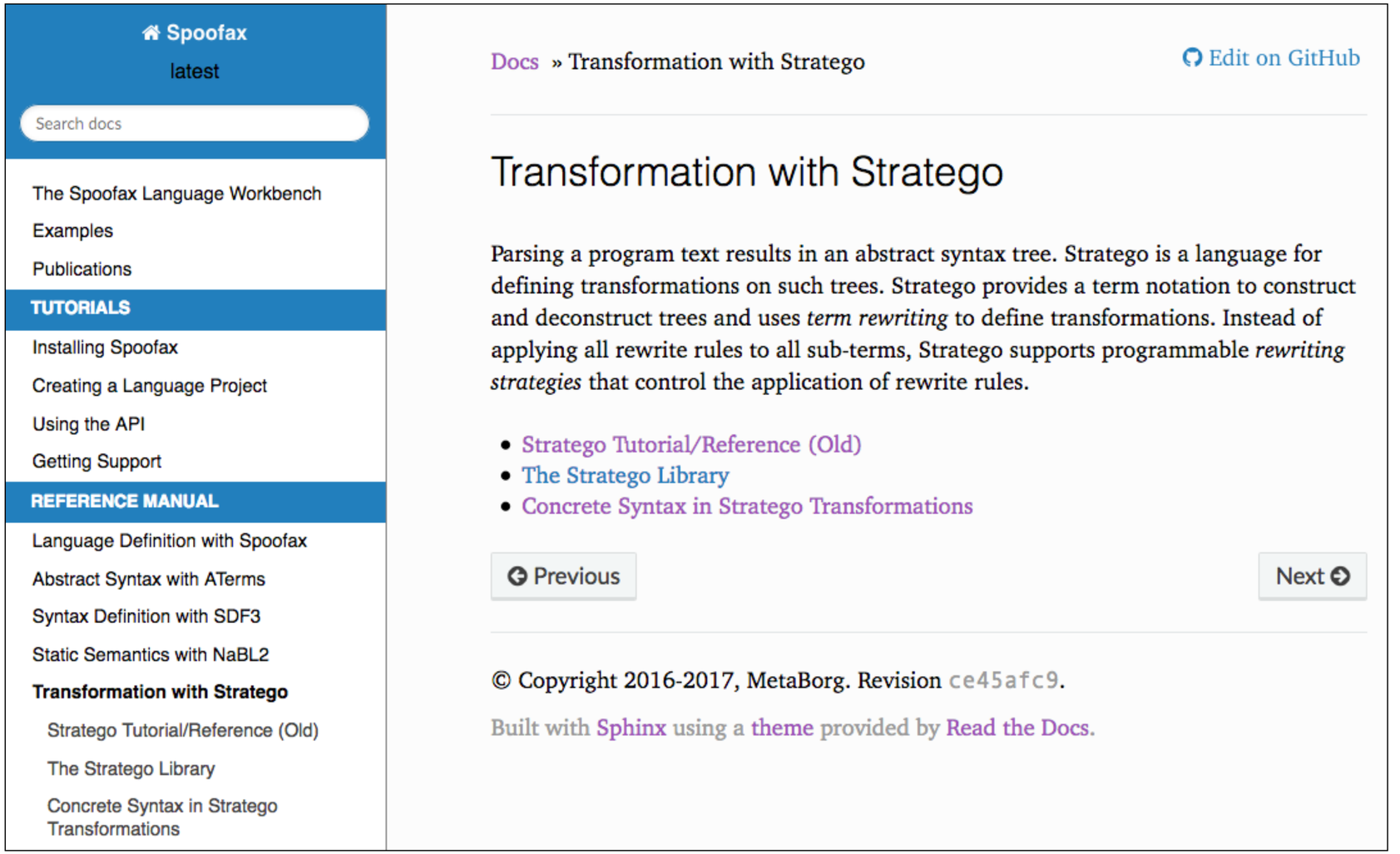
OOPSLA/SPLASH'10, October 17–21, 2010, Reno/Tahoe, Nevada, USA.

For developers to be productive with DSLs, good integrated development environments (IDEs) for these languages are essential. Over the past four decades, IDEs have slowly risen from novelty tool status to becoming a fundamental part of software engineering. In early 2001, IntelliJ IDEA [42] revolutionized the IDE landscape [17] with an IDE for the Java language that parsed files as they were typed (with error recovery in case of syntax errors), performed semantic analysis in the background, and provided code navigation with a live view of the program outline, references to declarations of identifiers, content completion proposals as programmers were typing, and the ability to transform the program based on the abstract representation (refactorings). The now prominent Eclipse platform, and soon after, Visual Studio, quickly adopted these same features. No longer would programmers be satisfied with code editors that provided basic syntax highlighting and a "build" button. For new languages to become a success, state-of-the-art IDE support is now mandatory. For the production of DSLs this requirement is a particular problem, since these languages are often developed with much fewer resources than general purpose languages.

There are five key ingredients for the construction of a new domain-specific language. (1) A parser for the *syntax* of the language. (2) Semantic *analysis* to validate DSL programs according to some set of constraints. (3) *Transformations* manipulate DSL programs and can convert a high-level, technology-independent DSL specification to a lower-level program. (4) A *code generator* that emits executable code. (5) Integration of the language into an *IDE*.

Traditionally, a lot of effort was required for each of these ingredients. However, there are now many tools that support the various aspects of DSL development. Parser generators can automatically create a parsers from a grammar. Modern parser generators can construct efficient parsers that can be used in an interactive environment, supporting error recovery in case of syntax-incorrect or incomplete programs. Meta-programming languages [3, 10, 12, 20, 35] and frameworks [39, 57] make it much easier to specify the semantics of a language. Tools and frameworks for IDE development such as IMP [7, 8] and TMF [56], simplify the implementation of IDE services. Other tools, such as the Synthesizer

Documentation for Stratego at the metaborg.org website.



http://www.metaborg.org/en/latest/source/langdev/meta/lang/stratego/index.html

This paper defines the formal semantics of the full Stratego language, including its scoped dynamic rules feature.

These slides document most features of the base language without dynamic rules and without giving the formal semantics.

If you want to dig deeper

Fundamenta Informaticae 69 (2006) 123–178
IOS Press

Program Transformation with Scoped Dynamic Rewrite Rules

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Abstract. The applicability of term rewriting to program transformation is limited by the lack of control over rule application and by the context-free nature of rewrite rules. The first problem is addressed by languages supporting user-definable rewriting strategies. The second problem is addressed by the extension of rewriting strategies with scoped dynamic rewrite rules. Dynamic rules are defined at run-time and can access variables available from their definition context. Rules defined within a rule scope are automatically retracted at the end of that scope. In this paper, we explore the design space of dynamic rules, and their application to transformation problems. The technique is formally defined by extending the operational semantics underlying the program transformation language Stratego, and illustrated by means of several program transformations in Stratego, including constant propagation, bound variable renaming, dead code elimination, function inlining, and function specialization.

1. Introduction

Program transformation is the mechanical manipulation of a program in order to improve it relative to some cost function C such that $C(P) > C(tr(P))$, i.e. the cost decreases as a result of applying the transformation [30, 29, 11]. The cost of a program can be measured in different dimensions such as performance, memory usage, understandability, flexibility, maintainability, portability, correctness, or satisfaction of requirements. Related to these goals, program transformations are applied in different settings; e.g. compiler optimizations improve performance [24] and refactoring tools aim at improving understandability [28, 14]. While transformations can be achieved by manual manipulation of programs, in general, the aim of program transformation is to increase programmer productivity by *automating*

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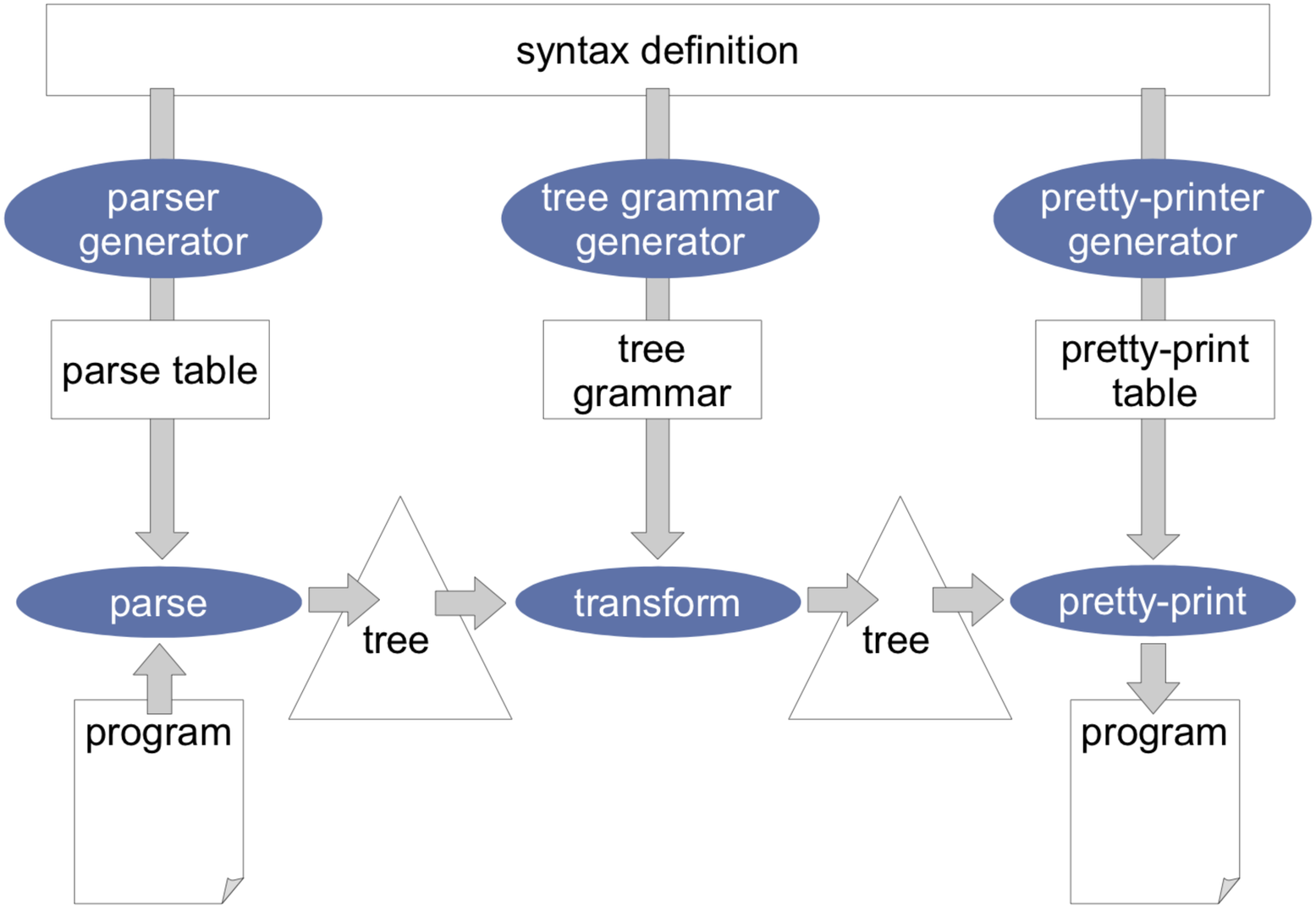
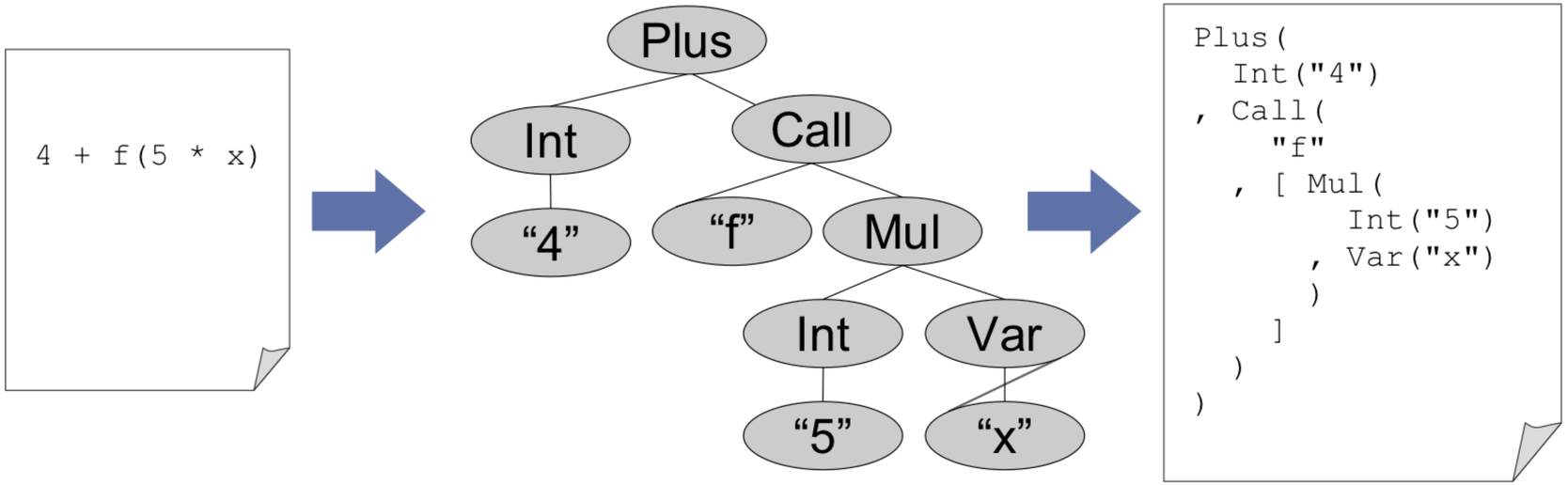
Transformation Architecture

This presentation uses the Stratego Shell for explaining the behavior of Stratego programs. The Stratego Shell is currently not supported by Spoofax

Architecture of Stratego/XT



Programs as Terms



Trees are represented as terms in the ATerm format

```
Plus(Int("4"), Call("f", [Mul(Int("5"), Var("x"))]))
```

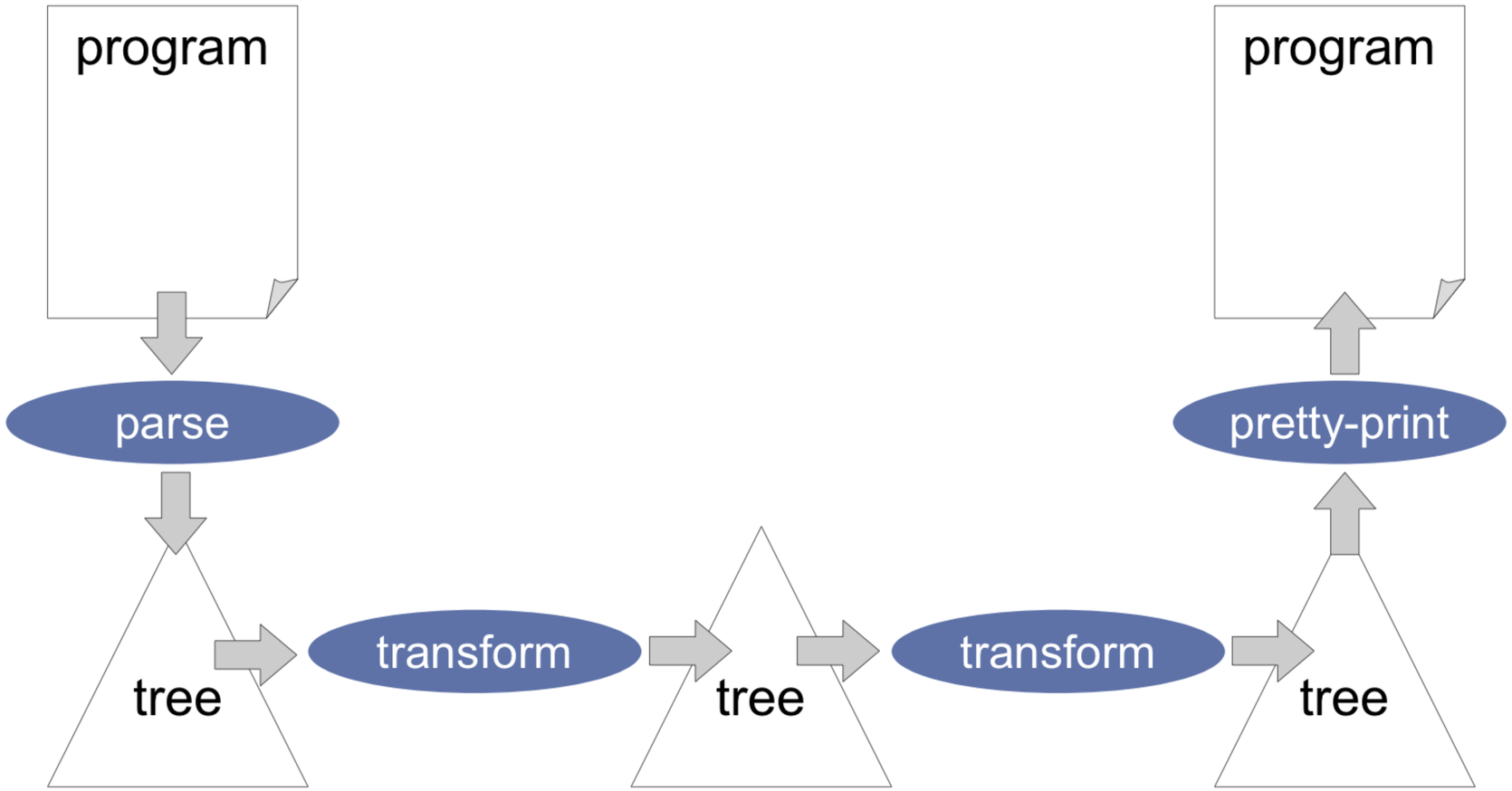
ATerm Format

Application	`Void()`, `Call(`t`, `t`)`
List	`[]`, `[`t`, `t`, `t`]`
Tuple	`(`t`, `t`)`, `(`t`, `t`, `t`)`
Integer	`25`
Real	`38.87`
String	`"Hello world"`
Annotated term	t{t, t, t}

- Exchange of structured data
- Efficiency through maximal sharing
- Binary encoding

Structured Data: comparable to XML
Stratego: internal is external representation

How to Realize Program Transformations?



Term Rewriting

Conventional Term Rewriting

- Rewrite system = set of rewrite rules
- Redex = reducible expression
- Normalization = exhaustive application of rules to term
- (Stop when no more redices found)
- Strategy = algorithm used to search for redices
- Strategy given by engine

Strategic Term Rewriting

- Select rules to use in a specific transformation
- Select strategy to apply
- Define your own strategy if necessary
- Combine strategies

Transformation Strategies

A transformation strategy

- transforms the **current term** into a new term or **fails**
- may bind term variables
- may have side-effects (I/O, call other process)
- is composed from a few **basic operations and combinators**

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Stratego Shell: An Interactive Interpreter for Stratego

```
<current term>
```

Transformation Strategies

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Stratego Shell: An Interactive Interpreter for Stratego

```
<current term>
stratego> <strategy expression>
<transformed term>
```

Transformation Strategies

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- transforms the **current term** into a new term or **fails**
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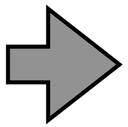
Stratego Shell: An Interactive Interpreter for Stratego

```
<current term>
stratego> <strategy expression>
<transformed term>
stratego> <strategy expression>
command failed
```

Terms

Parsing: From Text to Terms

```
let function fact(n : int) : int =
      if n < 1 then 1 else (n * fact(n - 1))
 in fact(10)
end
```



```
Let(
  [ FunDec(
      "fact"
    , [FArg("n", Tp(Tid("int")))]
    , Tp(Tid("int"))
    , If(
        Lt(Var("n"), Int("1"))
      , Int("1")
      , Seq(
          [ Times(
              Var("n")
            , Call(
                Var("fact")
              , [Minus(Var("n"), Int("1"))]
              )
            )
          ]
        )
      )
    )
  ]
, [Call(Var("fact"), [Int("10")])]
)
```

Syntax of Terms

```
module Terms

sorts Cons Term

lexical syntax

   Cons = [a-zA-Z][a-zA-Z0-9]*

context-free syntax

   Term.App = <<Cons>(<{Term ","}*>)>
```

```
Zero()

Succ(Zero())

Cons(A(), Cons(B(), Nil()))
```

Syntax of Terms

```
module Terms

sorts Cons Term

lexical syntax

   Cons = [a-zA-Z][a-zA-Z0-9]*

context-free syntax

   Term.App   = <<Cons>(<{Term ","}*>)>
   Term.List  = <[<{Term ","}*>]>
   Term.Tuple = <(<{Term ","}*>)>
```

```
Zero()

Succ(Zero())

[A(), B()]
```

Syntax of Terms

```
module ATerms

sorts Cons Term

lexical syntax
   Cons       = [a-zA-Z][a-zA-Z0-9]*
   Cons       = String
   Int        = [0-9]+
   String     = "\"" StringChar* "\""
   StringChar = ~[\"\\n]
   StringChar = "\\" [\"\\]

context-free syntax
   Term.Str   = <<String>>
   Term.Int   = <<Int>>
   Term.App   = <<Cons>(<{Term ","}*>)>
   Term.List  = <[<{Term ","}*>]>
   Term.Tuple = <(<{Term ","}*>)>
```

```
0

1

[A(), B()]

Var(“x\\”)

Let(
  [ Decl(“x”, IntT()),
    Decl(“y”, BoolT())
  ]
  , Eq(Var(“x”), Int(0))
)
```

Syntax of A(nnotated) Terms

```
module ATerms

sorts Cons Term

lexical syntax
   Cons = [a-zA-Z][a-zA-Z0-9]*
   // more lexical syntax omitted

context-free syntax

   Term.Anno     = <<PreTerm>{<{Term “,"}*>}>
   Term          = <<PreTerm>>

   PreTerm.Str   = <<String>>
   PreTerm.Int   = <<Int>>
   PreTerm.App   = <<Cons>(<{Term ","}*>)>
   PreTerm.List  = <[<{Term ","}*>]>
   PreTerm.Tuple = <(<{Term ","}*>)>
```

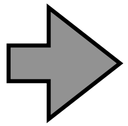
```
Var(“x”){Type(IntT())}
```

Signatures

Signatures

```
context-free syntax

  Exp.Uminus  = [- [Exp]]
  Exp.Power   = [[Exp] ** [Exp]]
  Exp.Times   = [[Exp] *  [Exp]]
  Exp.Divide  = [[Exp] /  [Exp]]
  Exp.Plus    = [[Exp] +  [Exp]]
  Exp.Minus   = [[Exp] -  [Exp]]
  Exp.CPlus   = [[Exp] +i [Exp]]
  Exp.CMinus  = [[Exp] -i [Exp]]
  Exp.Eq      = [[Exp] =  [Exp]]
  Exp.Neq     = [[Exp] <> [Exp]]
  Exp.Gt      = [[Exp] >  [Exp]]
  Exp.Lt      = [[Exp] <  [Exp]]
  Exp.Geq     = [[Exp] >= [Exp]]
  Exp.Leq     = [[Exp] <= [Exp]]
  Exp.True    = <true>
  Exp.False   = <false>
  Exp.And     = [[Exp] & [Exp]]
  Exp.Or      = [[Exp] | [Exp]]
```

Signature is automatically generated from SDF3 productions



Signature declares argument and return types of term constructors

```
signature
  constructors
    Uminus     : Exp -> Exp
    Power      : Exp * Exp -> Exp
    Times      : Exp * Exp -> Exp
    Divide     : Exp * Exp -> Exp
    Plus       : Exp * Exp -> Exp
    Minus      : Exp * Exp -> Exp
    CPlus      : Exp * Exp -> Exp
    CMinus     : Exp * Exp -> Exp
    Eq         : Exp * Exp -> Exp
    Neq        : Exp * Exp -> Exp
    Gt         : Exp * Exp -> Exp
    Lt         : Exp * Exp -> Exp
    Geq        : Exp * Exp -> Exp
    Leq        : Exp * Exp -> Exp
    True       : Exp
    False      : Exp
    And        : Exp * Exp -> Exp
    Or         : Exp * Exp -> Exp
```

Stratego compiler only checks *arity* of constructor applications

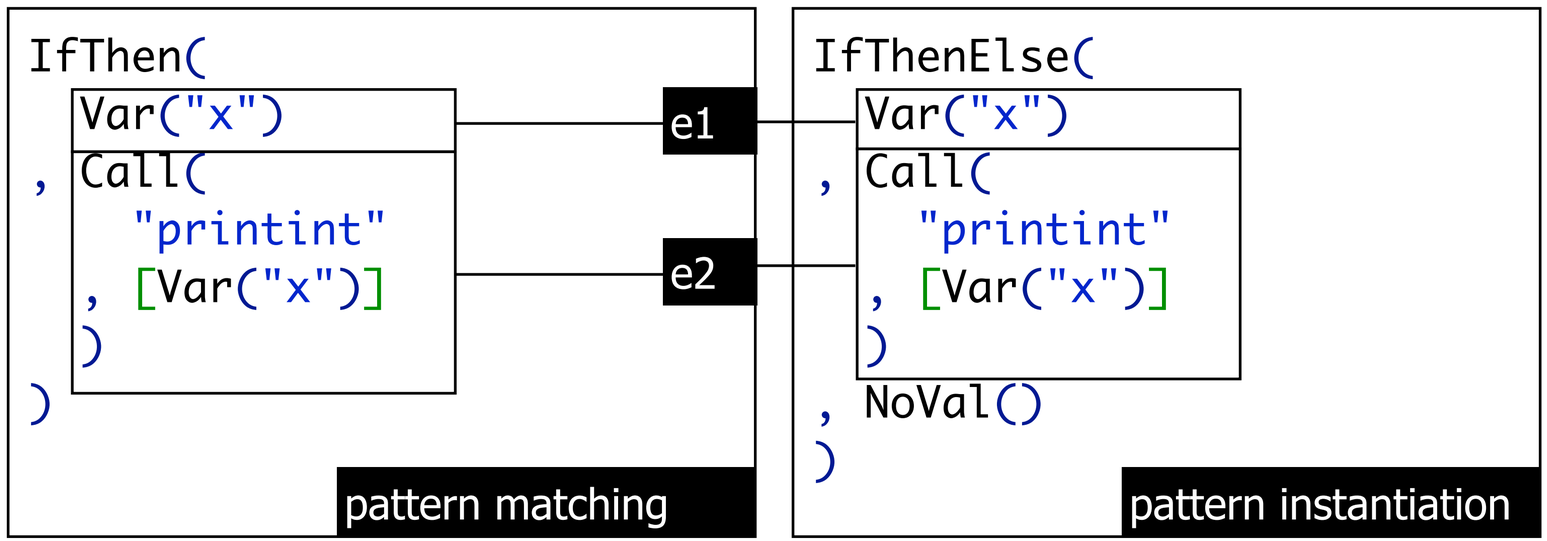
Rewrite Rules

TU Delft

Desugaring

```
if x then
   printint(x)
```

```
if x then
   printint(x)
else
   ()
```




```
desugar: IfThen(e1, e2) -> IfThenElse(e1, e2, NoVal())
```

Lists of ElseIfs

```
signature
  constructors
    If : Exp * Exp * List(ElseIf) -> Exp

    ElseIf : Exp * Exp -> ElseIf

    IfThen : Exp * Exp * Exp -> Exp
```

```
If(c, e1, [
  ElseIf(c2, e2),
  ElseIf(c3, e3),
  …
])
```

```
Desugar :
  If(c, e, []) -> IfThen(c, e, NoVal())

Desugar :
  If(c, e, [ElseIf(c2, e2) | es]) -> IfThen(c, e, If(c2, e2, es))
```

More Desugaring

```
signature
  constructors
    PLUS:    BinOp
    MINUS:   BinOp
    MUL:  BinOp
    DIV:  BinOp

    EQ:   RelOp
    NE:   RelOp
    LE:   RelOp
    LT:   RelOp

    Bop: BinOp * Expr * Expr -> Expr
    Rop: RelOp * Expr * Expr -> Expr
```

```
desugar: Uminus(e)      -> Bop(MINUS(), Int("0"), e)

desugar: Plus(e1, e2)   -> Bop(PLUS(), e1, e2)
desugar: Minus(e1, e2)  -> Bop(MINUS(), e1, e2)
desugar: Times(e1, e2)  -> Bop(MUL(), e1, e2)
desugar: Divide(e1, e2) -> Bop(DIV(), e1, e2)

desugar: Eq(e1, e2)  -> Rop(EQ(), e1, e2)
desugar: Neq(e1, e2) -> Rop(NE(), e1, e2)
desugar: Leq(e1, e2) -> Rop(LE(), e1, e2)
desugar: Lt(e1, e2)  -> Rop(LT(), e1, e2)
desugar: Geq(e1, e2) -> Rop(LE(), e2, e1)
desugar: Gt(e1, e2)  -> Rop(LT(), e2, e1)

desugar: And(e1, e2) -> IfThenElse(e1, e2, Int("0"))
```

Constant Folding

```
x := 21 + 21 + x
```

```
x := 42 + x
```

```
Assign(
  Var("x")
, Plus(
    Plus(
      Int("21")
    , Int("21")
    )
  , Var("x")
  )
)
```

```
Assign(
  Var("x")
, Plus(
    Int("42")
  , Var("x")
  )
)
```

```
eval: Plus(Int(i1), Int(i2)) -> Int(i3)
      where <addS> (i1, i2) => i3
```

More Constant Folding

```
eval: Bop(PLUS(), Int(i1), Int(i2))  -> Int(<addS> (i1, i2))

eval: Bop(MINUS(), Int(i1), Int(i2)) -> Int(<subtS> (i1, i2))

eval: Bop(MUL(), Int(i1), Int(i2))   -> Int(<mulS> (i1, i2))

eval: Bop(DIV(), Int(i1), Int(i2))   -> Int(<divS> (i1, i2))

eval: Rop(EQ(), Int(i), Int(i))   -> Int("1")
eval: Rop(EQ(), Int(i1), Int(i2)) -> Int("0") where not( <eq> (i1, i2) )

eval: Rop(NE(), Int(i), Int(i))   -> Int("0")
eval: Rop(NE(), Int(i1), Int(i2)) -> Int("1") where not( <eq> (i1, i2) )

eval: Rop(LT(), Int(i1), Int(i2)) -> Int("1") where <ltS> (i1, i2)
eval: Rop(LT(), Int(i1), Int(i2)) -> Int("0") where not( <ltS> (i1, i2) )

eval: Rop(LE(), Int(i1), Int(i2)) -> Int("1") where <leqS> (i1, i2)
eval: Rop(LE(), Int(i1), Int(i2)) -> Int("0") where not( <leqS> (i1, i2))
```

Application: Spoofax Builders

Spoofax Builders

```
rules

  build :
    (node, _, ast, path, project-path) -> result
    with
      <some-transformation> ast => result
```

Builder gets AST as parameter

Tiger: AST Builder

```
module Syntax

menus

  menu: "Syntax" (openeditor)

    action: "Format"           = editor-format (source)
    action: "Show parsed AST" = debug-show-aterm (source)
```

editor/syntax.esv

trans/tiger.str

```
rules // Debugging

  debug-show-aterm:
    (node, _, _, path, project-path) -> (filename, result)
    with
      filename := <guarantee-extension(|"aterm")> path
    ; result   := node
```

Builder gets AST as parameter

Application: Formatting

Tiger: Formatting Builder

```
module Syntax

menus

  menu: "Syntax" (openeditor)

    action: "Format"           = editor-format (source)
    action: "Show parsed AST" = debug-show-aterm (source)
```

editor/syntax.esv

trans/pp.str

```
rules

  editor-format:
    (node, _, ast, path, project-path) -> (filename, result)
    with
      ext      := <get-extension> path
    ; filename := <guarantee-extension(|$[pp.[ext]])> path
    ; result   := <pp-debug> node
```

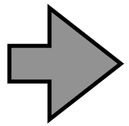
trans/pp.str

```
rules

  pp-Tiger-string =
    parenthesize-Tiger
    ; prettyprint-Tiger-start-symbols
    ; !V([], <id>)
    ; box2text-string(|120)

  pp-debug :
    ast -> result
    with
       result := <pp-Tiger-string> ast
    <+ …
    ;  result := “"
```

Tiger: Parenthesize

```
module pp/Tiger-parenthesize

imports
  libstratego-lib
  signatures/-

strategies

  parenthesize-Tiger =
    innermost(TigerParenthesize)
```

```
context-free priorities

  Exp.And
  > Exp.Or
  > Exp.Array
  > Exp.Assign
  > …
```



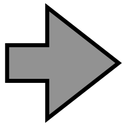
```
rules
  TigerParenthesize :
    Or(t_0, t_1) -> Or(t_0, Parenthetical(t_1))
    where <(?For(_, _, _, _)
            + ?While(_, _)
            + ?IfThen(_, _)
            + ?If(_, _, _)
            + ?Assign(_, _)
            + ?Array(_, _, _)
            + ?Or(_, _)
            + fail)> t_1

  TigerParenthesize :
    And(t_0, t_1) -> And(Parenthetical(t_0), t_1)
    where <(?For(_, _, _, _)
            + ?While(_, _)
            + ?IfThen(_, _)
            + ?If(_, _, _)
            + ?Assign(_, _)
            + ?Array(_, _, _)
            + ?Or(_, _)
            + fail)> t_0
```

pp/Tiger-parenthesize.str

Tiger: Pretty-Print Rules

```
context-free syntax

  Exp.If = <
    if <Exp> then
      <Exp>
    else
      <Exp>
  >
```

syntax/Control-Flow.sdf3



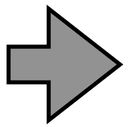
```
rules
  prettyprint-Tiger-Exp :
    If(t1__, t2__, t3__) -> [ H(
                                [SOpt(HS(), "0")]
                              , [ S("if ")
                                , t1__'
                                , S(" then")
                                ]
                              )
                            , t2__'
                            , H(
                                [SOpt(HS(), "0")]
                              , [S("else")]
                              )
                            , t3__'
                            ]
    with t1__' := <pp-one-Z(prettyprint-Tiger-Exp)
                   <+ pp-one-Z(prettyprint-completion-aux)> t1__
    with t2__' := <pp-indent(|"2")> [
      <pp-one-Z(prettyprint-Tiger-Exp)
      <+ pp-one-Z(prettyprint-completion-aux)> t2__ ]
    with t3__' := <pp-indent(|"2")> [
      <pp-one-Z(prettyprint-Tiger-Exp)
      <+ pp-one-Z(prettyprint-completion-aux)> t3__ ]
```

pp/Control-Flow-pp.str

Application: Desugaring

Tiger: Desugaring

```
function printboard() = (
  for i := 0 to N-1 do (
    for j := 0 to N-1 do
      print(if col[i]=j then " O" else " .");
    print("\n")
  );
  print("\n")
)
```



```
function printboard() = (
  let
    var i : int := 0
  in
    while i < N - 1 do ( (
      let
        var j : int := 0
      in
        while j < N - 1 do (
          print(if col[i] = j then
                  " O"
                else
                  " .");
          j := j + 1
        )
      end;
      print("\n")
    );
    i := i + 1
  )
  end;
  print("\n")
)
```

Expressing for in terms of while++

Tiger: Desugaring Builder

```
module Transformation

menus

  menu: "Transform" (openeditor) (realtime)

    action: "Desugar"        = editor-desugar (source)
    action: "Desugar AST"    = editor-desugar-ast (source)
```

editor/Transformation.esv

```
rules // Desugaring

  editor-desugar :
    (node, _, _, path, project-path) -> (filename, result)
    with
      filename := <guarantee-extension(|"des.tig")> path
    ; result   := <desugar-all; pp-Tiger-string>node

  editor-desugar-ast :
    (node, _, _, path, project-path) -> (filename, result)
    with
      filename := <guarantee-extension(|"aterm")> path
    ; result   := <desugar-all>node
```

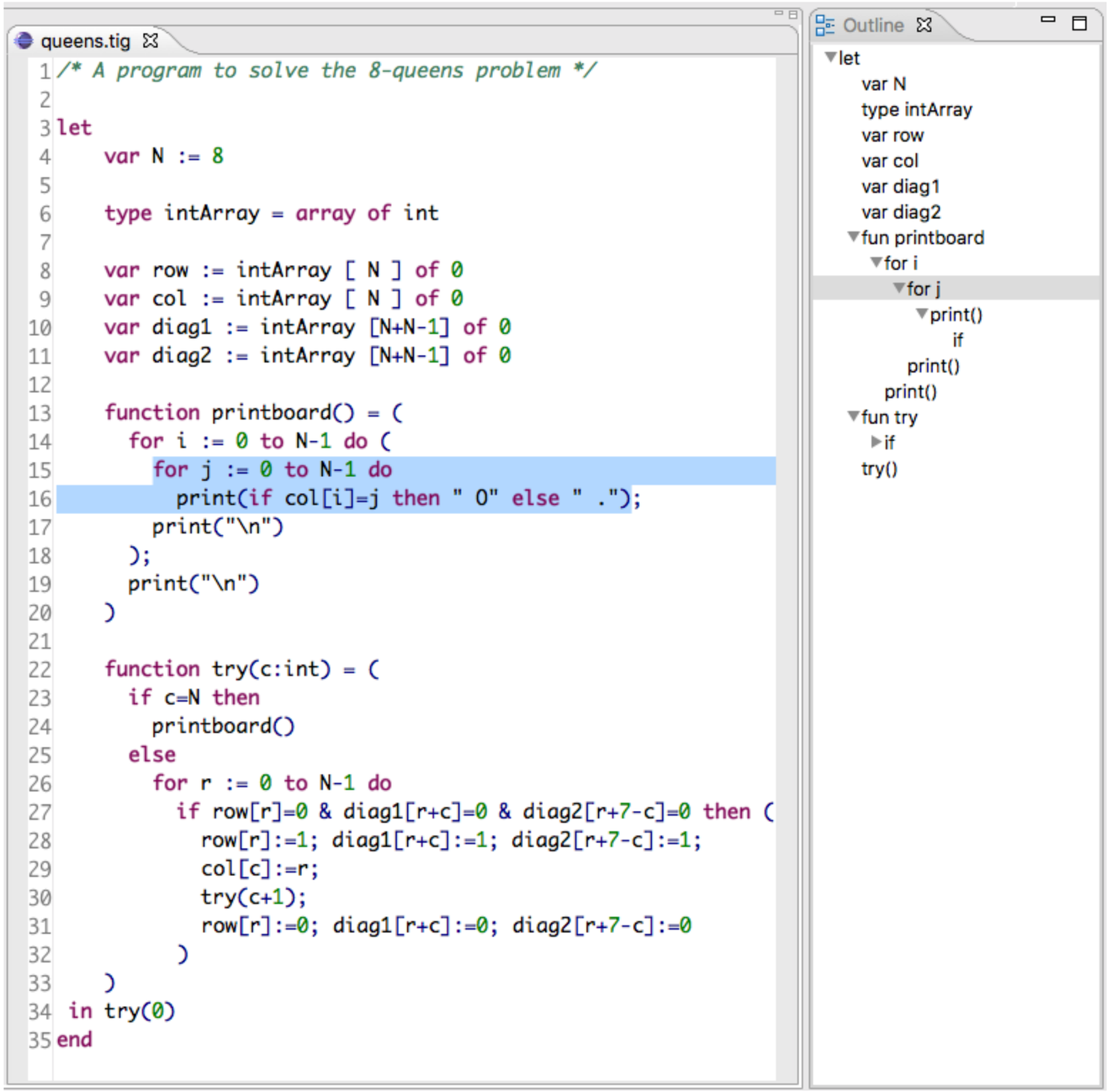
trans/tiger.str

Tiger: Desugaring Transformation

```
module desugar
imports signatures/Tiger-sig
imports …
strategies
  desugar-all = topdown(try(desugar))
rules
  desugar :
    For(
      Var(i)
    , e1
    , e2
    , e_body
    ) ->
    Let(
      [VarDec(i, Tid("int"), e1)]
    , [ While(
          Lt(Var(i), e2)
        , Seq(
            [ e_body
            , Assign(Var(i), Plus(Var(i), Int("1")))
            ]
          )
        )
      ]
    )
```

Application: Outline View

Tiger: Outline View



Tiger: Outline View Builder

```
module Syntax

views

  outline view: editor-outline (source)
    expand to level: 3
```

editor/syntax.esv

trans/outline.str

```
module outline

imports
  signatures/Tiger-sig
  signatures/Types-sig
  signatures/Records-sig
  signatures/Variables-sig
  signatures/Functions-sig
  signatures/Bindings-sig
  libspoofax/editor/outline
  pp

rules

  editor-outline:
    (_, _, ast, path, project-path) -> outline
    where
      outline := <simple-label-outline(to-outline-label)> ast
```

Tiger: Outline View Rules

```
rules

  to-outline-label :
    Let(_, _) -> $[let]

  to-outline-label :
    TypeDec(name, _) -> $[type [name]]

  to-outline-label :
    FunDec(name, _, t, _) -> $[fun [name] : [<pp-tiger-type> t]]

  to-outline-label :
    ProcDec(name, _, _) -> $[fun [name]]

  to-outline-label :
    VarDecNoType(name, _) -> $[var [name]]

  to-outline-label :
    VarDec(name, _, _) -> $[var [name]]
```

trans/outline.str

```
rules

  to-outline-label :
    Call(f, _) -> $[[f]()]

  to-outline-label :
    If(_, _, _) -> $[if]

  to-outline-label :
    For(Var(name), _, _, _) -> $[for [name]]

  // etc.
```

Outline View: Generic Strategy

```
module libspoofax/editor/outline
imports …
signature
  constructors
    Node : Label * Children -> Node
rules

  simple-label-outline(s1) =
    collect-om(to-outline-node(s1, fail), conc)

  custom-label-outline(s1, s2) =
    collect-om(origin-track-forced(s2) <+ to-outline-node(s1, s2), conc)

  to-outline-node(s1, s2):
    term -> Node(label, children)
    where
      random := <next-random>;
      label := <origin-track-forced(s1; term-to-outline-label)> term;
      children := <get-arguments; custom-label-outline(s1, s2)> term

  term-to-outline-label =
    is-string
    <+ ?term{a}; origin-text; ?label; !label{a}
    <+ write-to-string // fallback
```

Term structure for outline nodes

Language-independent strategy for collecting outline nodes

Application: Completion

Tiger: Completion Rules

syntax/Control-Flow.sdf3

```
context-free syntax

  Exp.If = <
    if <Exp> then
      <Exp>
    else
      <Exp>
  >
```

completion/Control-Flow-cp.str

```
rules

  suggest-completions(|completions):
    Exp-Plhdr() -> <add-completions(
                     | ( "If"
                       , If(
                           <try(inline-completions(|Exp-Plhdr()))> Exp-Plhdr()
                         , <try(inline-completions(|Exp-Plhdr()))> Exp-Plhdr()
                         , <try(inline-completions(|Exp-Plhdr()))> Exp-Plhdr()
                         )
                       )
                     )
                     ; fail> completions
```

Rewriting =
Matching & Building

Building and Matching Terms

Atomic actions of program transformation

1. Creating (building) terms from patterns
2. Matching terms against patterns

Building and Matching Terms

Atomic actions of program transformation

1. Creating (building) terms from patterns
2. Matching terms against patterns

Build pattern

- Syntax: `!`*p*
- Replace current term by instantation of pattern *p*
- A pattern is a term with *meta-variables*

```
stratego> :binding e
e is bound to Var("b")
stratego> !Plus(Var("a"),e)
Plus(Var("a"),Var("b"))
```

Matching Terms

Match pattern

- Syntax: $?p$
- Match current term (t) against pattern p
- Succeed if there is a substitution σ such that $\sigma(p) = t$

```
Plus(Var("a"),Int("3"))
stratego> ?Plus(e,_)
```

Matching Terms

Match pattern

- Syntax: `?`p
- Match current term (t) against pattern p
- Succeed if there is a substitution σ such that $\sigma(p) = t$
- Wildcard `_` matches any term

```
Plus(Var("a"),Int("3"))
stratego> ?Plus(e,_)
```

Matching Terms

Match pattern

- Syntax: ?p
- Match current term (t) against pattern p
- Succeed if there is a substitution σ such that $\sigma(p) = t$
- Wildcard _ matches any term
- Binds variables in p in the environment

```
Plus(Var("a"),Int("3"))
stratego> ?Plus(e,_)
stratego> :binding e
e is bound to Var("a")
```

Matching Terms

Match pattern

- Syntax: ?*p*
- Match current term (t) against pattern p
- Succeed if there is a substitution σ such that $\sigma(p) = t$
- Wildcard _ matches any term
- Binds variables in p in the environment
- Fails if pattern does not match

```
Plus(Var("a"),Int("3"))
stratego> ?Plus(e,_)
stratego> :binding e
e is bound to Var("a")
stratego> ?Plus(Int(x),e2)
command failed
```

Recognizing Dubious Statements and Expressions

control-flow statement with empty statement

```
while ((c = inputStream.read()) != -1);
  outputStream.write(c);
```

```
  ?While(_, Empty())
  ?If(_, Empty(), _)
  ?If(_, _, Empty())
```

equality operator with literal `true` operand; e.g. `e == true`

```
  ?Eq(_, Lit(Bool(True())))
  ?Eq(Lit(Bool(True())), _)
```

Combining Match and Build

Basic transformations are combinations of match and build

Combination requires

1. Sequential composition of transformations
2. Restricting the scope of term variables

Syntactic abstractions (sugar) for typical combinations

1. Rewrite rules
2. Apply and match
3. Build and apply
4. Where
5. Conditional rewrite rules

Combining Match and Build

Sequential composition

- Syntax: s_1 ; s_2
- Apply s_1, then s_2
- Fails if either s_1 or s_2 fails
- Variable bindings are propagated

```
Plus(Var("a"),Int("3"))
stratego> ?Plus(e1, e2); !Plus(e2, e1)
Plus(Int("3"),Var("a"))
```

Combining Match and Build

Anonymous rewrite rule (sugar)

- Syntax: `(`p_1 `->` p_2`)`
- Match p_1, then build p_2
- Equivalent to: `?`p_1`;` `!`p_2

```
Plus(Var("a"),Int("3"))
stratego> (Plus(e1, e2) -> Plus(e2, e1))
Plus(Int("3"),Var("a"))
```

Combining Match and Build

Apply and match (sugar)

- Syntax: *s* `=>` *p*
- Apply *s*, then match *p*
- Equivalent to: *s* `;` `?`*p*

Build and apply (sugar)

- Syntax: `<`*s*`>` *p*
- Build *p*, then apply *s*
- Equivalent to: `!`*p* `;` *s*

```
stratego> <addS>("1","2") => x
"3"
stratego> :binding x
x is bound to "3"
```

Combining Match and Build

Assign (sugar)

- Syntax: p_2 `:=` p_1
- Build p_1, then match p_2
- Equivalent to: `!`p_1`;` `?`p_2

```
stratego> x := <addS> ("1","2")
"3"
stratego> :binding x
x is bound to "3"
```

Combining Match and Build

Term variable scope

- Syntax: $\{x_1, \ldots, x_n : s\}$
- Restrict scope of variables x_1,...,x_n to s

```
Plus(Var("a"),Int("3"))
stratego> (Plus(e1,e2) -> Plus(e2,e1))
Plus(Int("3"),Var("a"))
stratego> :binding e1
e1 is bound to Var("a")

stratego> {e3,e4:(Plus(e3,e4) -> Plus(e4,e3))}
Plus(Var("a"),Int("3"))
stratego> :binding e3
e3 is not bound to a term
```

Combining Match and Build

Where (sugar)

- Syntax: `where(`*s*`)`
- Test and compute variable bindings
- Equivalent to: `{x: ?x; `*s*`; !x}`
  for some fresh variable `x`

```
Plus(Int("14"),Int("3"))
stratego> where(?Plus(Int(i),Int(j)); <addS>(i,j) => k)
Plus(Int("14"),Int("3"))
stratego> :binding i
i is bound to "14"
stratego> :binding k
k is bound to "17"
```

Combining Match and Build

Conditional rewrite rules (sugar)

- Syntax: `(`$p1$ `->` p_2 `where` s`)`
- Rewrite rule with condition s
- Equivalent to: `(?`$p1$`; where(`s`); !`p_2`)`

```
Plus(Int("14"),Int("3"))
> (Plus(Int(i),Int(j)) -> Int(k) where <addS>(i,j) => k)
Int("17")
```

Combining Match and Build

Term Wrap

- Syntax: `!`*p*`[<`*s*`>]`
- Strategy application in pattern to current subterm
- Equivalent to: `{x: where(`*s* `=> x); !`*p*`[x]}`
  for some fresh variable `x`

```
3
stratego> !(<id>,<id>)
(3,3)
stratego> !(<Fst; inc>,<Snd>)
(4,3)
```

```
"foobar"
stratego> !Call(<id>, [])
Call("foobar", [])
```

Combining Match and Build

Term Project

- Syntax: `?p[<s>]`
- Strategy application in pattern match
- Equivalent to: `{x: ?p[x]; <s>x}`
  for some fresh variable `x`

```
[1,2,3]
stratego> ?[_|<id>]
[2,3]
```

```
Block([ExprStm(PostIncr(ExprName(Id("x")))),Return(None)])
stratego> ?Block(<length>)
2
```

Combining Rewrite Rules with Strategies

TU Delft

Naming and Composing Strategies

Reuse of transformation requires definitions

1. Naming strategy expressions
2. Named rewrite rules
3. Reusing rewrite rules through modules

Simple strategy definition and call

- Syntax: *f* = *s*
- Name strategy expression *s*
- Syntax: *f*
- Invoke (call) named strategy *f*

```
Plus(Var("a"),Int("3"))
stratego> SwapArgs = {e1,e2:(Plus(e1,e2) -> Plus(e2,e1))}
stratego> SwapArgs
Plus(Int("3"),Var("a"))
```

Named Rewrite Rules

Named rewrite rules (sugar)

- Syntax: f `:` $p1$ `->` p_2 `where` s
- Name rewrite rule $p1$ `->` p_2 `where` s
- Equivalent to: f `= {`x_1`,...,`x_n`:` `(`p_1 `->` p_2 `where` s`)}`
  (with x_1,...,x_n the variables in p_1, p_2, and s)

```
Plus(Var("a"),Int("3"))
stratego> SwapArgs : Plus(e1,e2) -> Plus(e2,e1)
stratego> SwapArgs
Plus(Int("3"),Var("a"))
```

Example: Inverting If Not Equal

```
if(x != y)
  doSomething();
else
  doSomethingElse();
```

$\Rightarrow$

```
if(x == y)
  doSomethingElse();
else
  doSomething();
```

```
InvertIfNot :
  If(NotEq(e1, e2), stm1, stm2) ->
  If(Eq(e1, e2), stm2, stm1)
```

Modules with Reusable Transformation Rules

```
module Simplification-Rules
rules
  PlusAssoc :
    Plus(Plus(e1, e2), e3) -> Plus(e1, Plus(e2, e3))

  EvalIf :
    If(Lit(Bool(True())), stm1, stm2) -> stm1

  EvalIf :
    If(Lit(Bool(False())), stm1, stm2) -> stm2

  IntroduceBraces :
    If(e, stm) -> If(e, Block([stm]))
    where <not(?Block(_))> stm
```

```
stratego> import Simplification-Rules
```

Composing Strategies

Rules define one-step transformations

Program transformations require many one-step transformations and selection of rules

1. Choice
2. Identity, Failure, and Negation
3. Parameterized and Recursive Definitions

Composing Strategies

Deterministic choice (left choice)

- Syntax: s_1 <+ s_2
- First apply s_1, if that fails apply s_2
- Note: local backtracking

```
PlusAssoc :
  Plus(Plus(e1, e2), e3) -> Plus(e1, Plus(e2, e3))
EvalPlus :
  Plus(Int(i),Int(j)) -> Int(k) where <addS>(i,j) => k
```

```
Plus(Int("14"),Int("3"))
stratego> PlusAssoc
command failed
stratego> PlusAssoc <+ EvalPlus
Int("17")
```

Composing Strategies

Guarded choice

- Syntax: s_1 `<` s_2 `+` s_3
- First apply s_1 if that succeeds apply s_2 to the result
  else apply s_3 to the original term
- Do not backtrack to s_3 if s_2 fails!

Motivation

- s_1 `<+` s_2 always backtracks to s_2 if s_1 fails
- `(`s_1`;` s_2`)` `<+ s3` $\not\equiv$ s_1 `<` s_2 `+` s_3
- commit to branch if test succeeds, even if that branch fails

```
  test1 < transf1
+ test2 < transf2
+ transf3
```

Composing Strategies

Guarded choice

- Syntax: s_1 `<` s_2 `+` s_3
- First apply s_1 if that succeeds apply s_2 to the result
  else apply s_3 to the original term
- Do not backtrack to s_3 if s_2 fails!

Motivation

- s_1 `<+` s_2 always backtracks to s_2 if s_1 fails
- `(`s_1`;` s_2`)` `<+ s3` $\not\equiv$ s_1 `<` s_2 `+` s_3
- commit to branch if test succeeds, even if that branch fails

```
  test1 < transf1
+ test2 < transf2
+ transf3
```

If then else (sugar)

- Syntax: `if` s_1 `then` s_2 `else` s_3 `end`
- Equivalent to: `where(`s_1`)` `<` s_2 `+` s_3

Composing Strategies

Identity

- Syntax: `id`
- Always succeed
- Some laws
  - `id ;` $s \equiv s$
  - s `; id` $\equiv s$
  - `id <+` $s \equiv$ `id`
  - s `<+ id` $\not\equiv s$
  - s_1 `<` `id` `+` $s_2 \equiv s_1$ `<+` s_2

Failure

- Syntax: `fail`
- Always fail
- Some laws
  - `fail <+` $s \equiv s$
  - s `<+ fail` $\equiv s$
  - `fail ;` $s \equiv$ `fail`
  - s `; fail` $\not\equiv$ `fail`

Composing Strategies

Identity

- Syntax: `id`
- Always succeed
- Some laws
  - `id ;` $s \equiv s$
  - s `; id` $\equiv s$
  - `id <+` $s \equiv$ `id`
  - s `<+ id` $\not\equiv s$
  - s_1 `<` `id + ` $s_2 \equiv s_1$ `<+` s_2

Failure

- Syntax: `fail`
- Always fail
- Some laws
  - `fail <+` $s \equiv s$
  - s `<+ fail` $\equiv s$
  - `fail ;` $s \equiv$ `fail`
  - s `; fail` $\not\equiv$ `fail`

Negation (sugar)

- Syntax: `not(`s`)`
- Fail if s succeeds, succeed if s fails
- Equivalent to: s `< fail + id`

Parameterizing Strategies

Parameterized and recursive definitions

- Syntax: $f\,(x_1\,,\ldots,x_n\,|\,y_1\,,\ldots,y_m)\;=\;s$
- Strategy definition parameterized with strategies (x_1,...,x_n) and terms (y_1,...,y_m)
- Note: definitions may be recursive

Parameterizing Strategies

Parameterized and recursive definitions

- Syntax: $f(x_1, \ldots, x_n \,|\, y_1, \ldots, y_m) = s$
- Strategy definition parameterized with strategies (x_1,...,x_n) and terms (y_1,...,y_m)
- Note: definitions may be recursive

```
try(s)           = s <+ id

repeat(s)        = try(s; repeat(s))

while(c, s)      = if c then s; while(c,s) end

do-while(s, c) = s; if c then do-while(s, c) end
```

Parameterized Rewrite Rules

Parameterized Rewrite Rules

```
f(x,y|a,b): lhs -> rhs
```

- strategy or rule parameters x,y
- term parameters a,b
- no matching

```
f(|a,b): lhs -> rhs
```

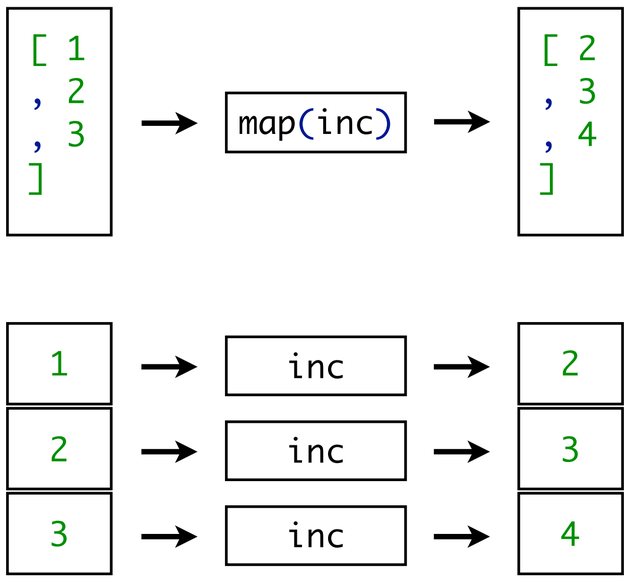
- optional strategy parameters

```
f(x,y): lhs -> rhs
```

- optional term parameters

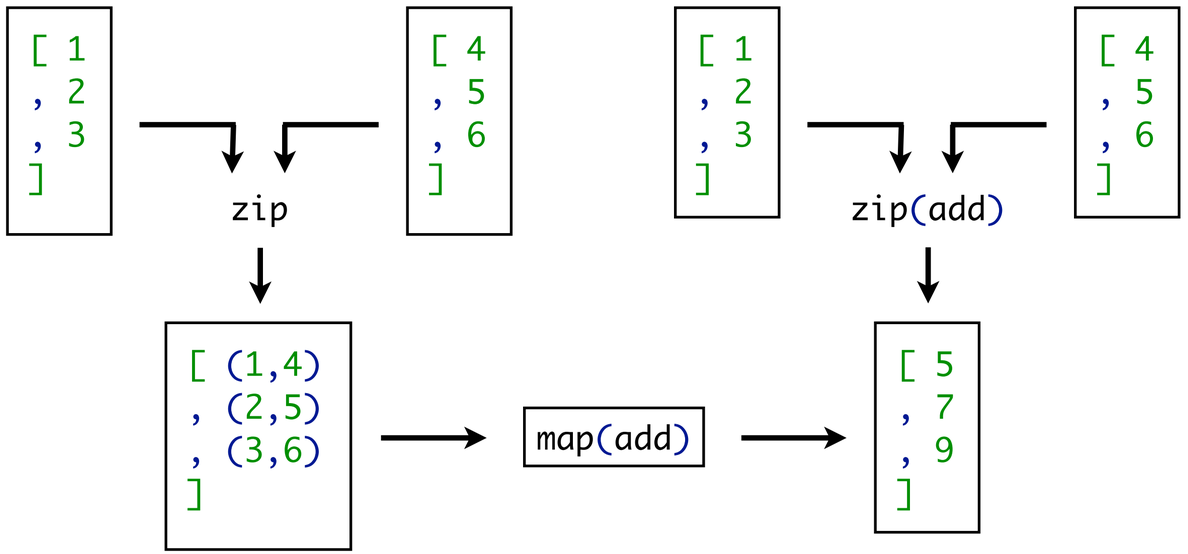
```
f: lhs -> rhs
```

Parameterized Rewrite Rules: Map



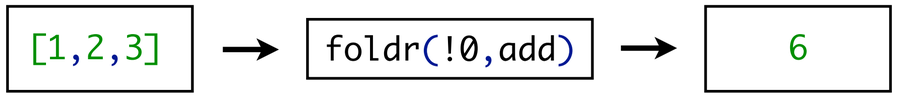

```
map(s): []     -> []
map(s): [x|xs] -> [<s> x | <map(s)> xs]
```

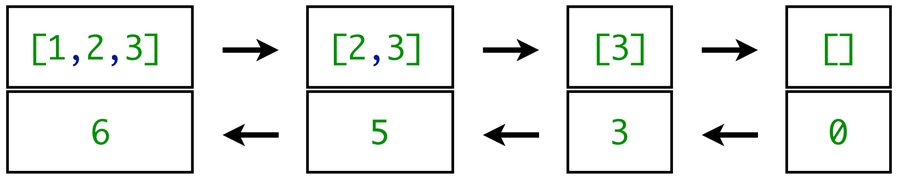
Parameterized Rewrite Rules: Zip




```
zip(s): ([],[])          -> []
zip(s): ([x|xs],[y|ys]) -> [<s> (x,y) | <zip(s)> (xs,ys)]

zip = zip(id)
```

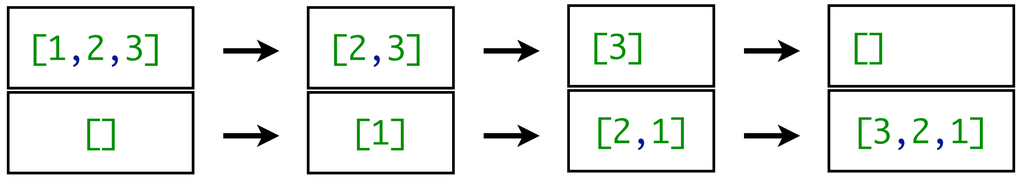
Parameterized Rewrite Rules: Fold






```
foldr(s1,s2): []     -> <s1>
foldr(s1,s2): [x|xs] -> <s2> (x,<foldr(s1,s2)> xs)
```

Parameterized Rewrite Rules: Inverse




```
inverse(|is): []     -> is
inverse(|is): [x|xs] -> <inverse(|[x|is])> xs
```

Traversal Strategies

Term Rewriting for Program Transformation

Term Rewriting

- apply set of rewrite rules exhaustively

Advantages

- First-order terms describe abstract syntax
- Rewrite rules express basic transformation rules (operationalizations of the algebraic laws of the language.)
- Rules specified separately from strategy

Limitations

- Rewrite systems for programming languages often non-terminating and/or non-confluent
- In general: do not apply all rules at the same time or apply all rules under all circumstances

Term Rewriting for Program Transformation

```
signature
  sorts Prop
  constructors
    False : Prop
    True  : Prop
    Atom  : String -> Prop
    Not   : Prop -> Prop
    And   : Prop * Prop -> Prop
    Or    : Prop * Prop -> Prop
rules
  DAOL  : And(Or(x, y), z) -> Or(And(x, z), And(y, z))
  DAOR  : And(z, Or(x, y)) -> Or(And(z, x), And(z, y))
  DOAL  : Or(And(x, y), z) -> And(Or(x, z), Or(y, z))
  DOAR  : Or(z, And(x, y)) -> And(Or(z, x), Or(z, y))
  DN    : Not(Not(x))      -> x
  DMA   : Not(And(x, y))   -> Or(Not(x), Not(y))
  DMO   : Not(Or(x, y))    -> And(Not(x), Not(y))
```

Term Rewriting for Program Transformation

```
signature
  sorts Prop
  constructors
    False : Prop
    True  : Prop
    Atom  : String -> Prop
    Not   : Prop -> Prop
    And   : Prop * Prop -> Prop
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rules
  DAOL  : And(Or(x, y), z) -> Or(And(x, z), And(y, z))
  DAOR  : And(z, Or(x, y)) -> Or(And(z, x), And(z, y))
  DOAL  : Or(And(x, y), z) -> And(Or(x, z), Or(y, z))
  DOAR  : Or(z, And(x, y)) -> And(Or(z, x), Or(z, y))
  DN    : Not(Not(x))      -> x
  DMA   : Not(And(x, y))   -> Or(Not(x), Not(y))
  DMO   : Not(Or(x, y))    -> And(Not(x), Not(y))
```

This is a non-terminating rewrite system

Encoding Control with Recursive Rewrite Rules

Common solution

- Introduce additional constructors that achieve normalization under a restricted set of rules
- Replace a 'pure' rewrite rule

  p_1 `->` p_2

  with a functionalized rewrite rule:

  `f :` p_1 `->` p_2'

  applying f recursively in the right-hand side
- Normalize terms `f(t)` with respect to these rules
- The function now controls where rules are applied

Recursive Rewrite Rules: Disjunctive Normal Form

```
dnf  : True          -> True
dnf  : False         -> False
dnf  : Atom(x)       -> Atom(x)
dnf  : Not(x)        -> <not>(<dnf>x)
dnf  : And(x,y)      -> <and>(<dnf>x,<dnf>y)
dnf  : Or(x,y)       -> Or(<dnf>x,<dnf>y)

and1 : (Or(x,y),z)   -> Or(<and>(x,z),<and>(y,z))
and2 : (z,Or(x,y))   -> Or(<and>(z,x),<and>(z,y))
and3 : (x,y)          -> And(x,y)
and  = and1 <+ and2 <+ and3

not1 : Not(x)        -> x
not2 : And(x,y)      -> Or(<not>(x),<not>(y))
not3 : Or(x,y)       -> <and>(<not>(x),<not>(y))
not4 : x             -> Not(x)
not  = not1 <+ not2 <+ not3 <+ not4
```

Analysis

Functional encoding has two main problems

Overhead due to explicit specification of *traversal*

- A traversal rule needs to be defined for each constructor in the signature and for each transformation.

Separation of rules and strategy is lost

- Rules and strategy are completely *intertwined*
- Intertwining makes it more difficult to *understand* the transformation
- Intertwining makes it impossible to *reuse* the rules in a different transformation.

Analysis

Language Complexity

Traversal overhead and reuse of rules is important, considering the complexity of real programming languages:

language	# constructors
Tiger	65
C	140
Java 5	325
COBOL	300–1200

Requirements

- Control over application of rules
- No traversal overhead
- Separation of rules and strategies

Programmable Rewriting Strategies

Programmable Rewriting Strategies

- Select rules to be applied in specific transformation
- Select strategy to control their application
- Define your own strategy if necessary
- Combine strategie

Idioms

- Cascading transformations
- One-pass traversal
- Staged transformation
- Local transformation

Strategic Idioms

Rules for rewriting proposition formulae

```
signature
  sorts Prop
  constructors
    False : Prop
    True  : Prop
    Atom  : String -> Prop
    Not   : Prop -> Prop
    And   : Prop * Prop -> Prop
    Or    : Prop * Prop -> Prop
rules
  DAOL  : And(Or(x, y), z) -> Or(And(x, z), And(y, z))
  DAOR  : And(z, Or(x, y)) -> Or(And(z, x), And(z, y))
  DOAL  : Or(And(x, y), z) -> And(Or(x, z), Or(y, z))
  DOAR  : Or(z, And(x, y)) -> And(Or(z, x), Or(z, y))
  DN    : Not(Not(x))      -> x
  DMA   : Not(And(x, y))   -> Or(Not(x), Not(y))
  DMO   : Not(Or(x, y))    -> And(Not(x), Not(y))
```

Strategic Idioms: Cascading Transformation

Cascading Transformations

- Apply small, independent transformations in combination
- Accumulative effect of small rewrites

```
simplify = innermost(R1 <+ ... <+ Rn)
```

disjunctive normal form

```
dnf = innermost(DAOL <+ DAOR <+ DN <+ DMA <+ DMO)
```

conjunctive normal form

```
cnf = innermost(DOAL <+ DOAR <+ DN <+ DMA <+ DMO)
```

Strategic Idioms: One-Pass Traversal

One-pass Traversal

- Apply rules in a single traversal over a program tree

```
simplify1  = downup(repeat(R1 <+ ... <+ Rn))
simplify2  = bottomup(repeat(R1 <+ ... <+ Rn))
```

constant folding

```
Eval : And(True, e) -> e
Eval : And(False, e) -> False
Eval : ...

eval = bottomup(try(Eval))
```

Strategic Idioms: One-Pass Traversal

Example: Desugarings

```
DefN  : Not(x)      -> Impl(x, False)
DefI  : Impl(x, y) -> Or(Not(x), y)
DefE  : Eq(x, y)    -> And(Impl(x, y), Impl(y, x))
DefO1 : Or(x, y)    -> Impl(Not(x), y)
DefO2 : Or(x, y)    -> Not(And(Not(x), Not(y)))
DefA1 : And(x, y)   -> Not(Or(Not(x), Not(y)))
DefA2 : And(x, y)   -> Not(Impl(x, Not(y)))
IDefI : Or(Not(x), y) -> Impl(x, y)
IDefE : And(Impl(x, y), Impl(y, x)) -> Eq(x, y)

desugar = topdown(try(DefI <+ DefE))

impl-nf  = topdown(repeat(DefN <+ DefA2 <+ DefO1 <+ DefE))
```

Strategic Idioms: Staged Transformation

Staged Transformation

- Transformations are not applied to a subject term all at once, but rather in stages
- In each stage, only rules from some particular subset of the entire set of available rules are applied.

```
simplify =
  innermost(A1 <+ ... <+ Ak)
  ; innermost(B1 <+ ... <+ Bl)
  ; ...
  ; innermost(C1 <+ ... <+ Cm)
```

Strategic Idioms: Local Transformation

Local transformation

- Apply rules only to selected parts of the subject program

```
transformation =
  alltd(
    trigger-transformation
    ; innermost(A1 <+ ... <+ An)
  )
```

Traversal Combinators

Realizing Term Traversal

Requirements

- Control over application of rules
- No traversal overhead
- Separation of rules and strategies

Many ways to traverse a tree

- Bottom-up
- Top-down
- Innermost
- ...

What are the primitives of traversal?

Traversal Primitives

One-level traversal operators

- Apply a strategy to one or more direct subterms

Congruence: data-type specific traversal

- Apply a different strategy to each argument of a specific constructor

Generic traversal

- All: apply to all direct subterms
- One: apply to one direct subterm
- Some: apply to as many direct subterms as possible, and at least one

Congruence Operators

Congruence operator: data-type specific traversal

- Syntax: $c(s_1, \ldots, s_n)$ for each n-ary constructor c
- Apply strategies to direct sub-terms of a c term

```
Plus(Int("14"),Int("3"))
stratego> Plus(!Var("a"), id)
Plus(Var("a"),Int("3"))
```

```
map(s) = [] + [s | map(s)])

fetch(s) = [s | id] <+ [id | fetch(s)]

filter(s) =
  [] + ([s | filter(s)] <+ ?[_|<id>]; filter(s))
```

Generic Traversal

Data-type specific traversal requires tedious enumeration of cases

Even if traversal behaviour is uniform

Generic traversal allows concise specification of default traversals

Generic Traversal

Visiting all subterms

- Syntax: `all(`*s*`)`
- Apply strategy *s* to all direct sub-terms

```
Plus(Int("14"),Int("3"))
stratego> all(!Var("a"))
Plus(Var("a"),Var("a"))
```

Generic Traversal

Visiting all subterms

- Syntax: `all(`*s*`)`
- Apply strategy *s* to all direct sub-terms

```
Plus(Int("14"),Int("3"))
stratego> all(!Var("a"))
Plus(Var("a"),Var("a"))
```

```
bottomup(s) = all(bottomup(s)); s
topdown(s)  = s; all(topdown(s))
downup(s)   = s; all(downup(s)); s
alltd(s)    = s <+ all(alltd(s))
```

Generic Traversal

Visiting all subterms

- Syntax: `all(`*s*`)`
- Apply strategy *s* to all direct sub-terms

```
Plus(Int("14"),Int("3"))
stratego> all(!Var("a"))
Plus(Var("a"),Var("a"))
```

```
bottomup(s) = all(bottomup(s)); s
topdown(s)  = s; all(topdown(s))
downup(s)   = s; all(downup(s)); s
alltd(s)    = s <+ all(alltd(s))
```

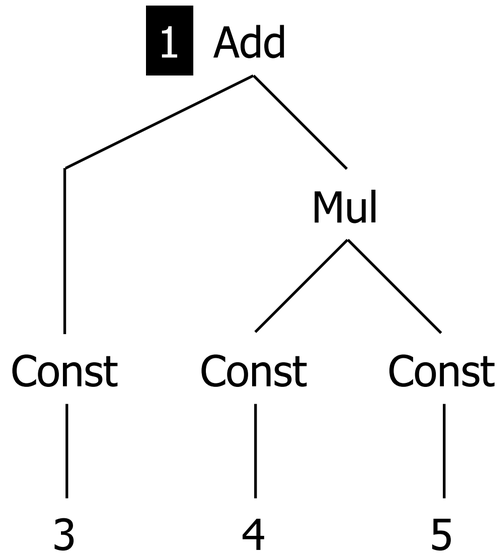
```
const-fold =
  bottomup(try(EvalBinOp <+ EvalCall <+ EvalIf))
```

Traversal: Topdown

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

topdown(s) = s ; all(topdown(s))

topdown(switch)
```

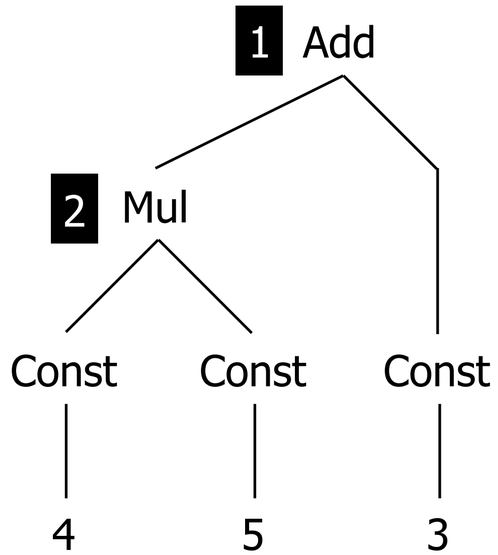


Traversal: Topdown

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

topdown(s) = s ; all(topdown(s))

topdown(switch)
```

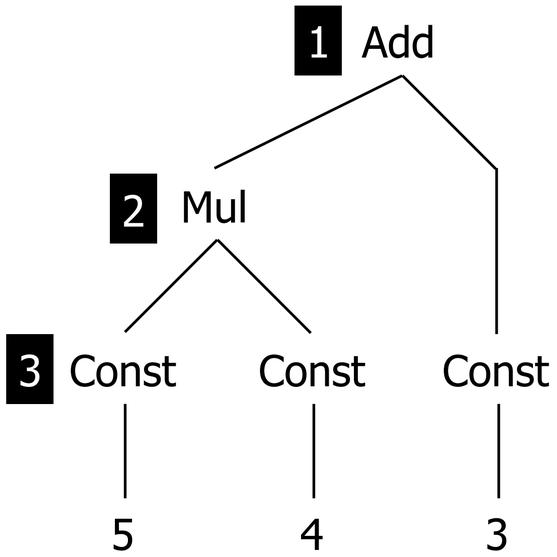


Traversal: Topdown

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

topdown(s) = s ; all(topdown(s))

topdown(switch)
```

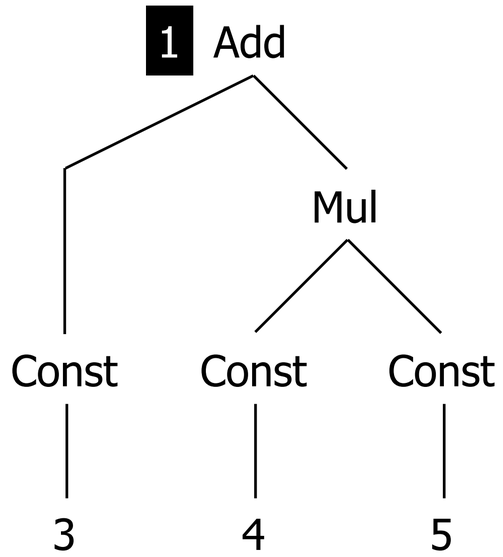


Traversal: Topdown/Try

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

topdown(s) = s ; all(topdown(s))

topdown(try(switch))
```

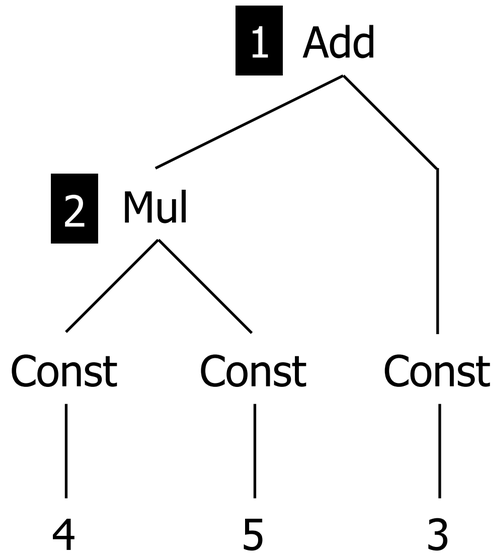


Traversal: Topdown/Try

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

topdown(s) = s ; all(topdown(s))

topdown(try(switch))
```

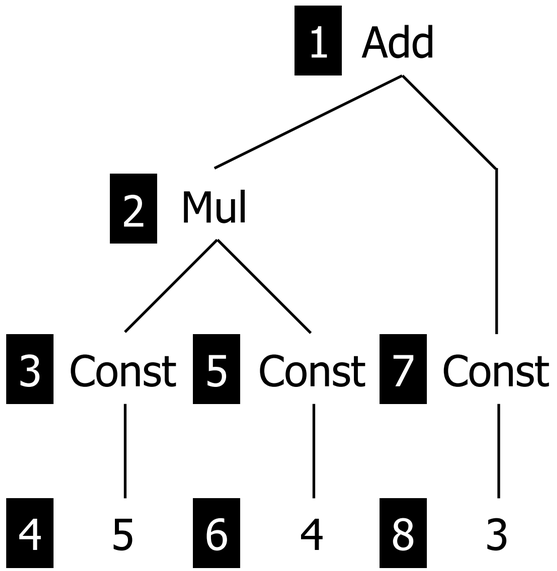


Traversal: Topdown/Try

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

topdown(s) = s ; all(topdown(s))

topdown(try(switch))
```

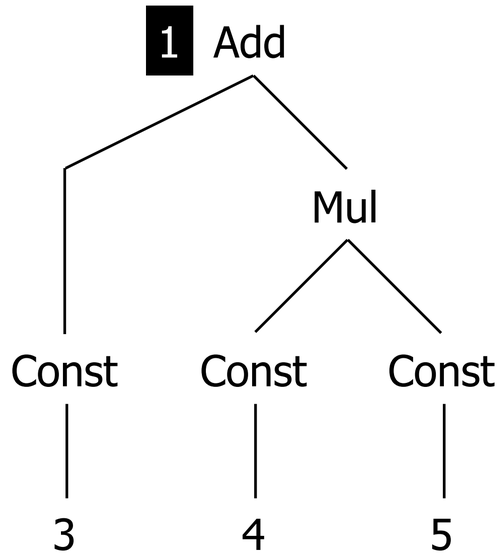


Traversal: Alltd

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

alltd(s) = s <+ all(alltd(s))

alltd(switch)
```

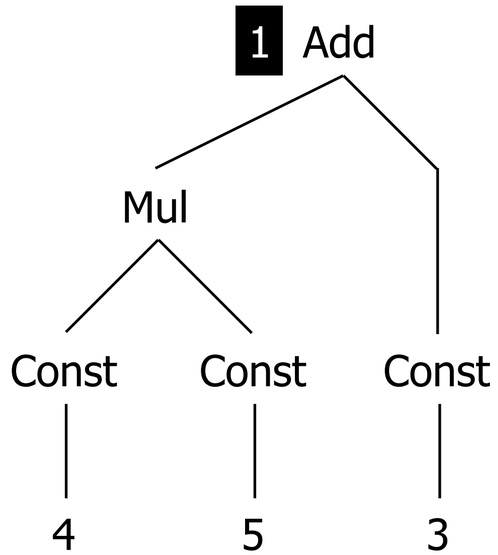


Traversal: Alltd

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

alltd(s) = s <+ all(alltd(s))

alltd(switch)
```

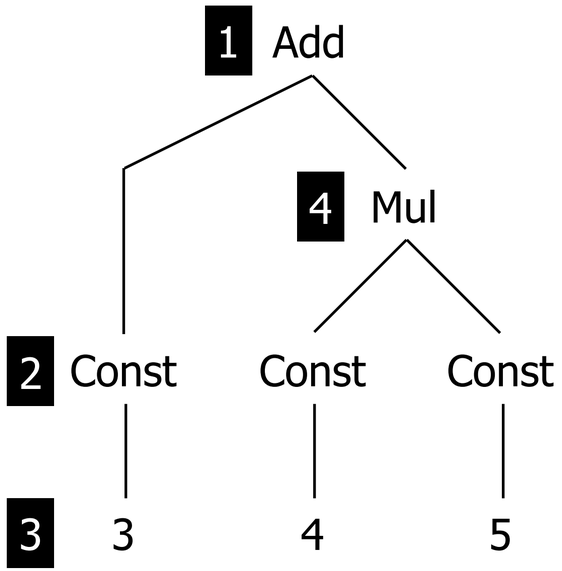


Traversal: bottomup

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

bottomup(s) = all(bottomup(s)) ; s

bottomup(switch)
```

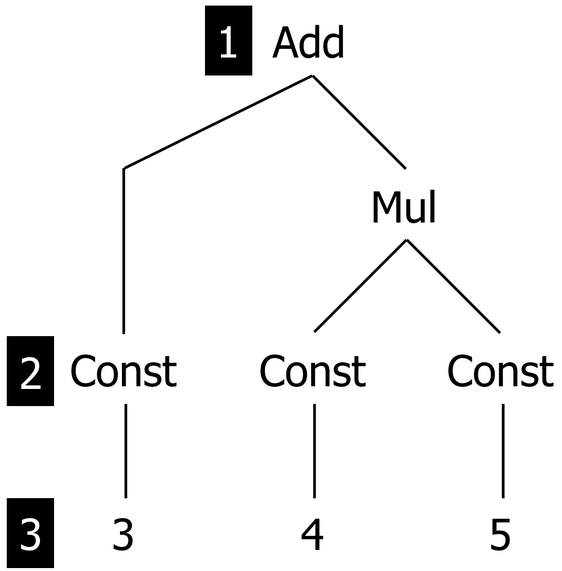


Traversal: Bottomup

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

bottomup(s) = all(bottomup(s)) ; s

bottomup(try(switch))
```

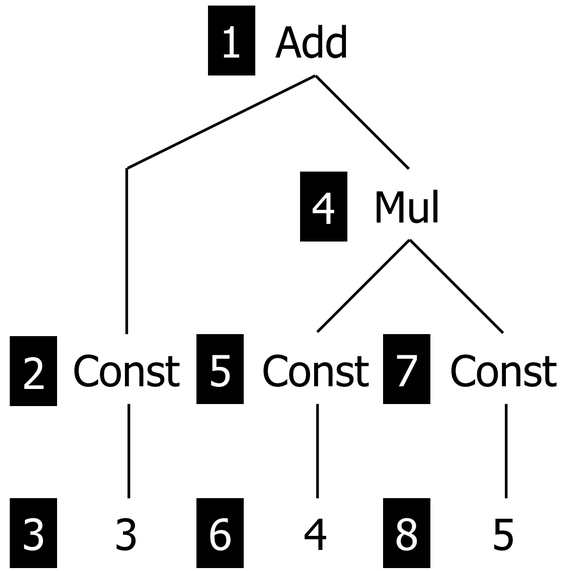


Traversal: Bottomup

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

bottomup(s) = all(bottomup(s)) ; s

bottomup(try(switch))
```

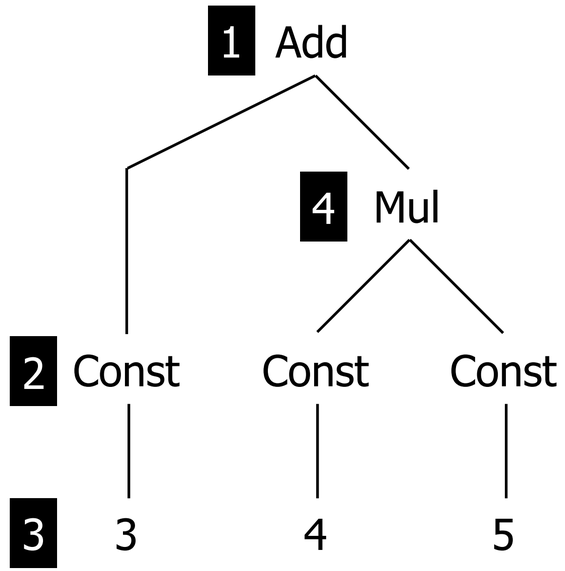


Traversal: Bottomup

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

bottomup(s) = all(bottomup(s)) ; s

bottomup(try(switch))
```

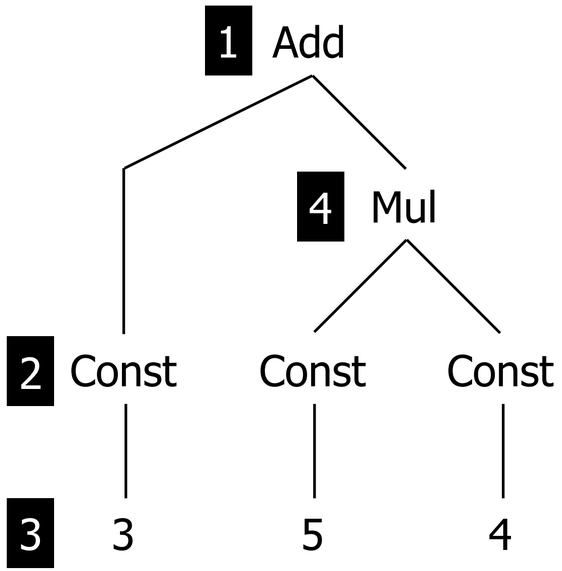


Traversal: Bottomup

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

bottomup(s) = all(bottomup(s)) ; s

bottomup(try(switch))
```

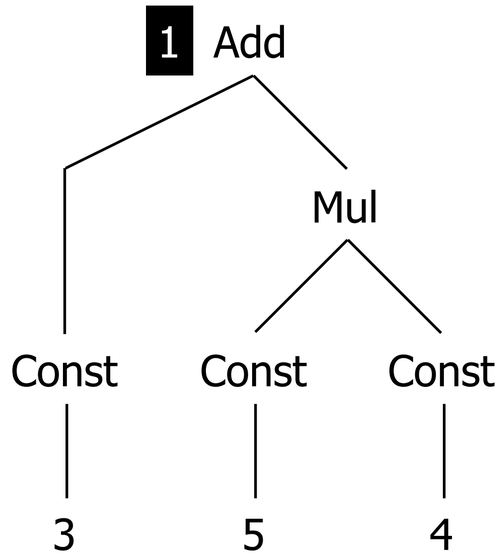


Traversal: Bottomup

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

bottomup(s) = all(bottomup(s)) ; s

bottomup(try(switch))
```

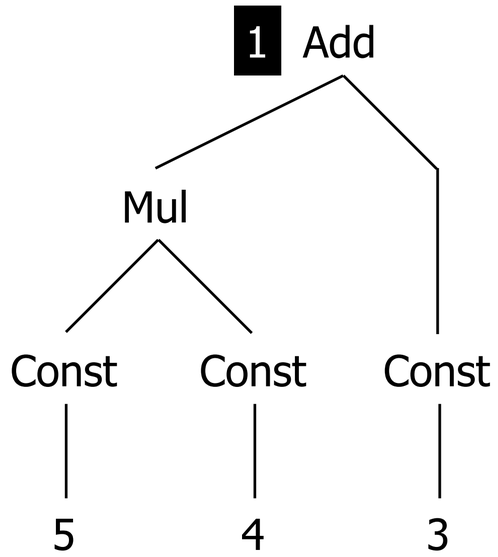


Traversal: Bottomup

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

bottomup(s) = all(bottomup(s)) ; s

bottomup(try(switch))
```



Generic Traversal: Desugaring

Example: Desugaring Expressions

```
DefAnd     : And(e1, e2) -> If(e1, e2, Int("0"))

DefPlus    : Plus(e1, e2) -> BinOp(PLUS(), e1, e2)

DesugarExp = DefAnd <+ DefPlus <+ ...

desugar    = topdown(try(DesugarExp)
```

```
IfThen(
  And(Var("a"),Var("b")),
  Plus(Var("c"),Int("3")))
stratego> desugar
IfThen(
  If(Var("a"),Var("b"),Int("0")),
  BinOp(PLUS,Var("c"),Int("3")))
```

Generic Traversal: Fixed-Point Traversal

Fixed-point traversal

```
innermost(s) = bottomup(try(s; innermost(s)))
```

Normalization

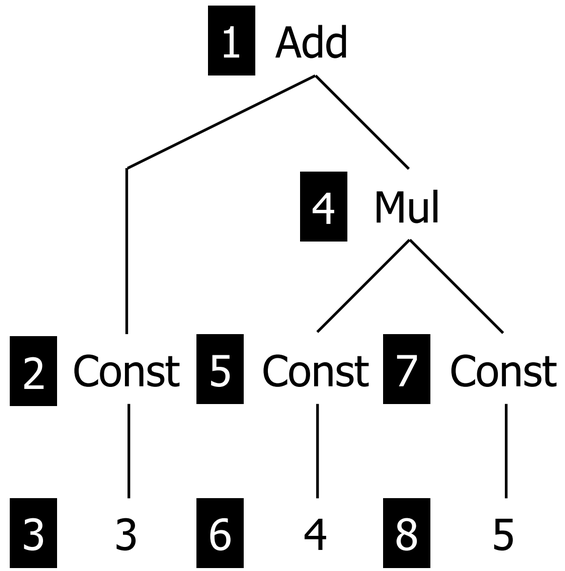
```
dnf = innermost(DAOL <+ DAOR <+ DN <+ DMA <+ DMO)
cnf = innermost(DOAL <+ DOAR <+ DN <+ DMA <+ DMO)
```

Traversal: Innermost

```
switch: Add(e1, e2) -> Add(e2, e1)
switch: Mul(e1, e2) -> Mul(e2, e1)

innermost(s) = bottomup(try(s ; innermost(s)))

innermost(switch)
```



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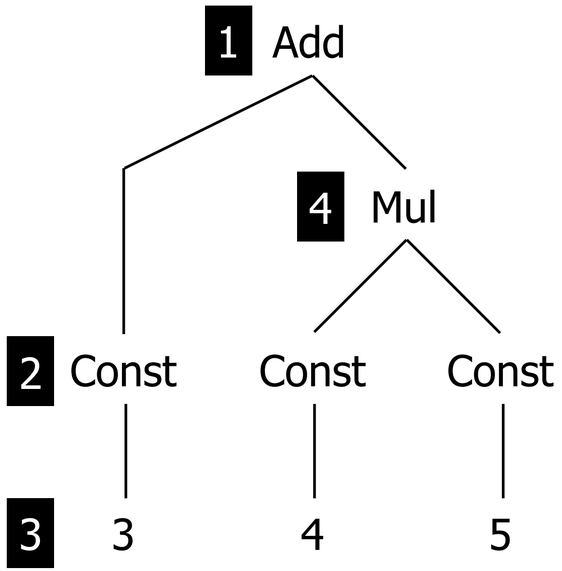

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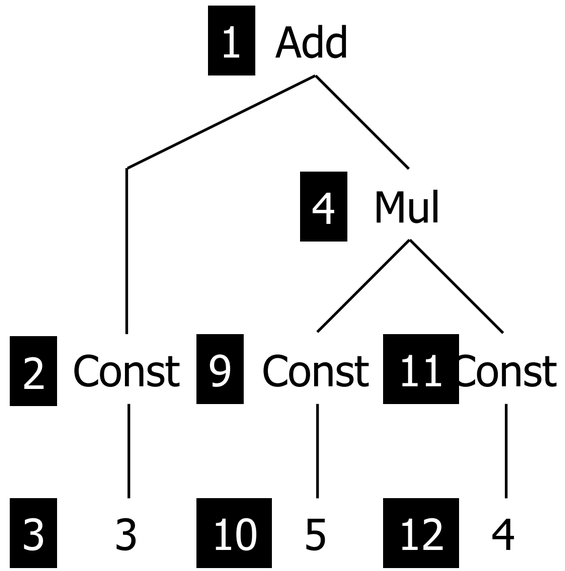

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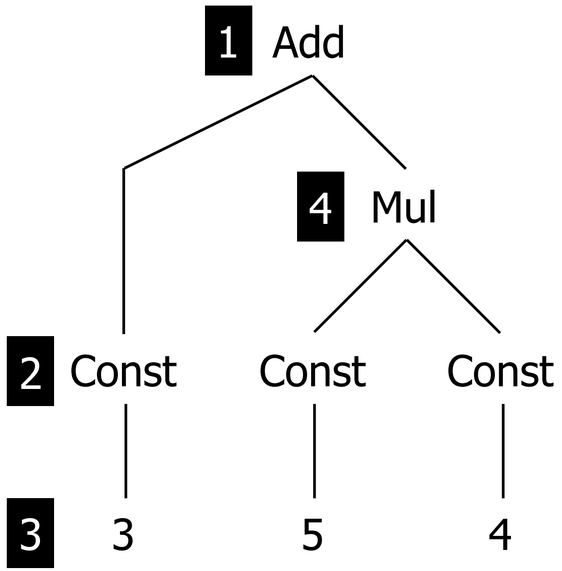

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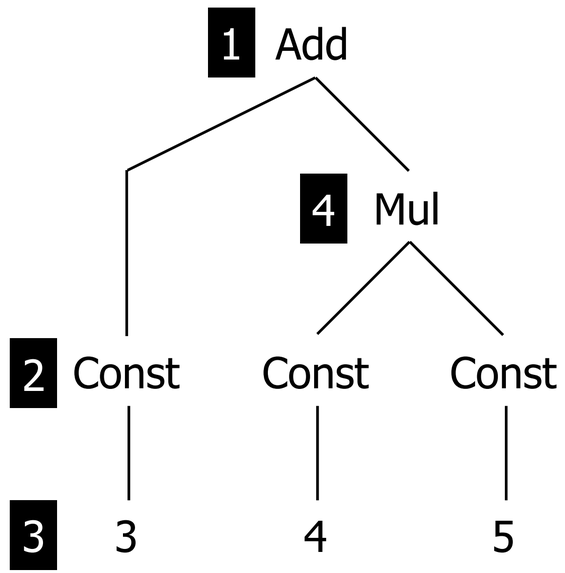

Generic Traversal: One

Visiting One Subterms

- Syntax: `one(`*s*`)`
- Apply strategy *s* to exactly one direct sub-terms

```
Plus(Int("14"),Int("3"))
stratego> one(!Var("a"))
Plus(Var("a"),Int("3"))
```

Generic Traversal: One

Visiting One Subterms

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- Apply strategy *s* to exactly one direct sub-terms

```
Plus(Int("14"),Int("3"))
stratego> one(!Var("a"))
Plus(Var("a"),Int("3"))
```

```
oncetd(s) = s <+ one(oncetd(s))
oncebu(s) = one(oncebu(s)) <+ s
spinetd(s) = s; try(one(spinetd(s)))
spinebu(s) = try(one(spinebu(s))); s
```

Generic Traversal: One

Visiting One Subterms

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- Apply strategy *s* to exactly one direct sub-terms

```
Plus(Int("14"),Int("3"))
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oncetd(s) = s <+ one(oncetd(s))
oncebu(s) = one(oncebu(s)) <+ s
spinetd(s) = s; try(one(spinetd(s)))
spinebu(s) = try(one(spinebu(s))); s
```

```
contains(|t) = oncetd(?t)
```

Generic Traversal: One

Visiting One Subterms

- Syntax: one(*s*)
- Apply strategy *s* to exactly one direct sub-terms

```
Plus(Int("14"),Int("3"))
stratego> one(!Var("a"))
Plus(Var("a"),Int("3"))
```

```
oncetd(s) = s <+ one(oncetd(s))
oncebu(s) = one(oncebu(s)) <+ s
spinetd(s) = s; try(one(spinetd(s)))
spinebu(s) = try(one(spinebu(s))); s
```

```
contains(|t) = oncetd(?t)
```

```
reduce(s) = repeat(rec x(one(x) + s))
outermost(s) = repeat(oncetd(s))
innermostI(s) = repeat(oncebu(s))
```

Generic Traversal: Some

Visiting some subterms (but at least one)

- Syntax: `some(s)`
- Apply strategy `s` to as many direct subterms as possible, and at least one

```
Plus(Int("14"),Int("3"))
stratego> some(?Int(_); !Var("a"))
Plus(Var("a"),Var("a"))
```

One-pass traversals

```
sometd(s) = s <+ some(sometd(s))
somebu(s) = some(somebu(s)) <+ s
```

Fixed-point traversal

```
reduce-par(s) = repeat(rec x(some(x) + s))
```

Summary

Summary

- Tangling of rules and strategy (traversal) considered harmful
- Separate traversal from rules
- One-level traversal primitives allow wide range of traversals

Type-Unifying Transformations

Type Preserving vs Type Unifying

Transformations are type preserving

- Structural transformation
- Types stay the same
- Application: transformation
- Examples: simplification, optimization, ...

Collections are type unifying

- Terms of different types mapped onto one type
- Application: analysis
- Examples: free variables, uncaught exceptions, call-graph

Example Problems

`term-size`

- Count the number of nodes in a term

`occurrences`

- Count number of occurrences of a subterm in a term

`collect-vars`

- Collect all variables in expression

`free-vars`

- Collect all *free* variables in expression

`collect-uncaught-exceptions`

- Collect all *uncaught* exceptions in a method

List Implementation: Size (Number of Nodes)

Replacing `Nil` by `s1` and `Cons` by `s2`

```
foldr(s1, s2) =
  []; s1 <+ \ [y|ys] -> <s2>(y, <foldr(s1, s2)> ys) \
```

Add the elements of a list of integers

```
sum = foldr(!0, add)
```

Fold and apply `f` to the elements of the list

```
foldr(s1, s2, f) =
  []; s1 <+ \ [y|ys] -> <s2>(<f>y,<foldr(s1,s2,f)>ys) \
```

Length of a list

```
length = foldr(!0, add, !1)
```

List Implementation: Number of Occurrences

Number of occurrences in a list

```
list-occurrences(s) = foldr(!0, add, s < !1 + !0)
```

Number of local variables in a list

```
list-occurrences(?ExprName(_))
```

List Implementation: Collect Terms

Filter elements in a list for which s succeeds

```
filter(s) = [] + [s | filter(s)] <+ ?[_|<filter(s)>]
```

Collect local variables in a list

```
filter(ExprName(id))
```

Collect local variables in first list, exclude elements in second list

```
(filter(ExprName(id)),id); diff
```

Folding Expressions

Generalize folding of lists to arbitrary terms

Example: Java expressions

```
fold-exp(plus, minus, assign, cond, ...) =
 rec f(
    \ Plus(e1, e2) -> <plus>(<f>e1, <f>e2) \
  + \ Minus(e1, e2) -> <minus>(<f>e1, <f>e2) \
  + \ Assign(lhs, e) -> <assign>(<f>lhs, <f>e) \
  + \ Cond(e1, e2, e3) -> <cond>(<f>e1, <f>e2, <f>e3) \
  + ...
  )
```

Term-Size with Fold

```
term-size =
  fold-exp(MinusSize, PlusSize, AssignSize, ...)

MinusSize :
  Minus(e1, e2) -> <add> (1, <add> (e1, e2))

PlusSize :
  Plus(e1, e2) -> <add> (1, <add> (e1, e2))

AssignSize :
  Assign(lhs, e) -> <add> (1, <add> (lhs, e))

// etc.
```

Limitations of Fold

Definition of fold

- One parameter for each constructor
- Define traversal for each constructor

Instantiation of fold

- One rule for each constructor
- Default behaviour not generically specified

Defining Fold with Generic Traversal

Fold is bottomup traversal:

```
fold-exp(s) =
  bottomup(s)

term-size =
  fold-exp(MinusSize <+ PlusSize <+ AssignSize <+ ...)
```

Definition of fold

- Recursive application to subterms defined generically
- One parameter: rules combined with choice

Instantiation: default behaviour not generically specified

Generic Term Deconstruction (1)

Specific definitions

```
MinusSize :
  Minus(e1, e2) -> <add> (1, <add> (e1, e2))

AssignSize :
  Assign(lhs, e) -> <add> (1, <add> (lhs, e))
```

Generic definition

```
CSize :
  C(e1, e2, ...) -> <add>(1,<add>(e1,<add>(e2, ...)))
```

Requires generic decomposition of constructor application

Generic Term Deconstruction (2)

Generic Term Deconstruction

- Syntax: $?p_1\#(p_2)$
- Semantics: when applied to a term $c(t_1, \ldots, t_n)$ matches
  - "c" against p_1
  - $[t_1, \ldots, t_n]$ against p_2
- Decompose constructor application into its constructor name and list of direct subterms

```
Plus(Lit(Deci("1")), ExprName(Id("x")))
stratego> ?c#(xs)
stratego> :binding c
variable c bound to "Plus"
stratego> :binding xs
variable xs bound to [Lit(Deci("1")), ExprName(Id("x"))]
```

Crush/3

Definition of Crush

```
crush(nul, sum, s) :
  _#(xs) -> <foldr(nul, sum, s)> xs
```

Applications of Crush

```
node-size =


term-size =


om-occurrences(s) =


occurrences(s) =
```

Crush/3

Definition of Crush

```
crush(nul, sum, s) :
  _#(xs) -> <foldr(nul, sum, s)> xs
```

Applications of Crush

```
node-size =
  crush(!0, add, !1)

term-size =


om-occurrences(s) =


occurrences(s) =
```

Crush/3

Definition of Crush

```
crush(nul, sum, s) :
  _#(xs) -> <foldr(nul, sum, s)> xs
```

Applications of Crush

```
node-size =
  crush(!0, add, !1)

term-size =
  crush(!1, add, term-size)

om-occurrences(s) =


occurrences(s) =
```

Crush/3

Definition of Crush

```
crush(nul, sum, s) :
  _#(xs) -> <foldr(nul, sum, s)> xs
```

Applications of Crush

```
node-size =
  crush(!0, add, !1)

term-size =
  crush(!1, add, term-size)

om-occurrences(s) =
  if s then !1 else crush(!0, add, om-occurrences(s)) end

occurrences(s) =
```

Crush/3

Definition of Crush

```
crush(nul, sum, s) :
  _#(xs) -> <foldr(nul, sum, s)> xs
```

Applications of Crush

```
node-size =
  crush(!0, add, !1)

term-size =
  crush(!1, add, term-size)

om-occurrences(s) =
  if s then !1 else crush(!0, add, om-occurrences(s)) end

occurrences(s) =
  <add> (<if s then !1 else !0 end>,
         <crush(!0, add, occurrences(s))>)
```

McCabe's cyclomatic complexity

```
public class Metric {
  public int foo() {
    if(1 > 2)
      return 0;
    else
      if(3 < 4)
        return 1;
      else
        return 2;
    if(5 > 6)
      return 3;
  }

  public int bar() {
    for(int i=0; i<5; i++) {}
  }
}
```

McCabe's cyclomatic complexity

- Computes the number of decision points in a function.
- Measure of minimum number of exection paths.
- Each control flow construct introduces another possible path.

```
cyclomatic-complexity =
  occurrences(is-control-flow)
  ; inc

is-control-flow =
  ?If(_, _)
  <+ ?If(_, _, _)
  <+ ?While(_, _)
  <+ ?For(_, _, _ ,_)
  <+ ?SwitchGroup(_, _)
```

NPATH complexity

```
public class Metric {
  public int foo() {
    if(1 > 2)
      return 0;
    else
      if(3 < 4)
        return 1;
      else
        return 2;
    if(5 > 6)
      return 3;
  }

  public int bar() {
    for(int i=0; i<5; i++) {}
  }
}
```

NPATH complexity

Complexity Analysis Algorithm (improved)

- Number of acyclic execution paths (not just nodes)
- Want to take into account the nesting of the control flow statements.
- Cost of a given control flow construct depends on its nesting level.

NPATH complexity: Implementation

```
npath-complexity =
  rec rec(
     ?Block(<map(rec)>)
     ; foldr(!1, mul)
  <+ {extra:
       is-control-flow
       ; where(extra := <AddPaths <+ !0>)
       ; crush(!0, add, rec)
       ; <add> (<id>, extra)
     }
  <+ is-BlockStm ; !1
  <+ crush(!0, add, rec)
  )

AddPaths: If(_, _) -> 1
AddPaths: While(_, _) -> 1
AddPaths: For(_, _, _, _) -> 1
```

Collect

Collect all (outermost) sub-terms for which `s` succeeds

```
collect(s) =
```

Collect all sub-terms for which `s` succeeds

```
collect-all(s) =
```

Collect all local variables in an expression

```
get-exprnames = collect(ExprName(id))
```

Collect

Collect all (outermost) sub-terms for which `s` succeeds

```
collect(s) =
  ![<s>] <+ crush(![], union, collect(s))
```

Collect all sub-terms for which `s` succeeds

```
collect-all(s) =
```

Collect all local variables in an expression

```
get-exprnames = collect(ExprName(id))
```

Collect

Collect all (outermost) sub-terms for which `s` succeeds

```
collect(s) =
  ![<s>] <+ crush(![], union, collect(s))
```

Collect all sub-terms for which `s` succeeds

```
collect-all(s) =
  ![<s> | <crush(![], union, collect-all(s))>]
  <+ crush(![], union, collect-all(s))
```

Collect all local variables in an expression

```
get-exprnames = collect(ExprName(id))
```

Uncaught Exceptions (1)

Collect all uncaught exceptions

- Collect thrown exceptions
- Remove caught exceptions

Example

```
void thrower() throws
    IOException, Exception, NullPointerException { }

void g() throws Exception {
  try { thrower(); }
  catch(IOException e) {}
}
```

Uncaught exceptions:

Uncaught Exceptions (1)

Collect all uncaught exceptions

- Collect thrown exceptions
- Remove caught exceptions

Example

```
void thrower() throws
    IOException, Exception, NullPointerException { }

void g() throws Exception {
  try { thrower(); }
  catch(IOException e) {}
}
```

Uncaught exceptions: {NullPointerException, Exception}

Uncaught Exceptions (2)

Algorithm

- Recurse over the method definitions.
- Consider control constructs that deal with exceptions:
  - Method invocation and `throw` add uncaught exceptions.
  - `Try/catch` will remove uncaught exceptions.

Uncaught Exceptions (2)

Algorithm

- Recurse over the method definitions.
- Consider control constructs that deal with exceptions:
  - Method invocation and `throw` add uncaught exceptions.
  - `Try/catch` will remove uncaught exceptions.

```
collect-uncaught-exceptions =
  rec rec(
    ThrownExceptions(rec)
    <+ crush(![], union, rec)
  )
```

Uncaught Exceptions (3)

Handling `throw`

```
ThrownExceptions(rec):
  Throw(e) -> <union> ([<type-attr> e], children)
  where
    children := <rec> e
```

Handling method invocation

Uncaught Exceptions (3)

Handling `throw`

```
ThrownExceptions(rec):
  Throw(e) -> <union> ([<type-attr> e], children)
  where
    children := <rec> e
```

Handling method invocation

```
ThrownExceptions(rec):
  e@Invoke(o, args) -> <union> (this, children)
  where
    children := <rec> (o, args)
    ; <compile-time-declaration-attr> e
    ; lookup-method
    ; this := <get-declared-exception-types>
```

Uncaught Exceptions (4)

Handling `try/catch`

```
ThrownExceptions(rec):
  try@Try(body, catches) ->
            <union> (uncaught, <rec> catches)
  where
    uncaught := <rec; remove-all-caught(|try)> body
```

Summary

Summary

Generic term construction and deconstruction support the definition of generic analysis and generic translation problems

Next

Context-sensitive transformation problems

- bound variable renaming
- function/method inlining
- data-flow transformation
- interpretation

Solution: dynamic definition of rewrite rules

Next: Type Checking