Term Rewriting
language specification

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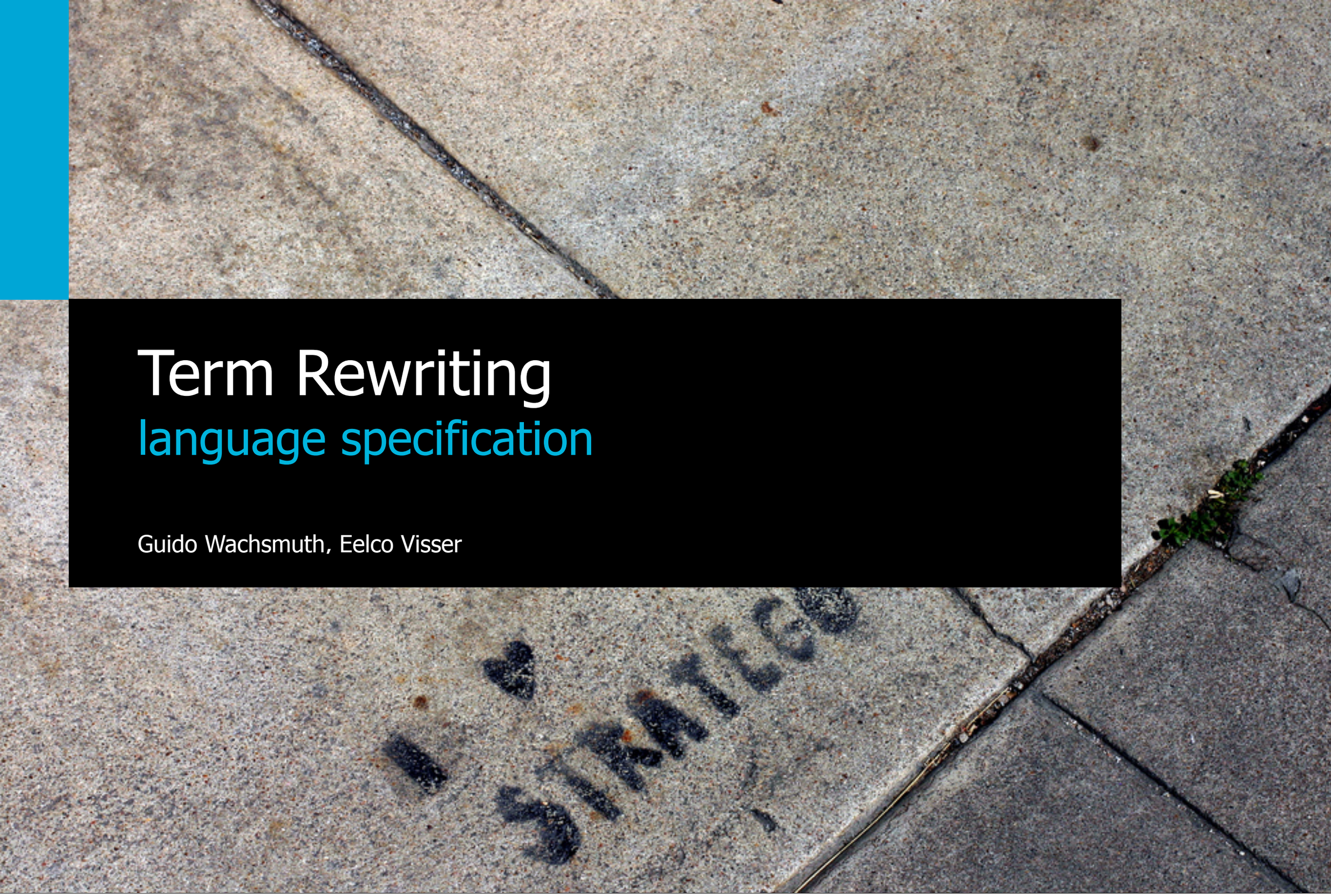
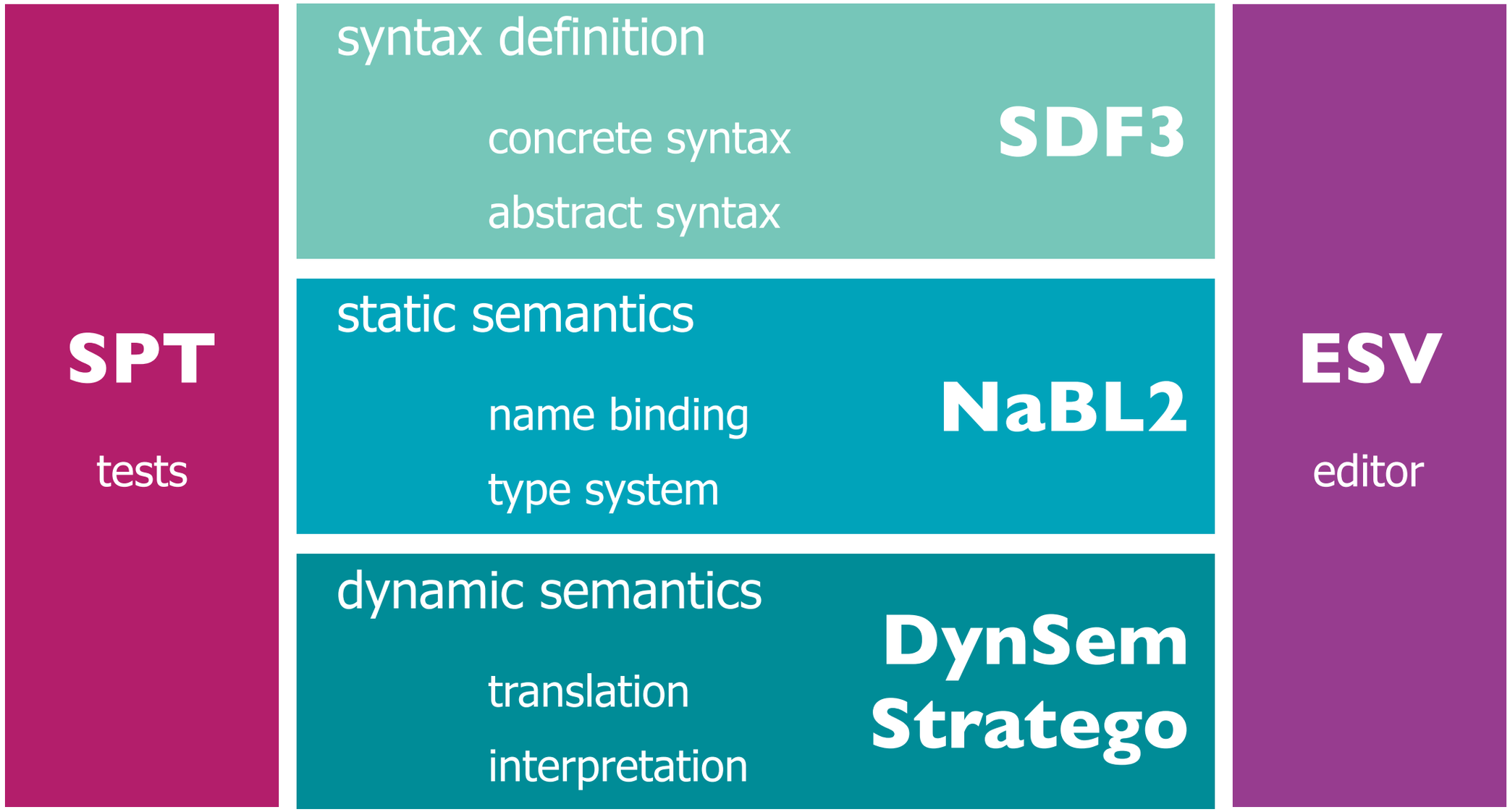
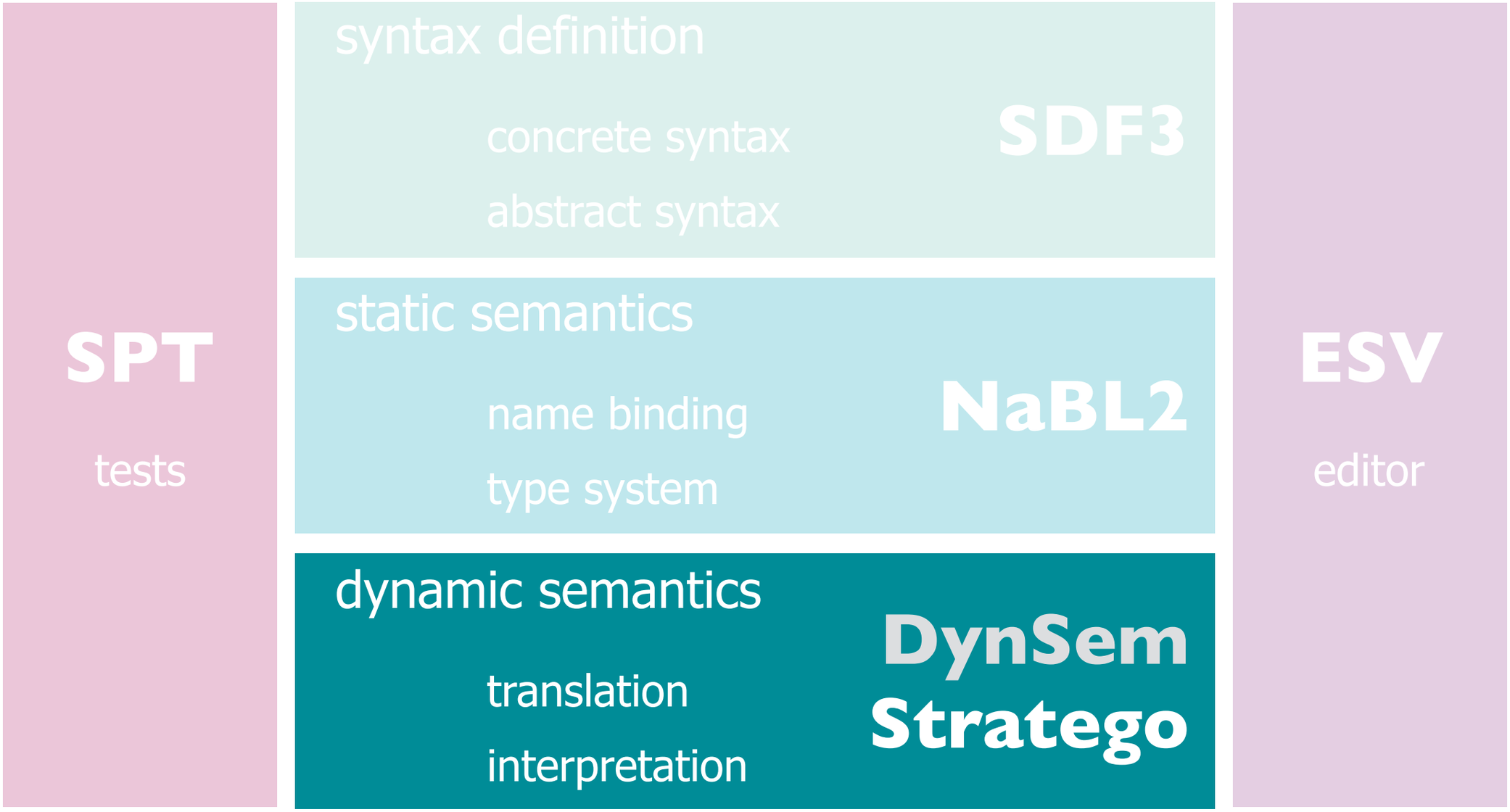


TU Delft

IN4303 2015-2017
Compiler Construction


SPT
tests
syntax definition
concrete syntax
abstract syntax
SDF3
static semantics
name binding
type system
NaBL2
dynamic semantics
translation
interpretation
DynSem
Stratego
ESV
editor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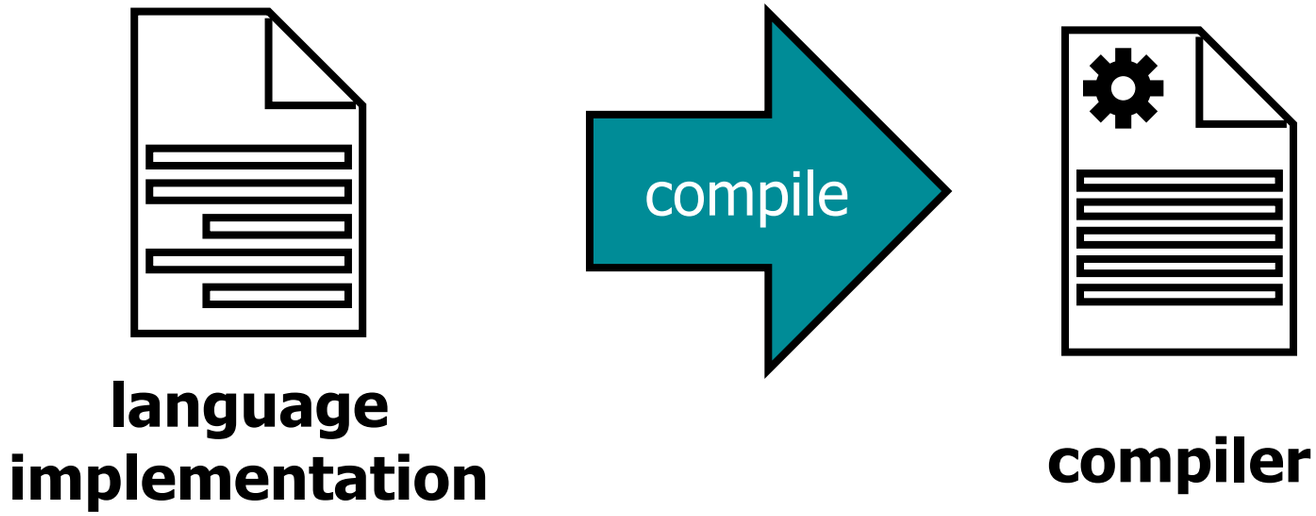
Language Software

compiler construction


meta language facility
THESAURUS

traditional compiler compilers

manual implementation



traditional compiler compilers

compilation + compilation

traditional compiler compilers

compilation + interpretation

Spoofax Language Workbench
manual implementation

Stratego

- declarative DSL
- domain: program transformation
- means to manipulate ASTs
- working on ATerms
- compiles to Java (or C)

Stratego in Spoofax

- static analysis & error checking
- code generation
- semantic editor services

Spoofax Language Workbench
manual implementation

Stratego

- declarative DSL
- domain: program transformation
- means to manipulate ASTs
- working on ATerms
- compiles to Java (or C)

Stratego in Spoofax

- static analysis & error checking
- code generation
- semantic editor services

Note: static analysis is replaced by the higher-level NaBL2 language

Stratego

concepts

signatures

rewrite rules

- transform term to term
- left-hand side
  - pattern matching & variable binding
- right-hand side
  - pattern instantiation & variable substitution

rewrite strategies

- algorithm for applying rewrite rules

Stratego

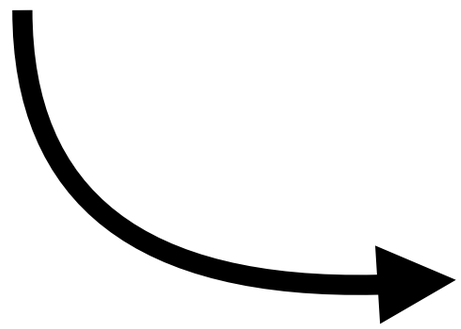
example

```
module desugar

imports

  include/Tiger
  operators

strategies

  desugar-all = innermost(desugar)

rules

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

Terms

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
  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
```

Rewrite Rules

Desugaring

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

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

Desugaring

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

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

```
IfThen(
  Var("x")
, Call(
    "printint"
  , [Var("x")]
  )
)
```

```
IfThenElse(
  Var("x")
, Call(
    "printint"
  , [Var("x")]
  )
, NoVal()
)
```

Desugaring

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

```
if x then
   printint(x)
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```
IfThen(
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, Call(
    "printint"
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)
```

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IfThenElse(
  Var("x")
, Call(
    "printint"
  , [Var("x")]
  )
, NoVal()
)
```

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

Desugaring

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

```
IfThen(
  Var("x")
, Call(
    "printint"
  , [Var("x")]
  )
)
```

pattern matching

```
IfThenElse(
  Var("x")
, Call(
    "printint"
  , [Var("x")]
  )
, NoVal()
)
```

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

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if x then
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IfThen(
   Var("x")
 , Call(
     "printint"
   , [Var("x")]
   )
)
```

e1

e2

pattern matching

```
IfThenElse(
   Var("x")
 , Call(
     "printint"
   , [Var("x")]
   )
 , NoVal()
)
```

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

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if x then
   printint(x)
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if x then
   printint(x)
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```
IfThen(
   Var("x")
 , Call(
     "printint"
   , [Var("x")]
   )
)
```

e1

e2

pattern matching

```
IfThenElse(
   Var("x")
 , Call(
     "printint"
   , [Var("x")]
   )
 , NoVal()
)
```

pattern instantiation

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

Desugaring

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

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

```
IfThen(
   Var("x")
,  Call(
      "printint"
   ,  [Var("x")]
   )
)
```

e1

e2

pattern matching

```
IfThenElse(
   Var("x")
,  Call(
      "printint"
   ,  [Var("x")]
   )
,  NoVal()
)
```

pattern instantiation

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

More Desugaring

```
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"))
desugar: Or(e1, e2)  -> IfThenElse(e1, Int("1"), e2)
```

```
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
```

Constant Folding

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

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

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")
  )
)
```

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: Bop(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))
```

Rewrite Rules

parameters

```
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

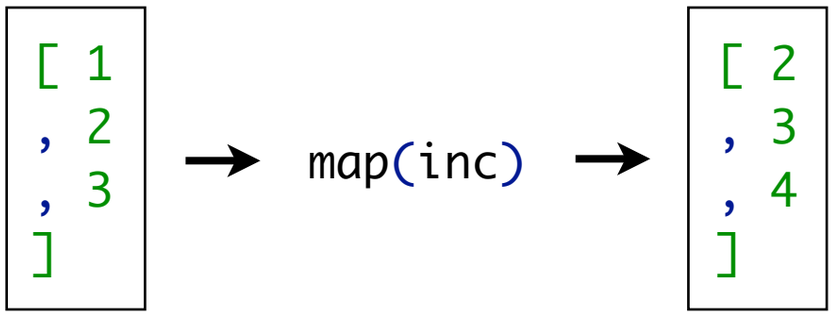
```
f(x,y): lhs -> rhs
```

- optional term parameters

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

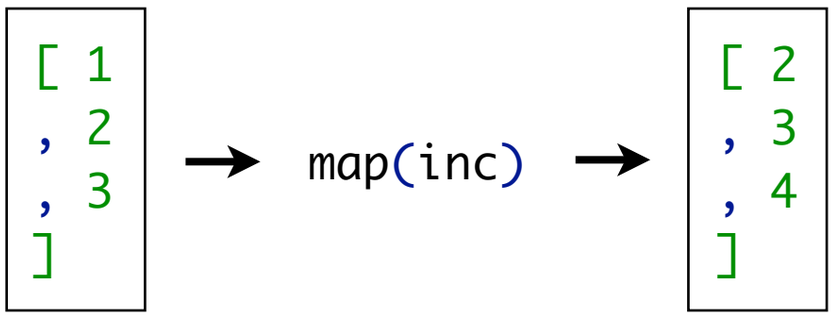
Rules with Parameters

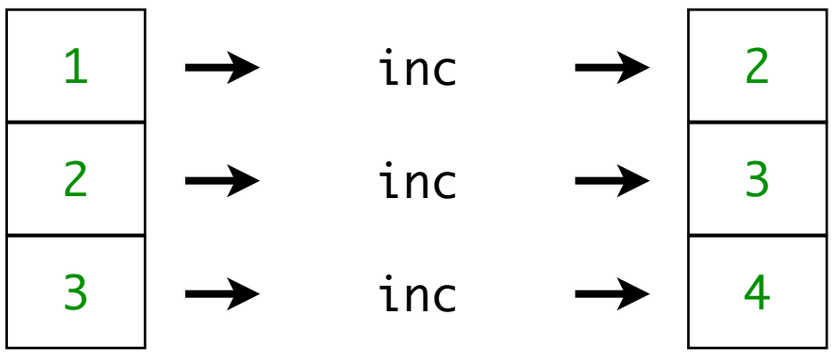
example: map



Rules with Parameters

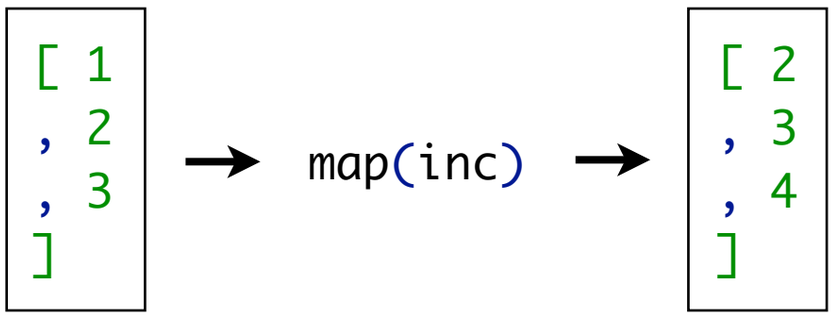
example: map

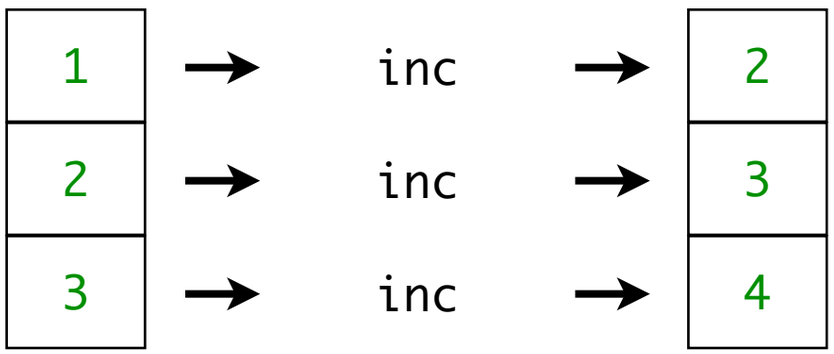




Rules with Parameters

example: map

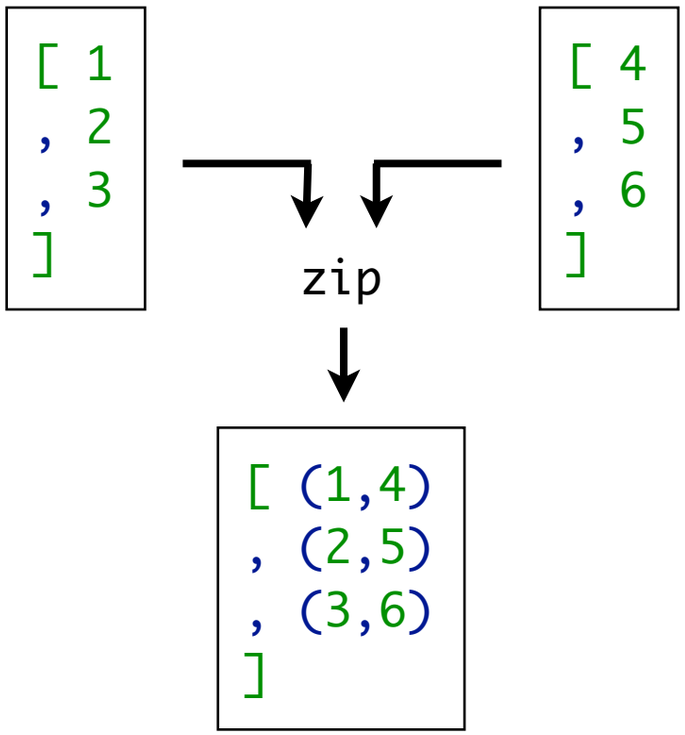





```
map(s): []     -> []
map(s): [x|xs] -> [<s> x | <map(s)> xs]
```

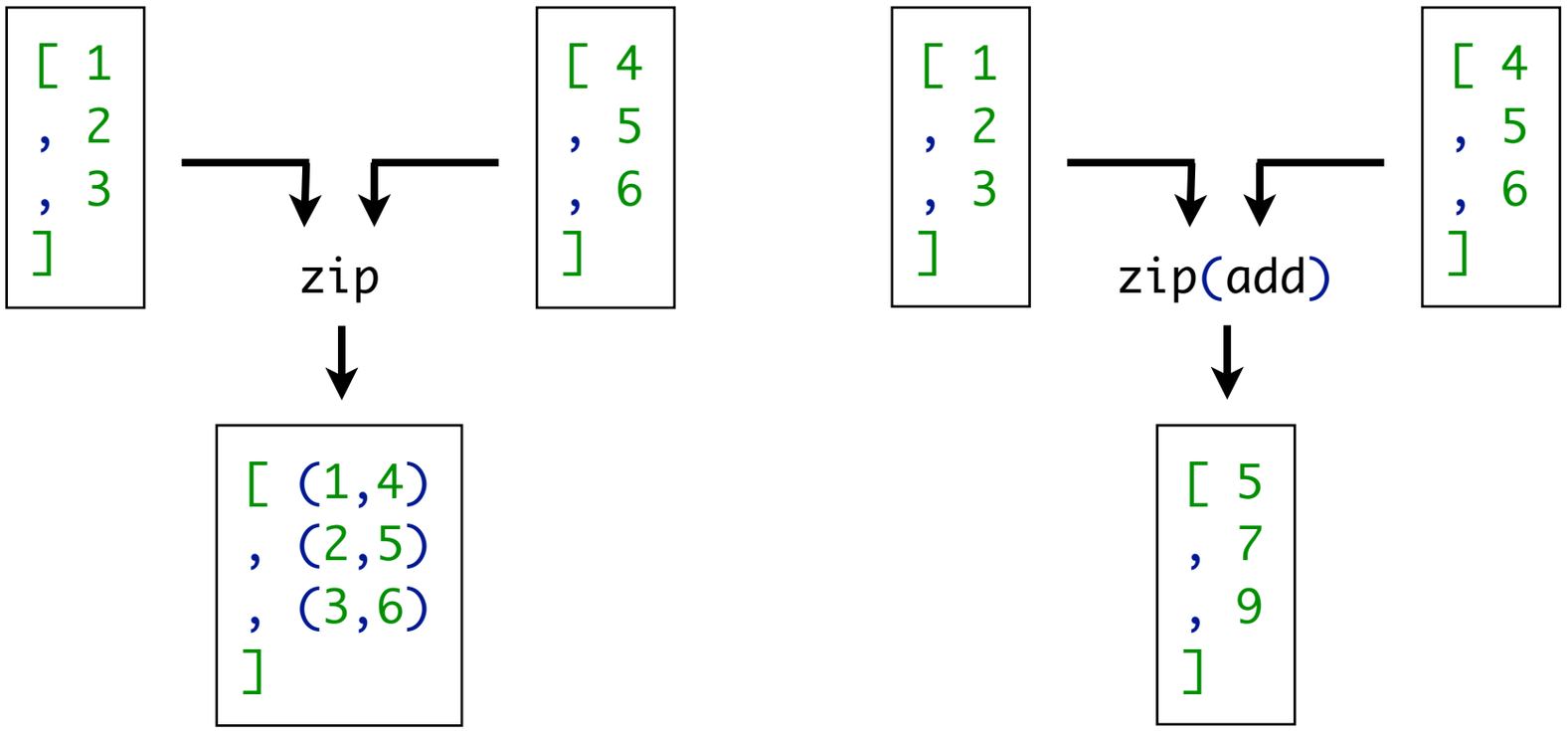
Rules with Parameters

example: zip



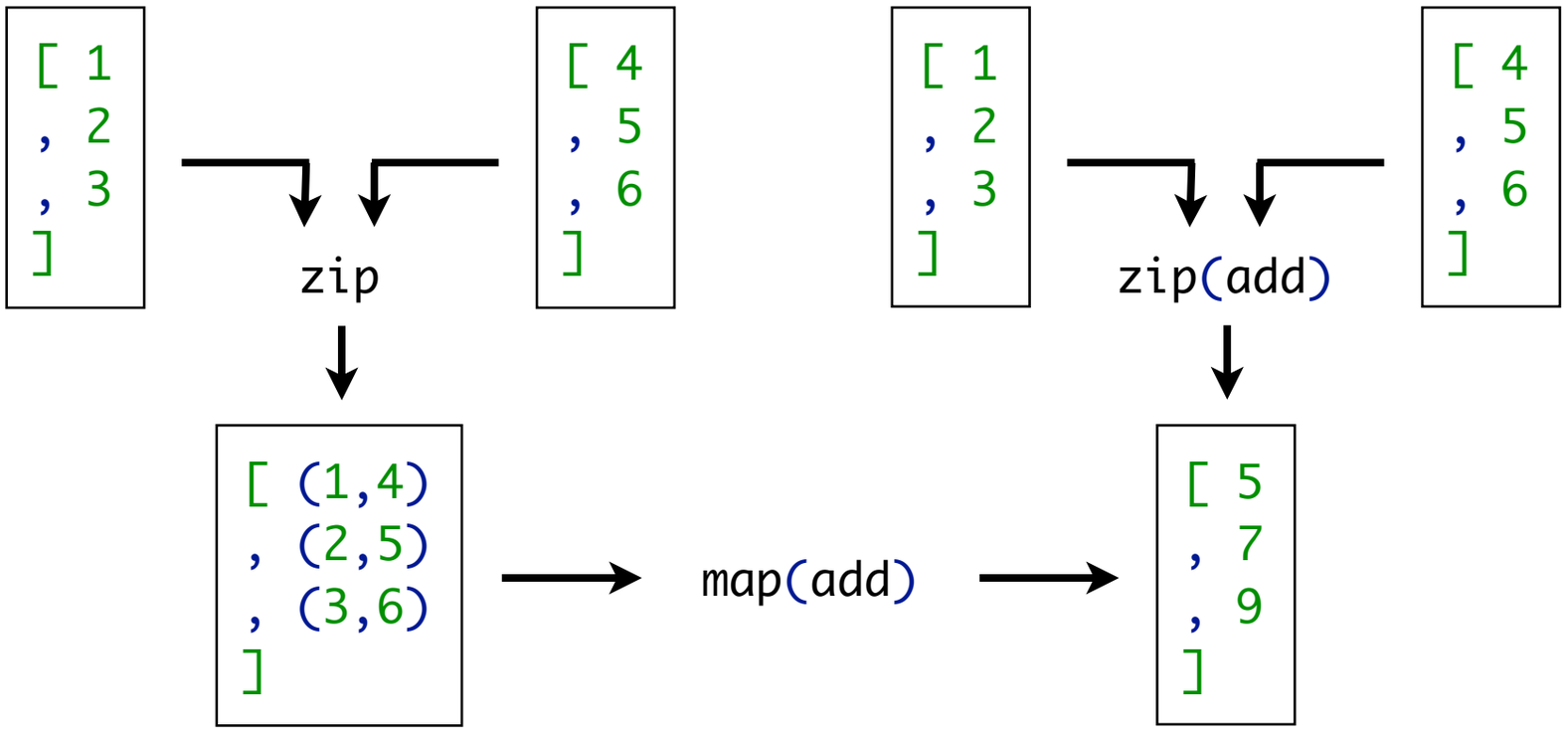
Rules with Parameters

example: zip



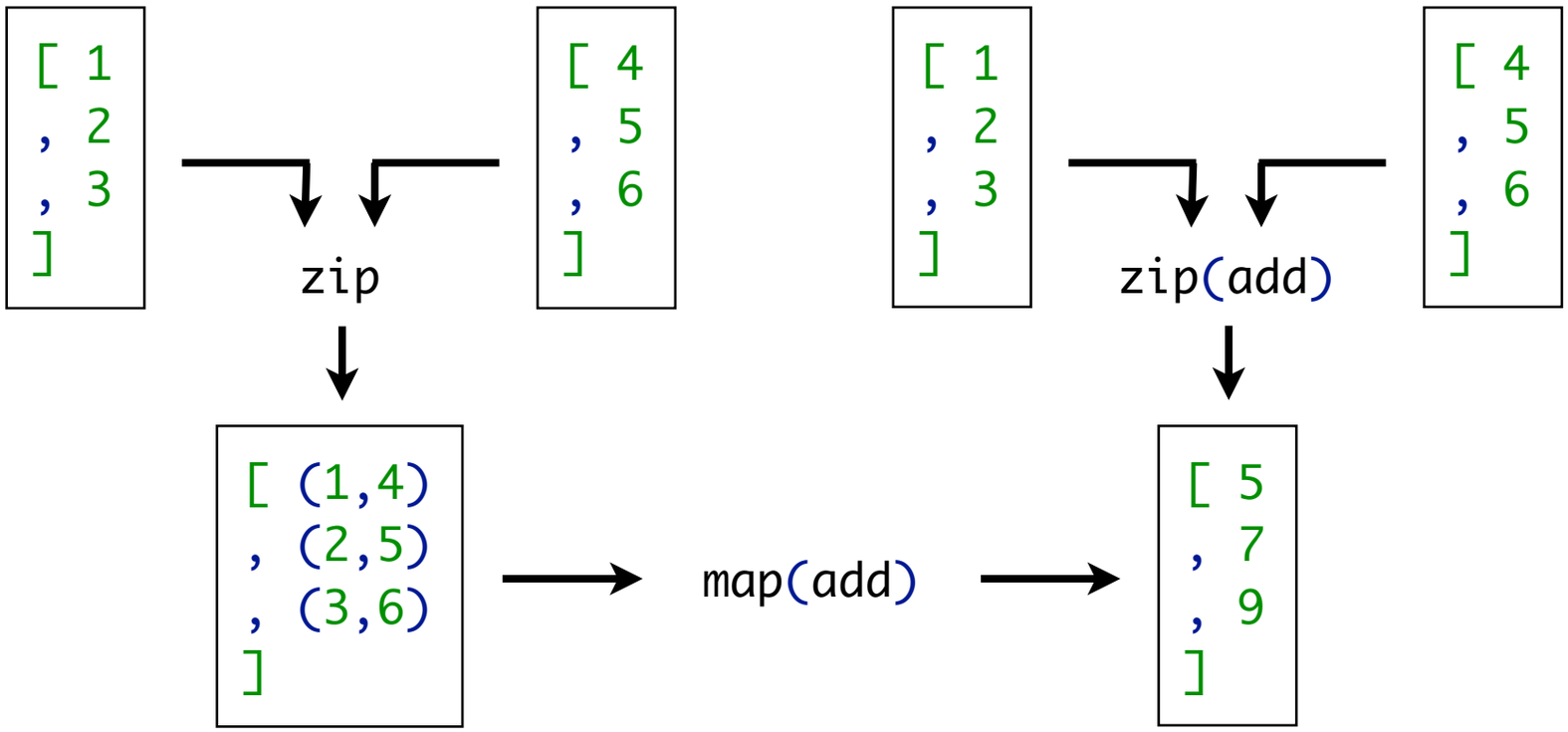
Rules with Parameters

example: zip



Rules with Parameters

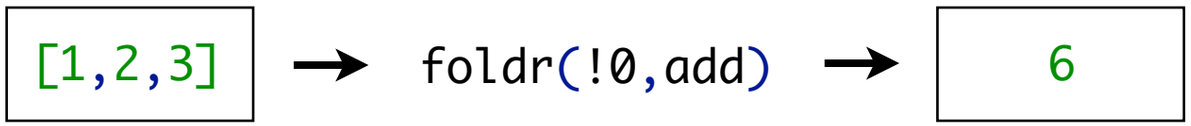
example: zip

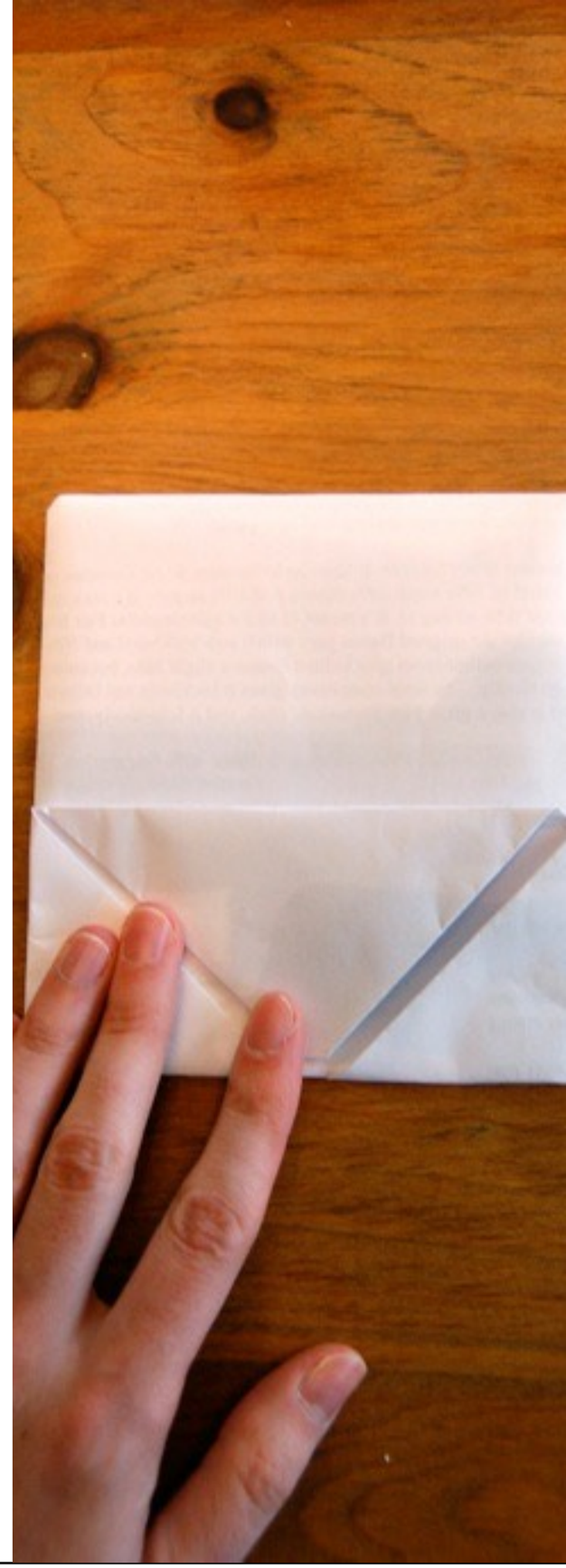



```
zip(s): ([],[])          -> []
zip(s): ([x|xs],[y|ys]) -> [<s> (x,y) | <zip(s)> (xs,ys)]

zip = zip(id)
```

Rules with Parameters

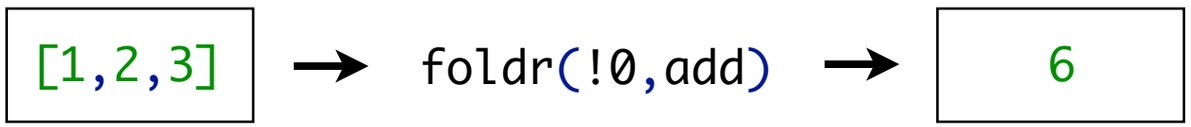
example: fold

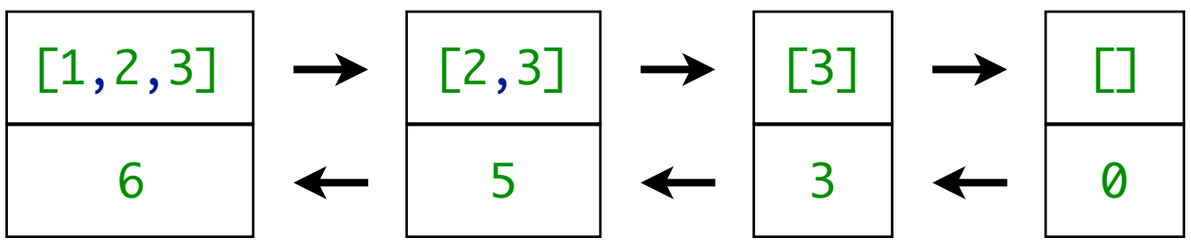


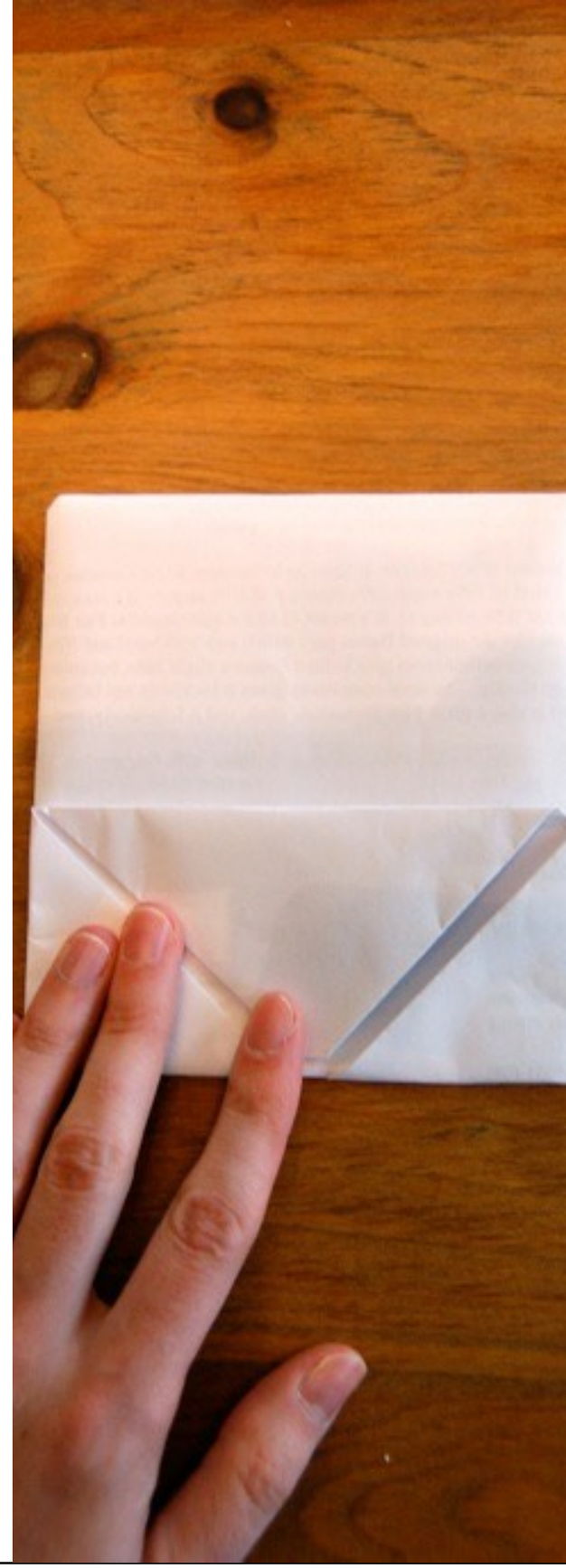


Rules with Parameters

example: fold

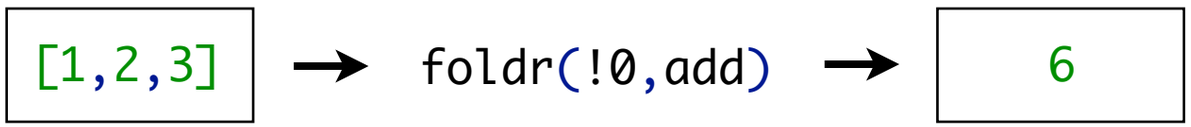


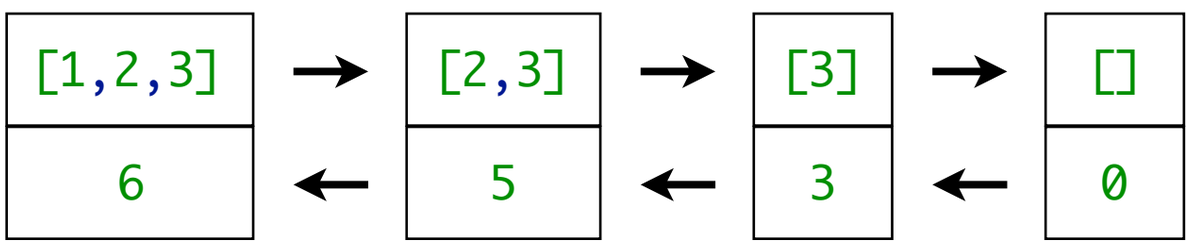




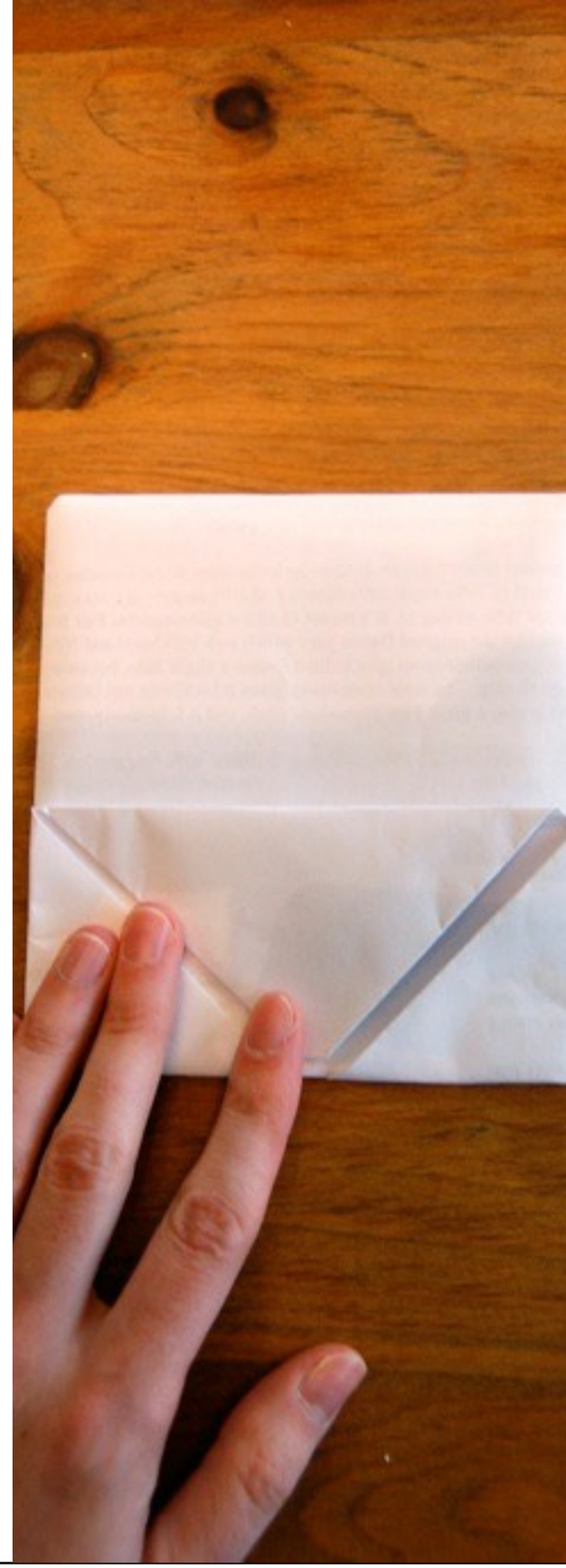
Rules with Parameters

example: fold






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

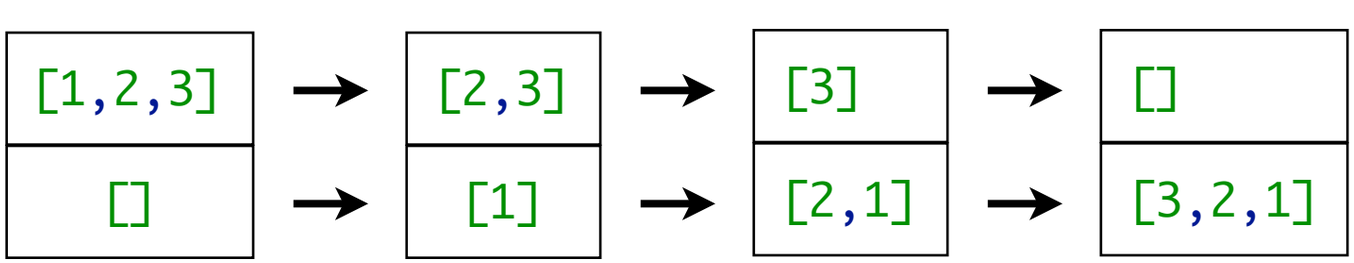


Rules with Parameters

example: inverse

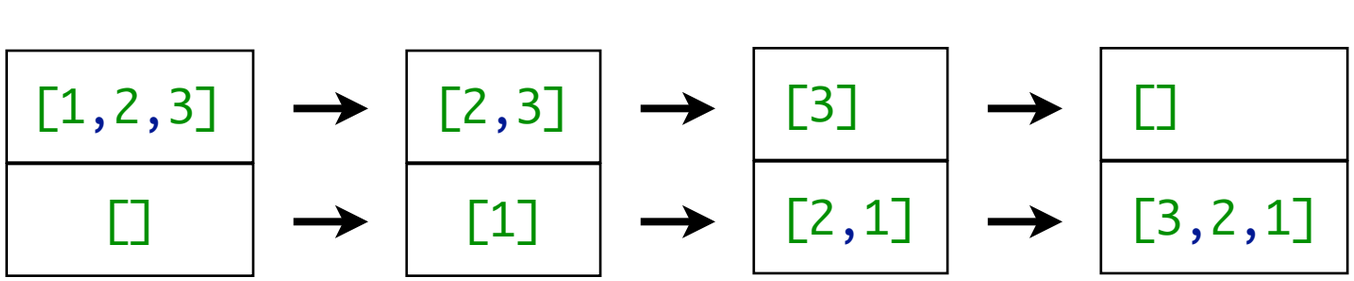
Rules with Parameters

example: inverse



Rules with Parameters

example: inverse




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

Rewrite Strategies

Transformation Definitions

rules and strategies

rewrite rules

- term to term
- left-hand side matching
- right-hand side instantiation
- conditional
- partial transformation

rewrite strategies

- rule selection
- algorithm
- composition of transformations

Stratego

example

```
module desugar

imports

  include/Tiger
  operators

strategies

  desugar-all = innermost(desugar)

rules

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

Stratego

example

```
module eval

imports
  include/Tiger
  operators
  desugar

strategies

  eval-all = innermost(desugar + eval)

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

Strategy Combinators

identity

```
id
```

Strategy Combinators

identity

```
id
```

failure

```
fail
```

Strategy Combinators

identity

```
id
```

failure

```
fail
```

sequential composition

```
s1 ; s2
```

Strategy Combinators

identity

```
id
```

failure

```
fail
```

sequential composition

```
s1 ; s2
```

deterministic choice

```
s1 <+ s2
```

Strategy Combinators

identity

```
id
```

failure

```
fail
```

sequential composition

```
s1 ; s2
```

deterministic choice

```
s1 <+ s2
```

non-deterministic choice

```
s1 + s2
```

Strategy Combinators

identity

```
id
```

failure

```
fail
```

sequential composition

```
s1 ; s2
```

deterministic choice

```
s1 <+ s2
```

non-deterministic choice

```
s1 + s2
```

guarded choice

```
s1 < s2 + s3
```

Strategy Combinators

variables

pattern matching

```
?t
```

Strategy Combinators
variables

pattern matching

```
?t
```

pattern instantiation

```
!t
```

Strategy Combinators

variables

pattern matching

```
?t
```

pattern instantiation

```
!t
```

strategy application

```
<s> t ≡ !t ; s
```

Strategy Combinators

variables

pattern matching

```
?t
```

pattern instantiation

```
!t
```

strategy application

```
<s> t ≡ !t ; s
```

result matching

```
s => t ≡ s ; ?t

<s> t1 => t2
t2 := <s> t1
```

Strategy Combinators

variables

pattern matching

```
?t
```

pattern instantiation

```
!t
```

strategy application

```
<s> t ≡ !t ; s
```

result matching

```
s => t ≡ s ; ?t
```

```
<s> t1 => t2
```

```
t2 := <s> t1
```

variable scope

```
{x,y: s}
```

Strategy Combinators

rules and strategies

named rewrite rule

```
l: t1 -> t2 where s ≡  l = ?t1 ; s ; !t2
```

Strategy Combinators

rules and strategies

named rewrite rule

```
l: t1 -> t2 where s ≡  l = ?t1 ; s ; !t2
```

unscoped rewrite rule

```
(t1 -> t2 where s) ≡ ?t1 ; s ; !t2
```

Strategy Combinators

rules and strategies

named rewrite rule

```
l: t1 -> t2 where s ≡  l = ?t1 ; s ; !t2
```

unscoped rewrite rule

```
(t1 -> t2 where s) ≡ ?t1 ; s ; !t2
```

strategy definition

```
f(x,y|a,b) = s
```

Strategy Combinators

examples

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

Strategy Combinators

examples

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

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

Strategy Combinators

examples

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

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

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

Strategy Combinators

examples

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

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

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

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

Strategy Combinators

examples

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

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

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

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

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

Strategy Combinators

examples

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

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

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

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

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

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

Strategy Combinators

examples

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

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

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

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

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

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

oncetd(s) = s <+ one(oncetd(s))
```

Strategy Combinators

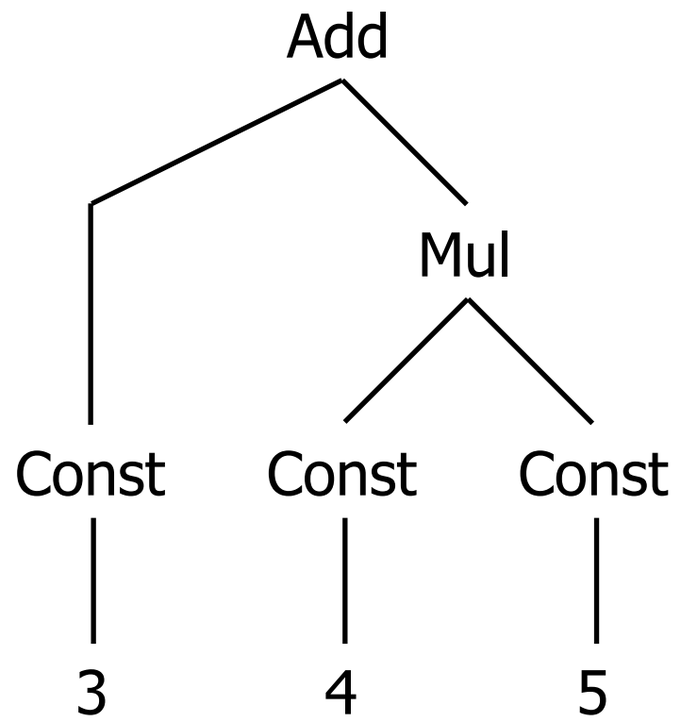
examples

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

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

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

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

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

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

oncetd(s) = s <+ one(oncetd(s))

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

Stratego

example

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

topdown(s) = s ; all(topdown(s))
topdown(switch)
```



Stratego

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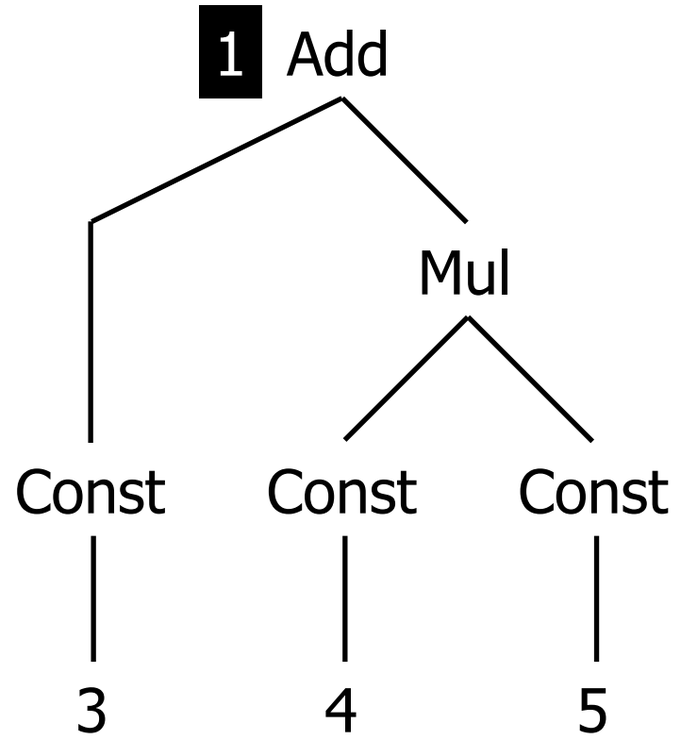

Stratego

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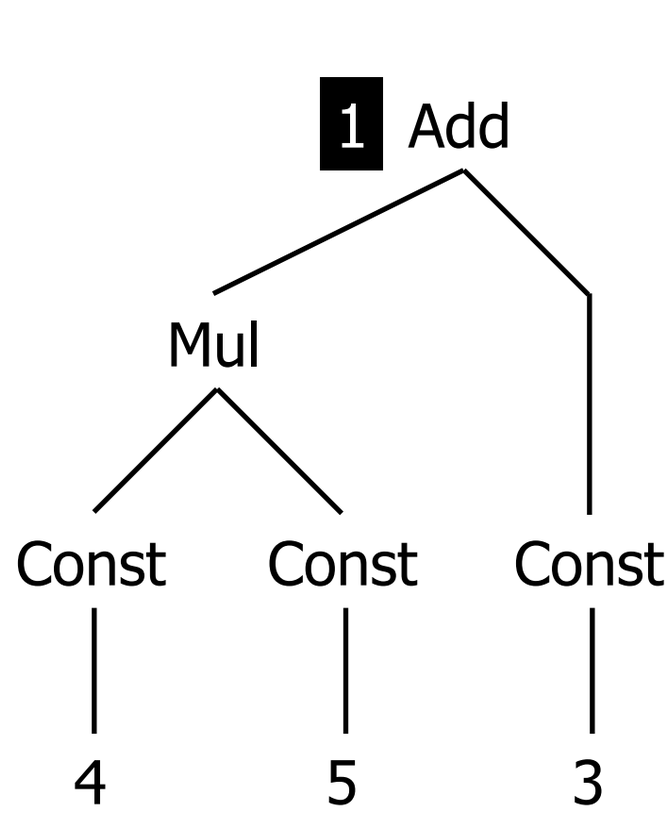

Stratego

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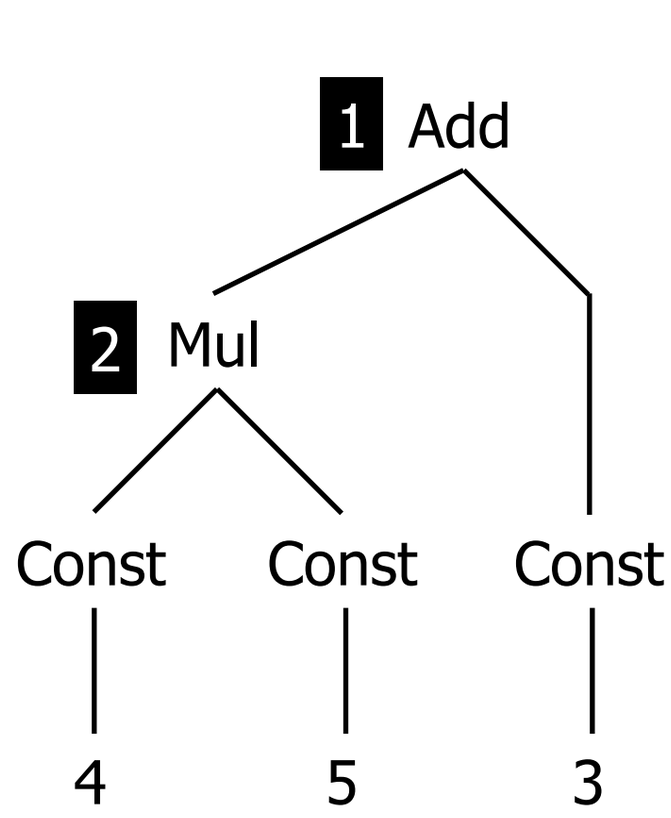

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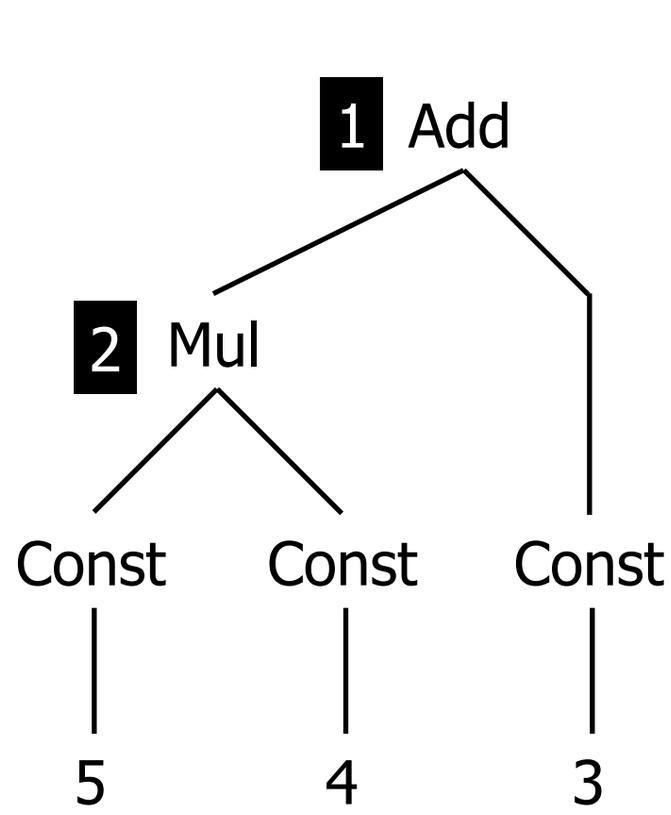

Stratego

example

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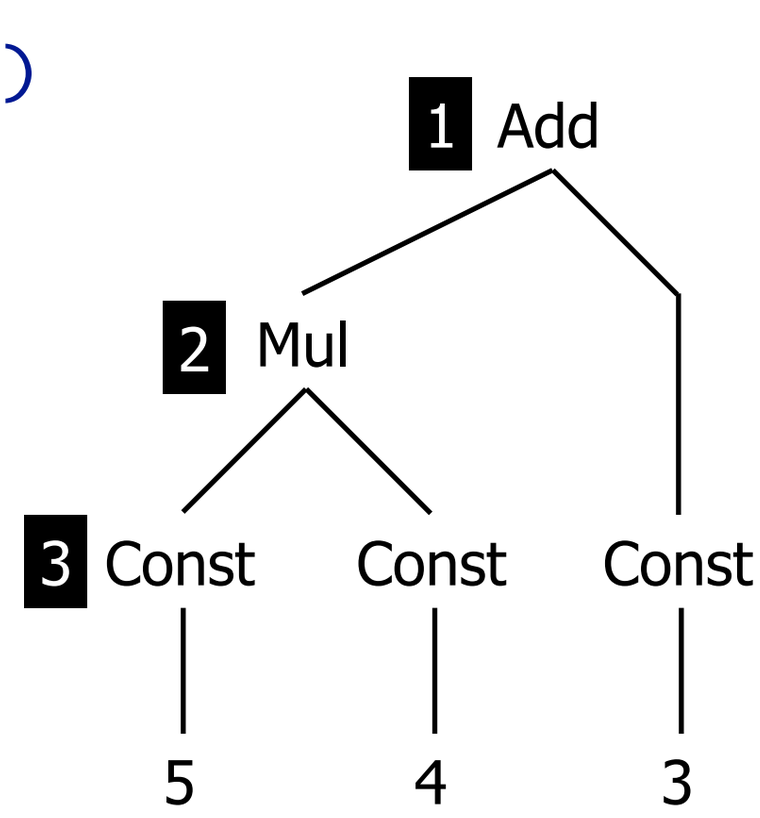
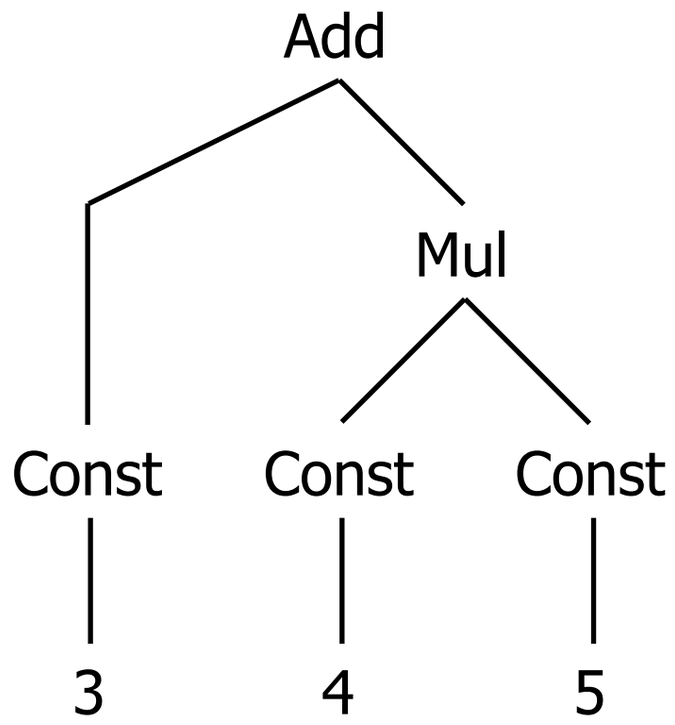


Stratego

example

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

topdown(s) = s ; all(topdown(s))
topdown(try(switch))
```



Stratego

example

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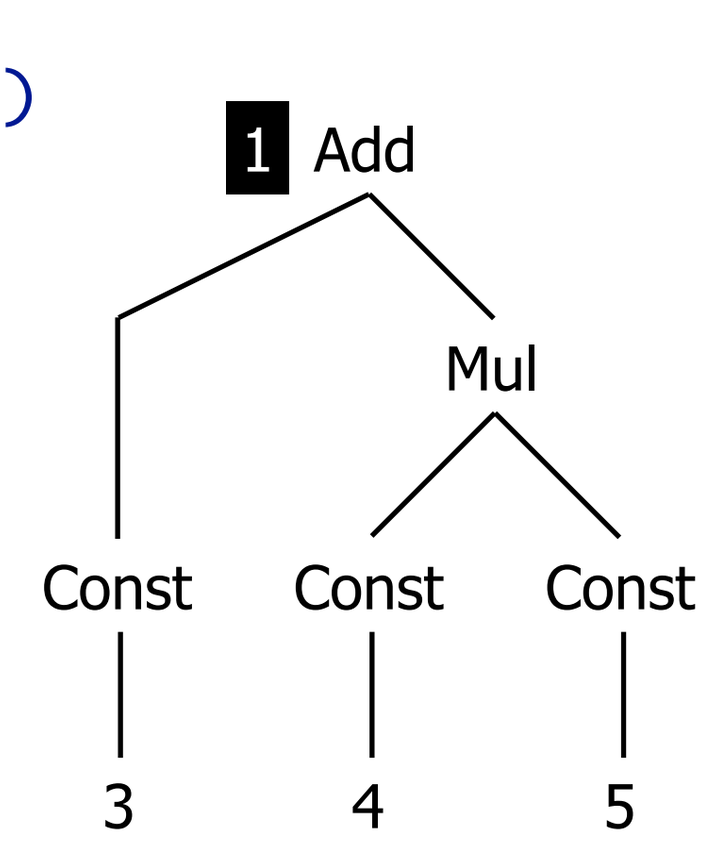

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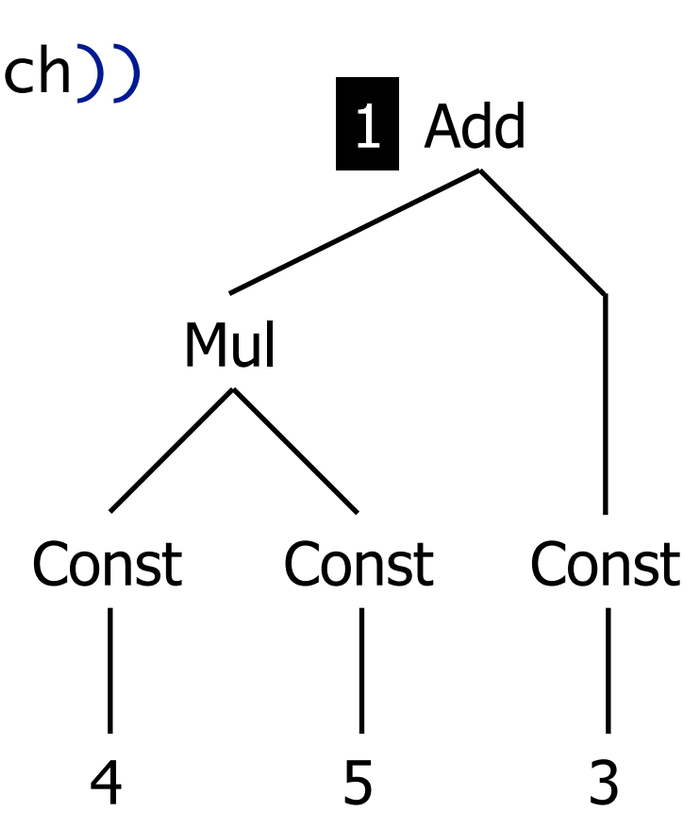

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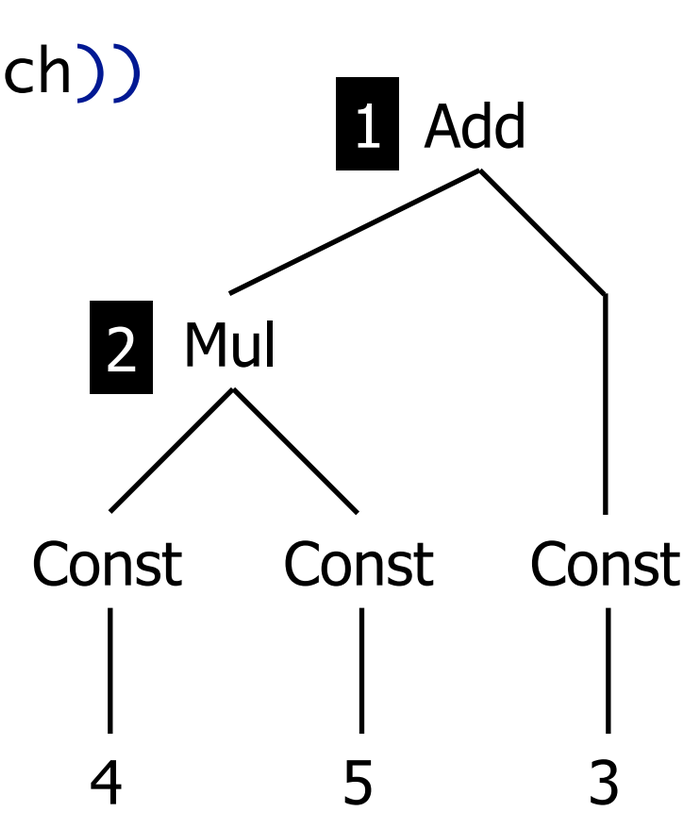

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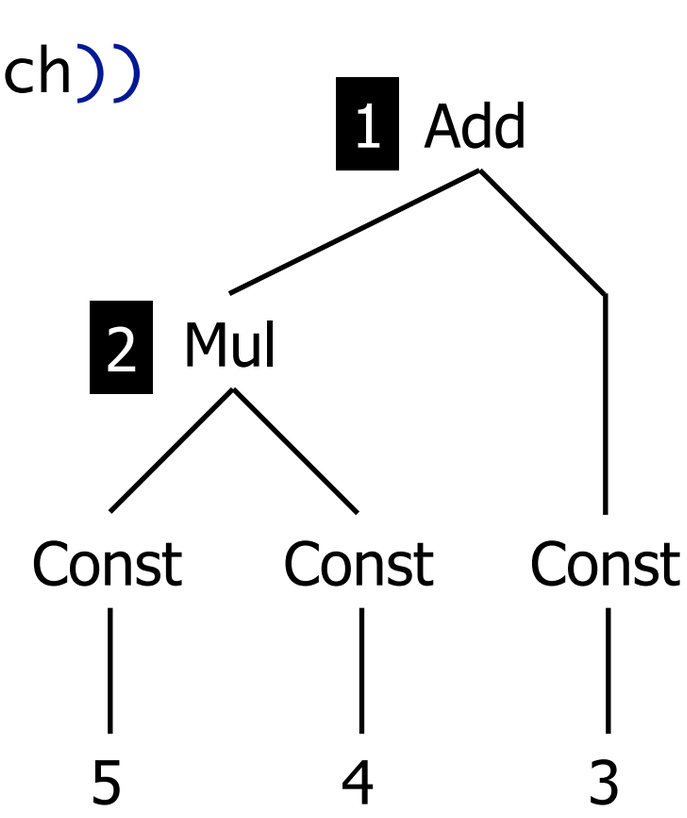

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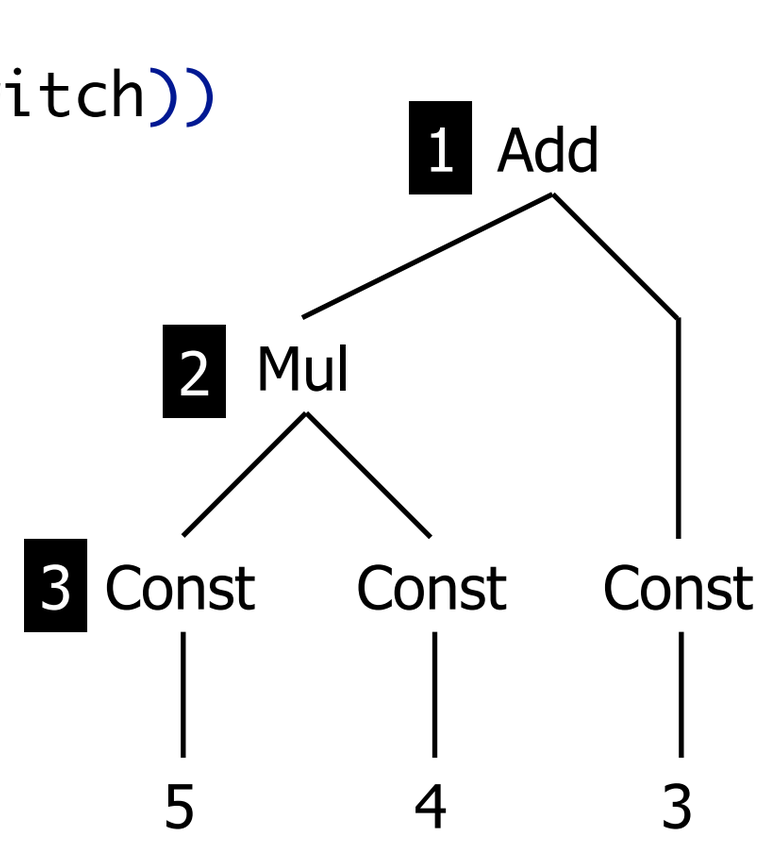

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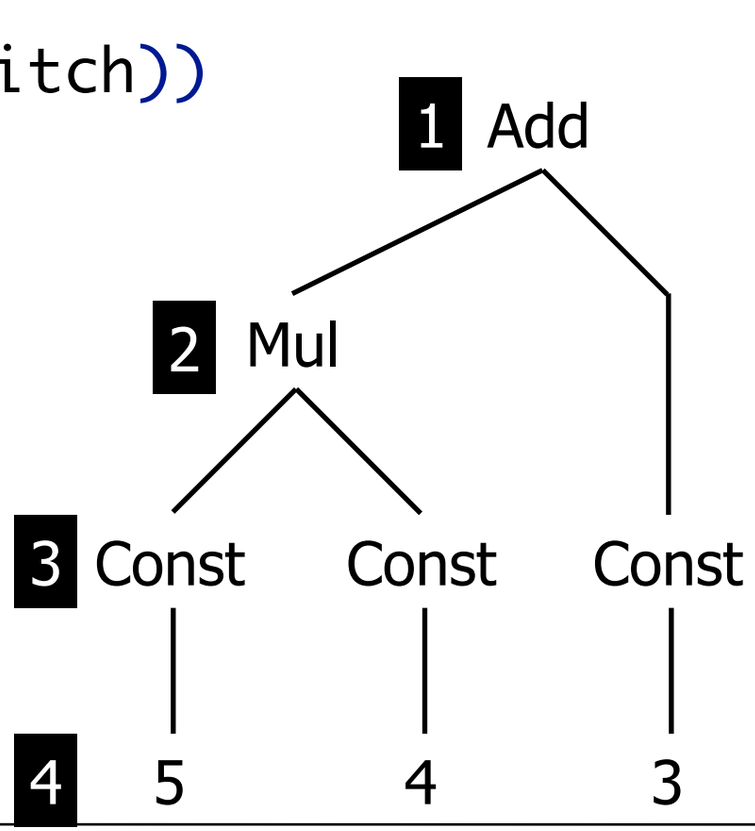

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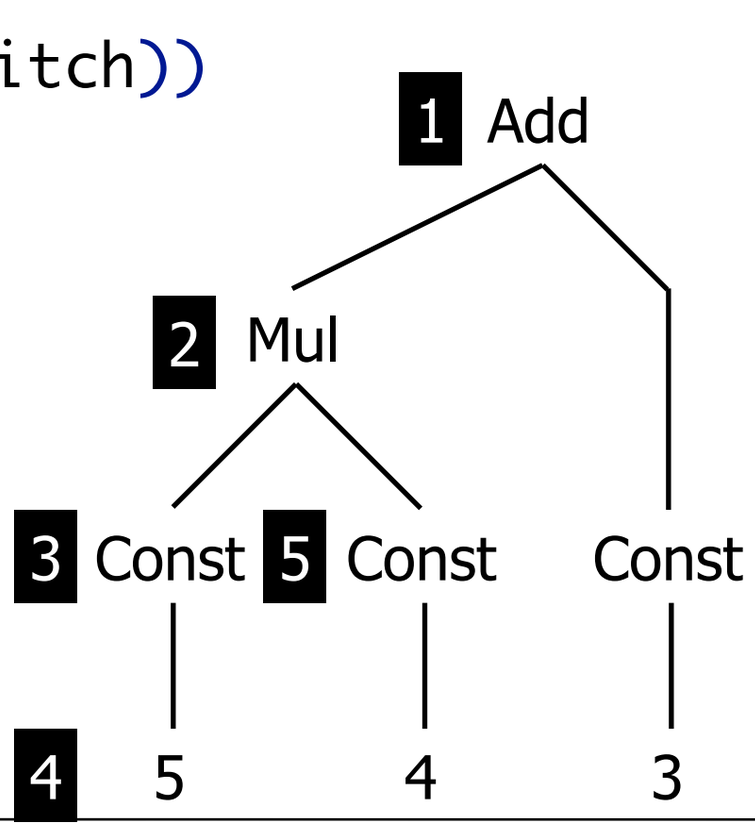

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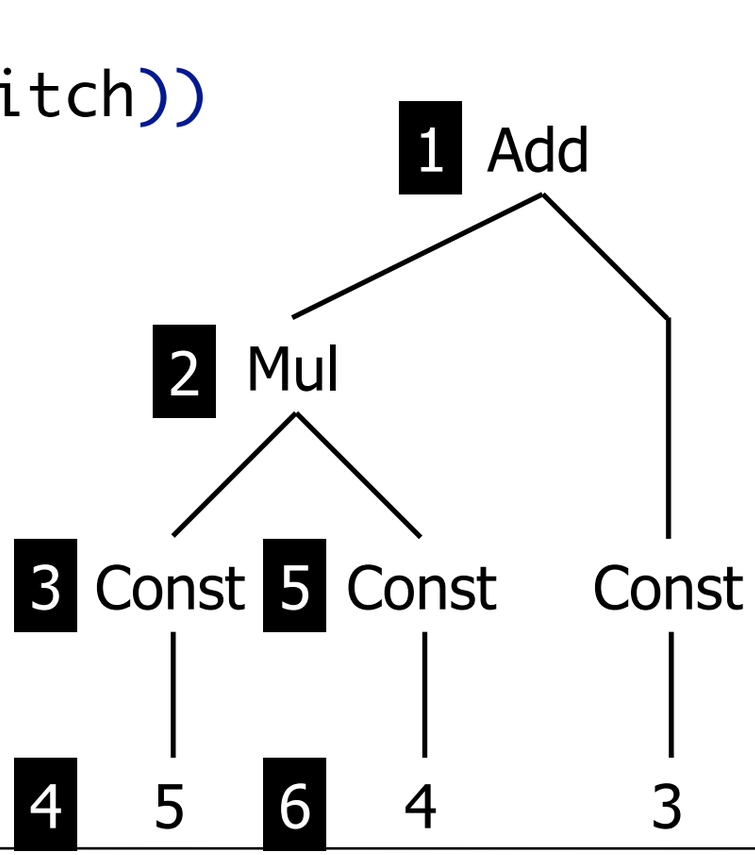

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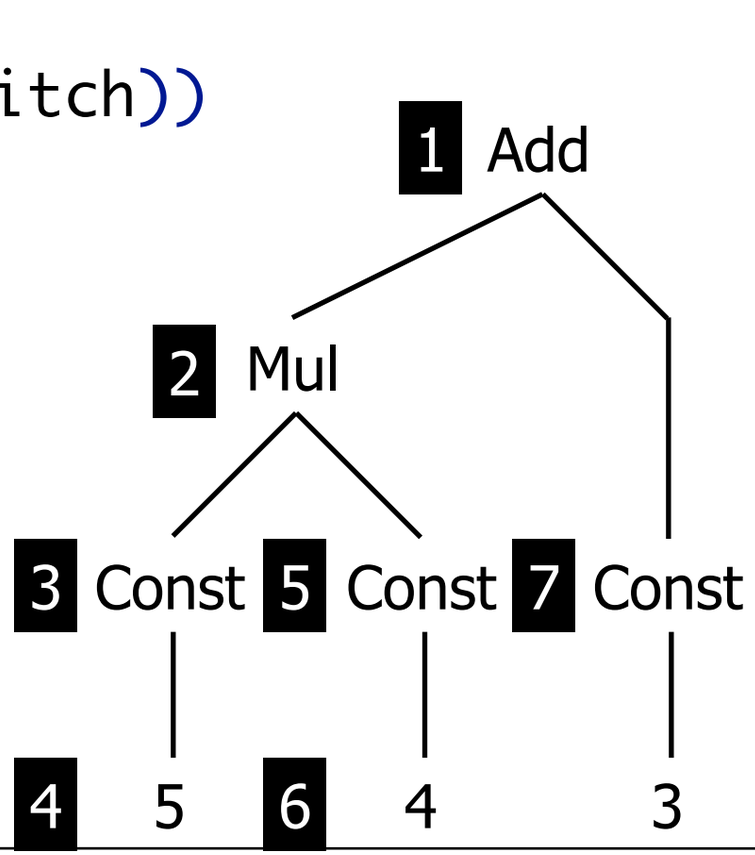

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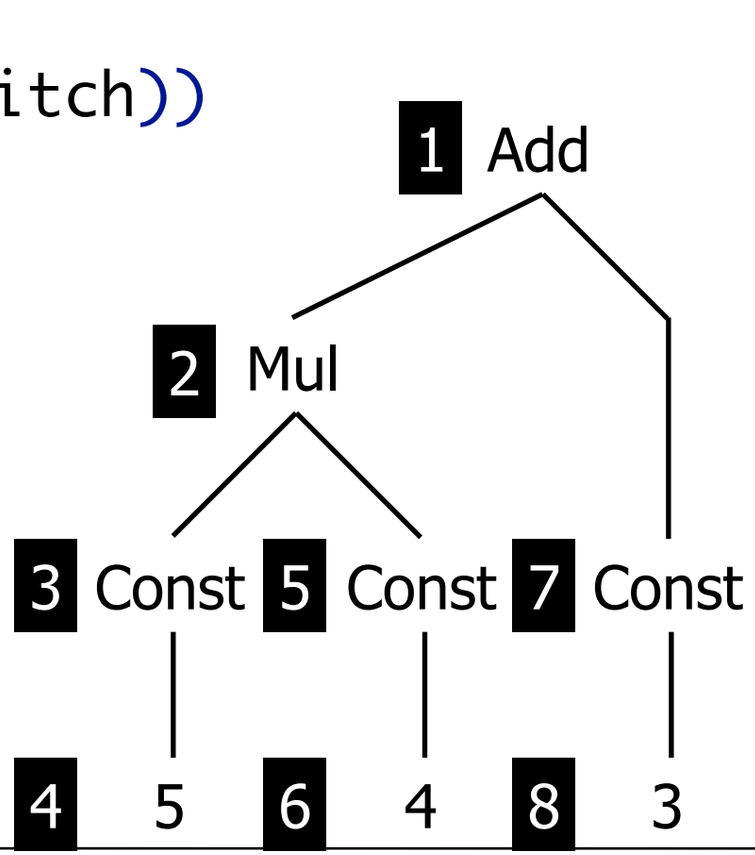

Stratego

example

```
switch: Add(e1, e2) -> Add(e2, e1)
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alltd(s) = s <+ all(alltd(s))

alltd(switch)
```

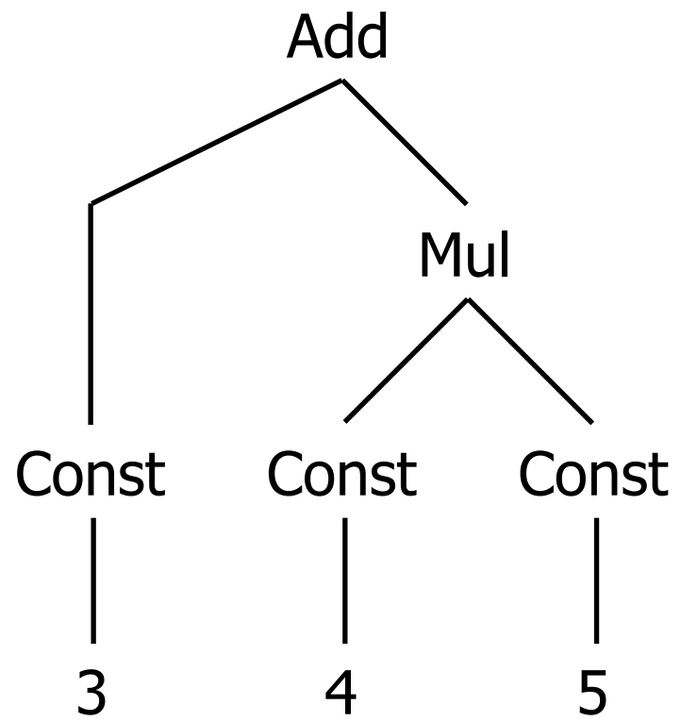

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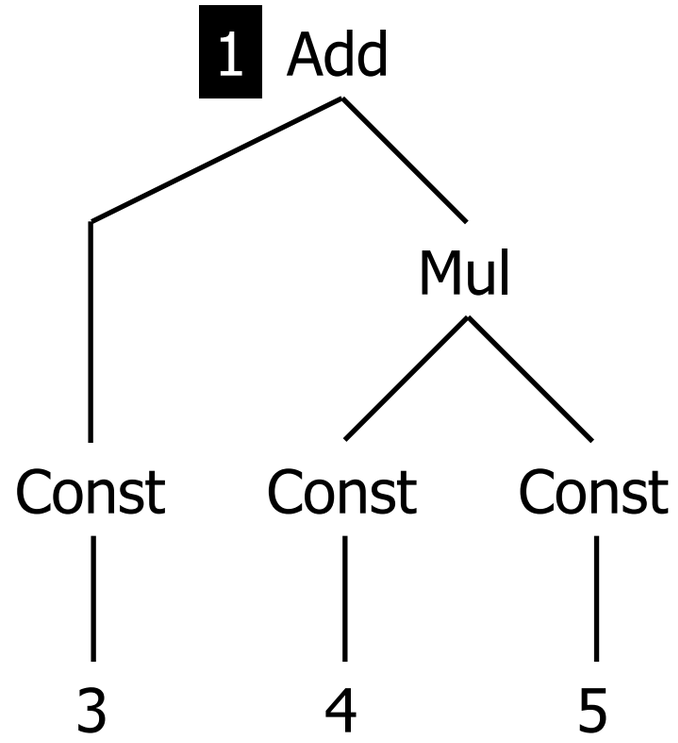

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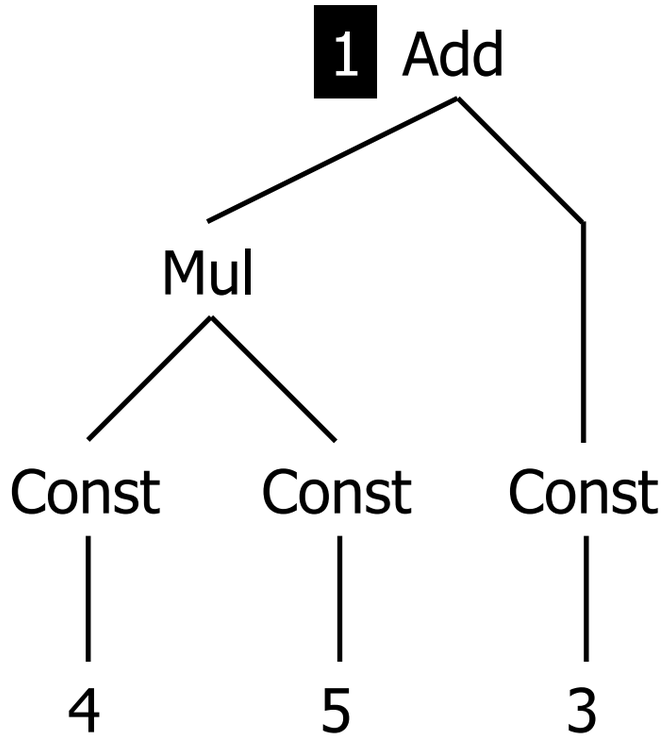

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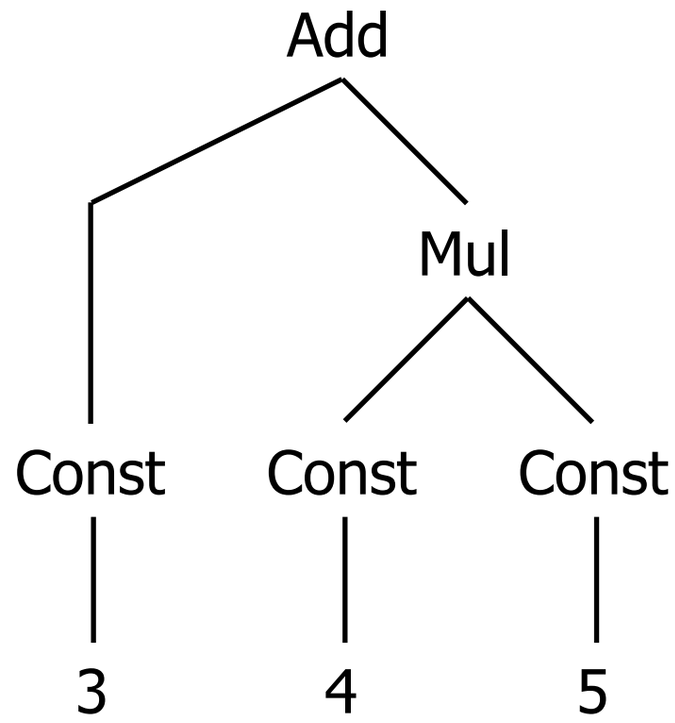

Stratego

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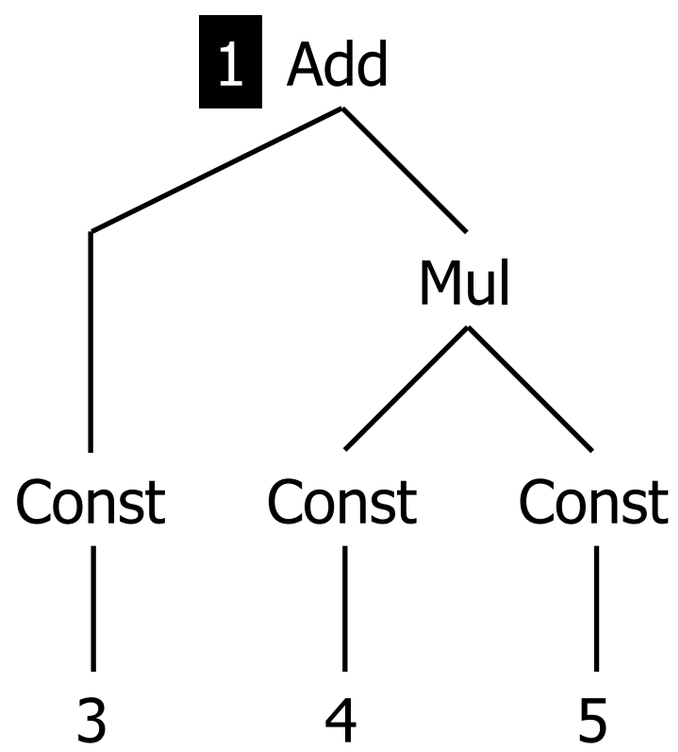

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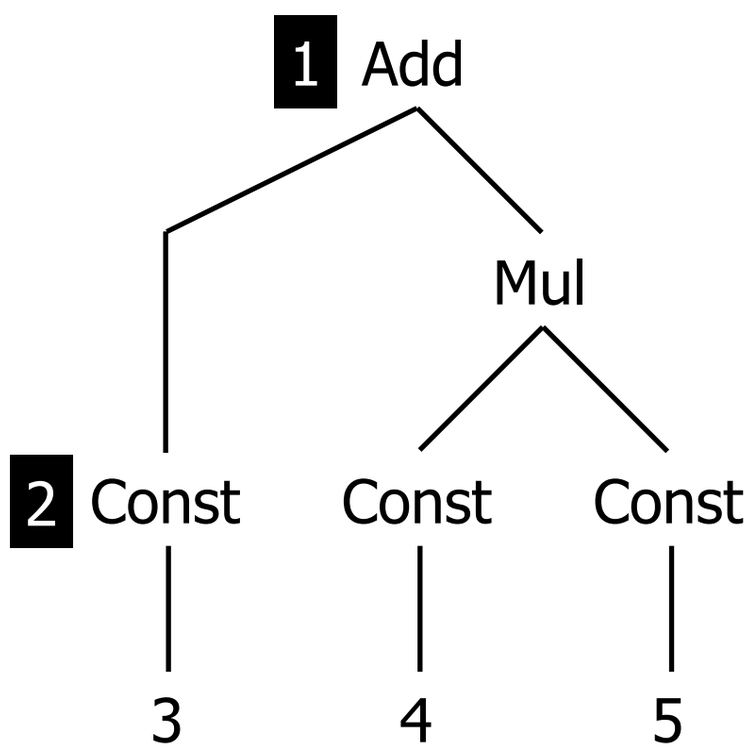

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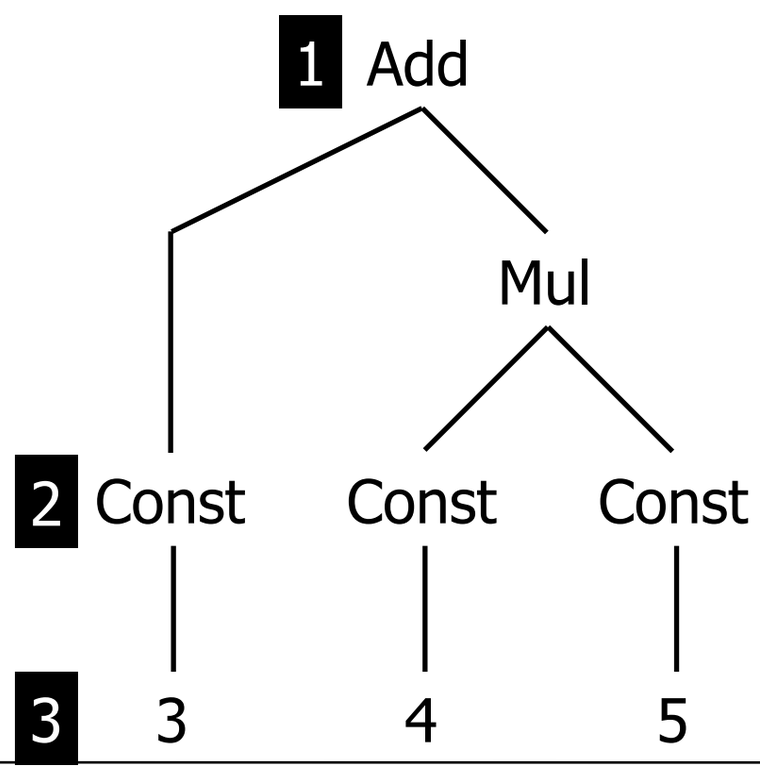

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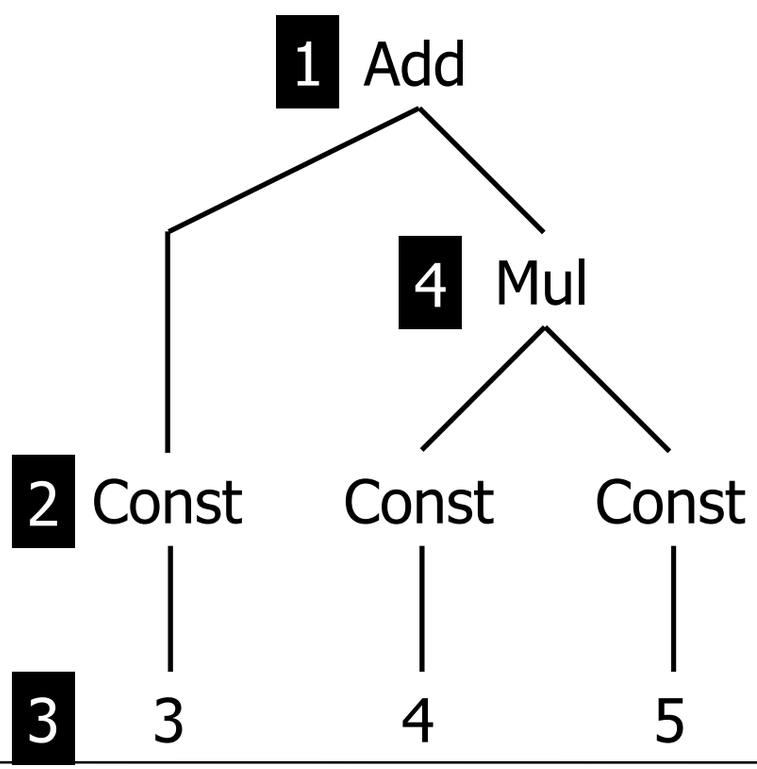

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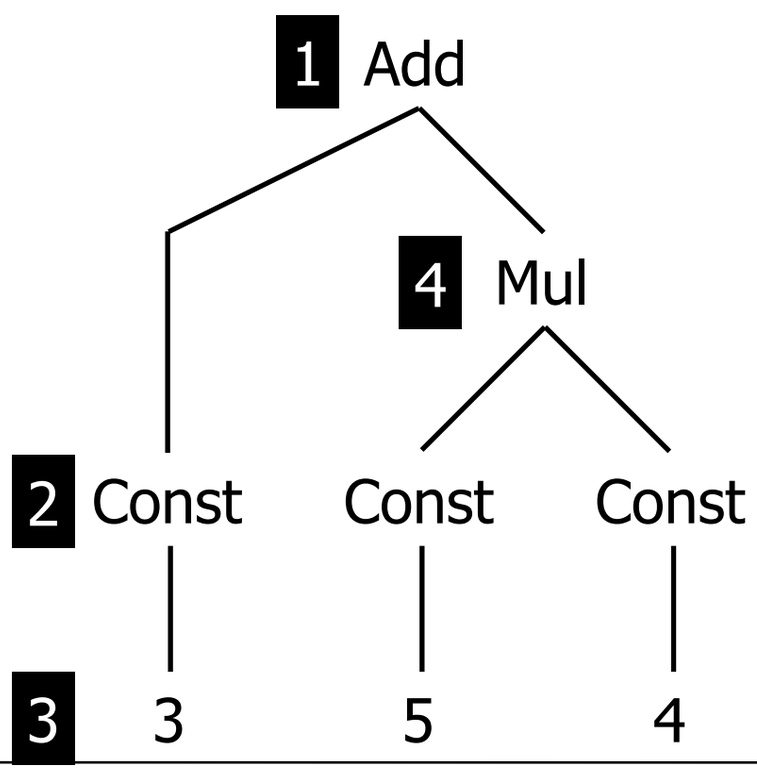


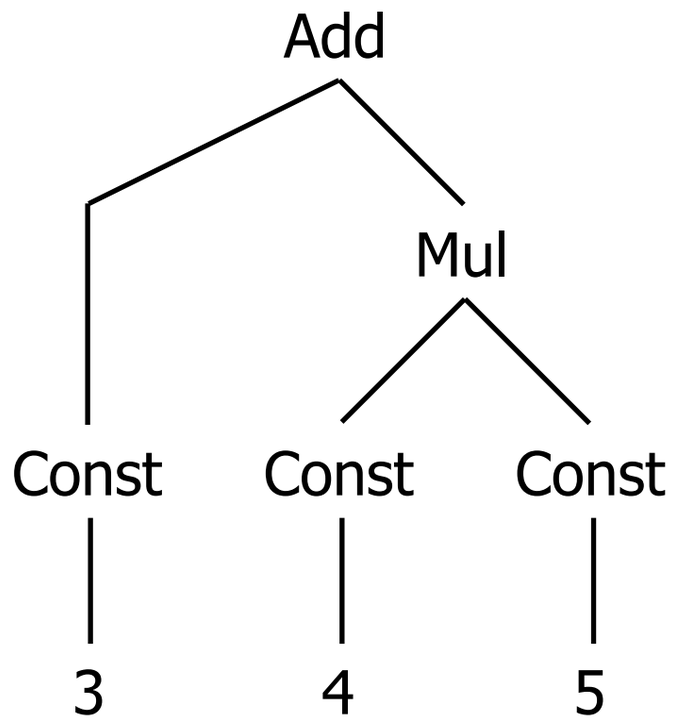
Stratego

example

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

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

bottomup(switch)
```



Stratego

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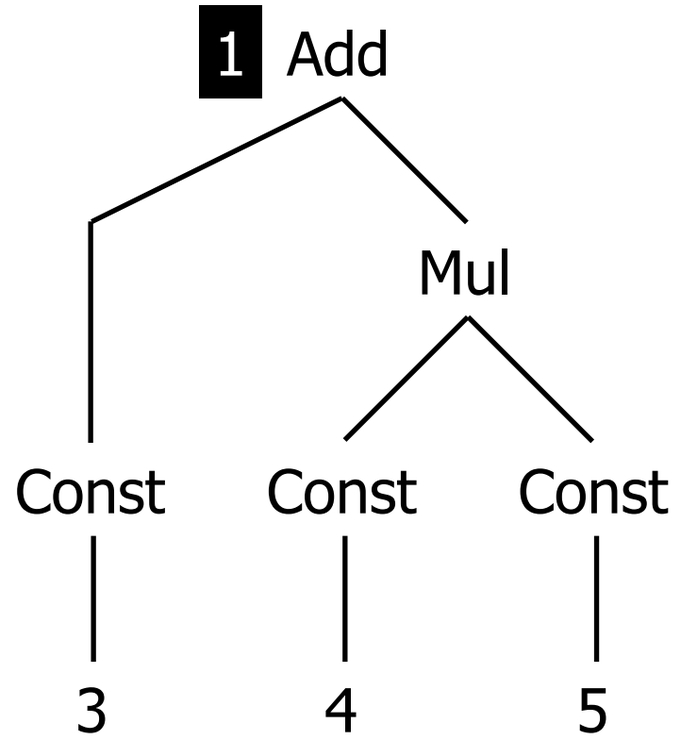

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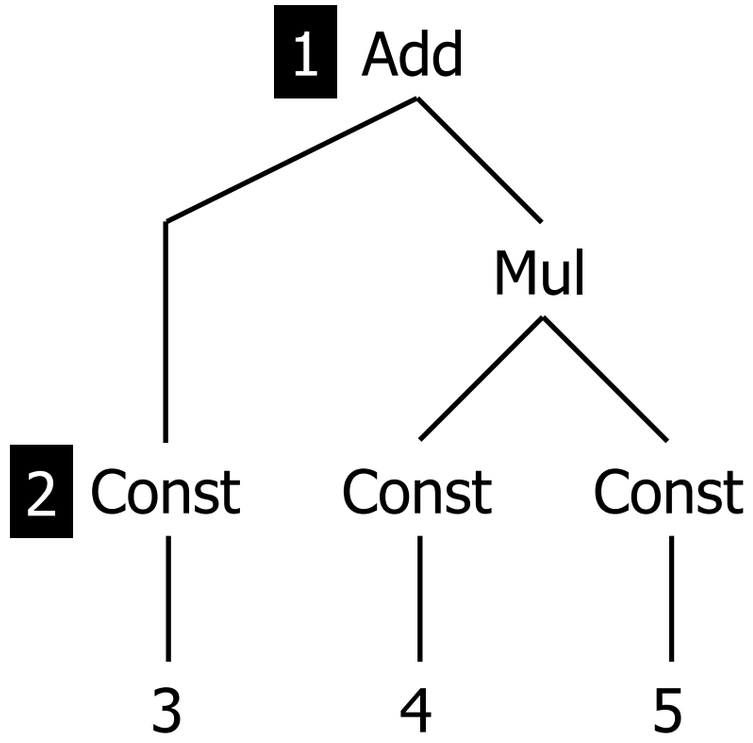

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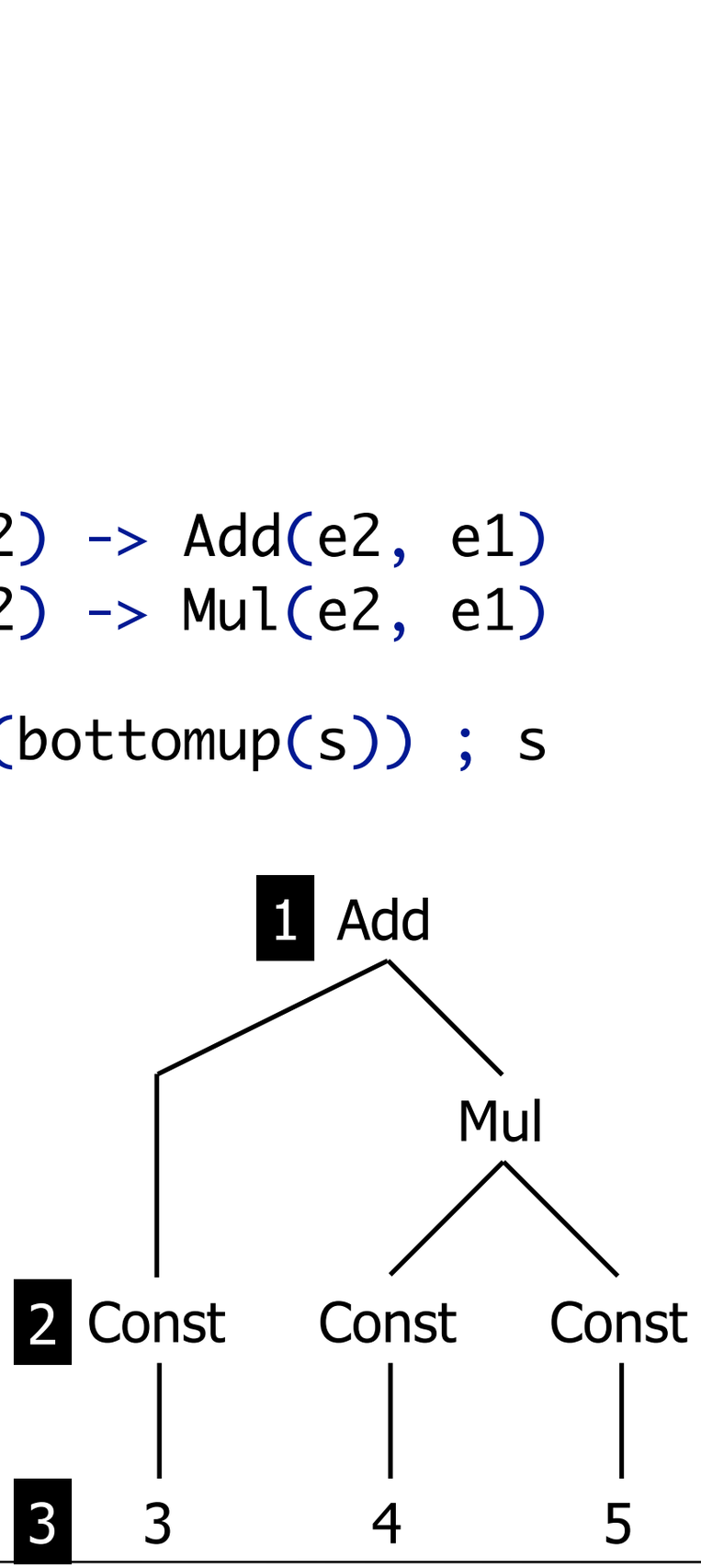

Stratego

example

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

bottomup(s) = all(bottomup(s)) ; s
bottomup(try(switch))
```

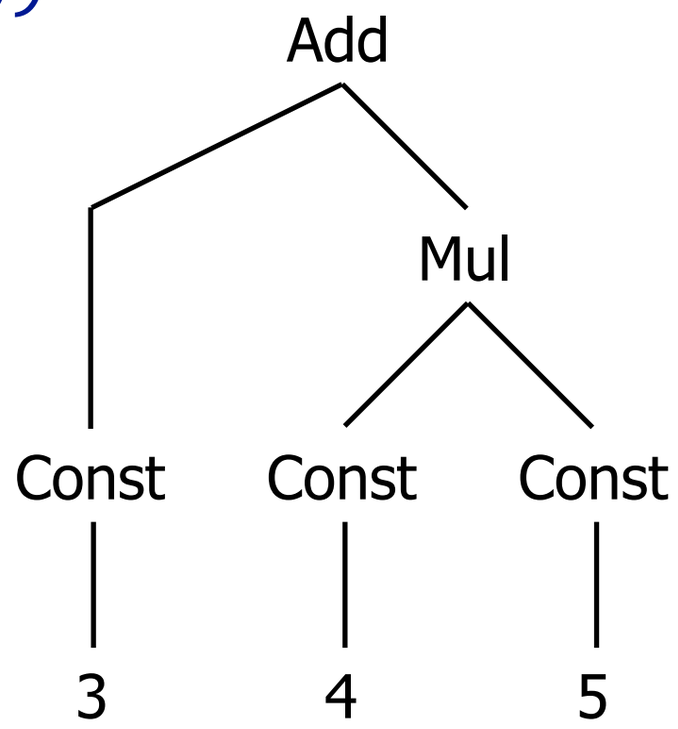

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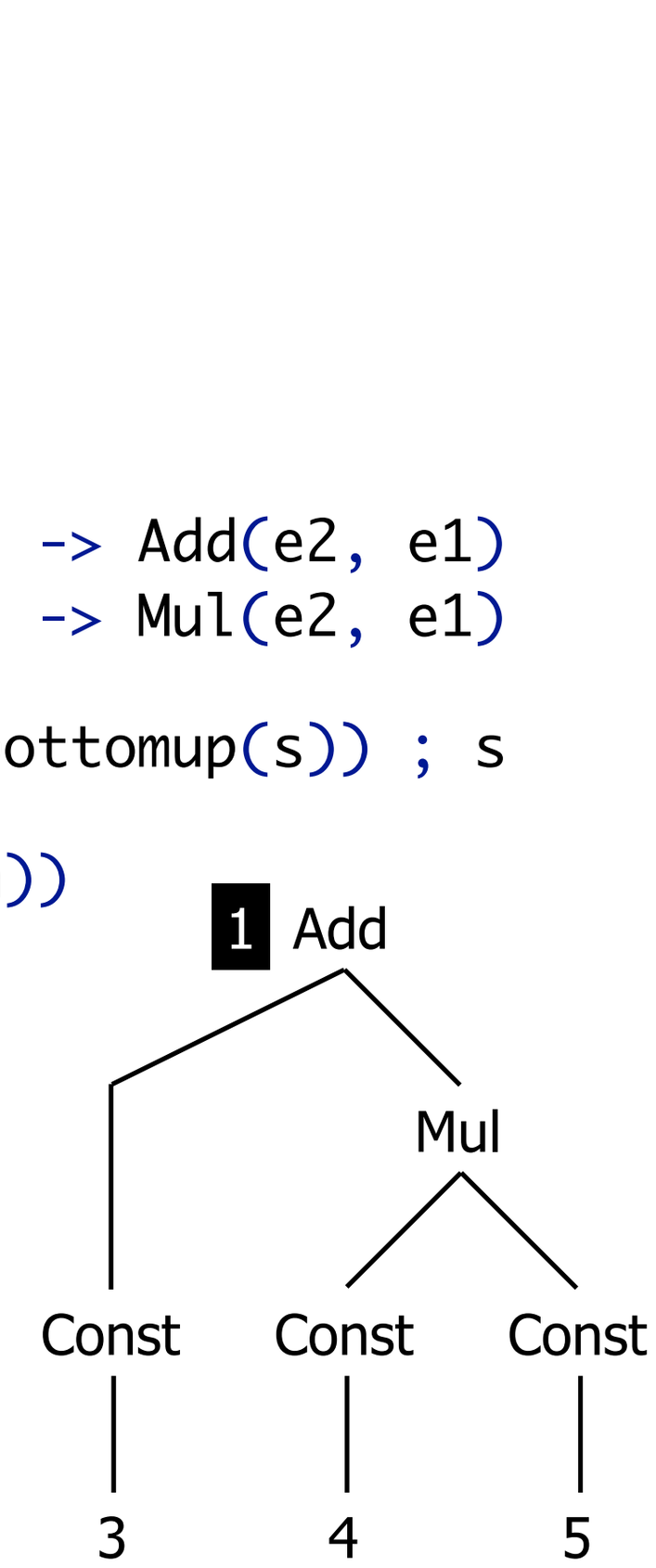

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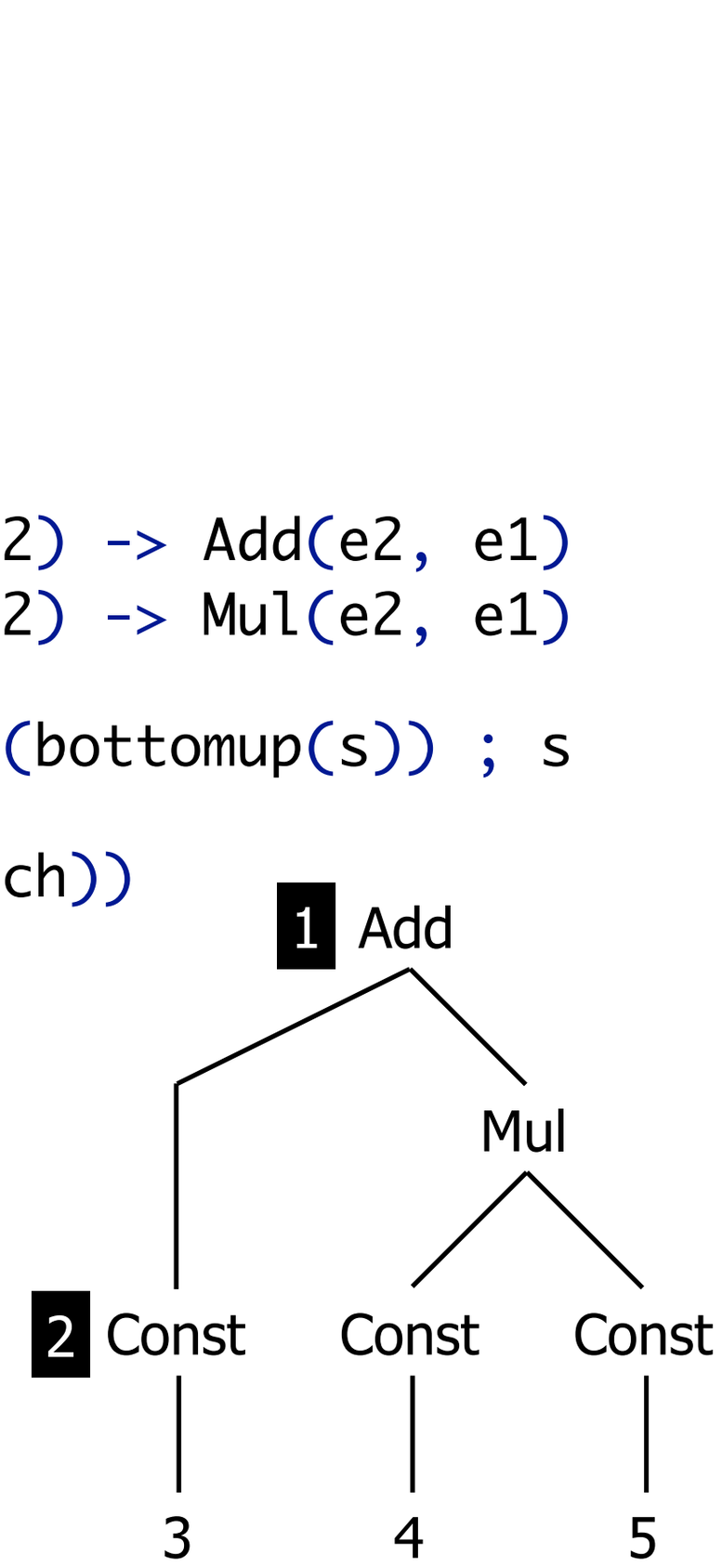

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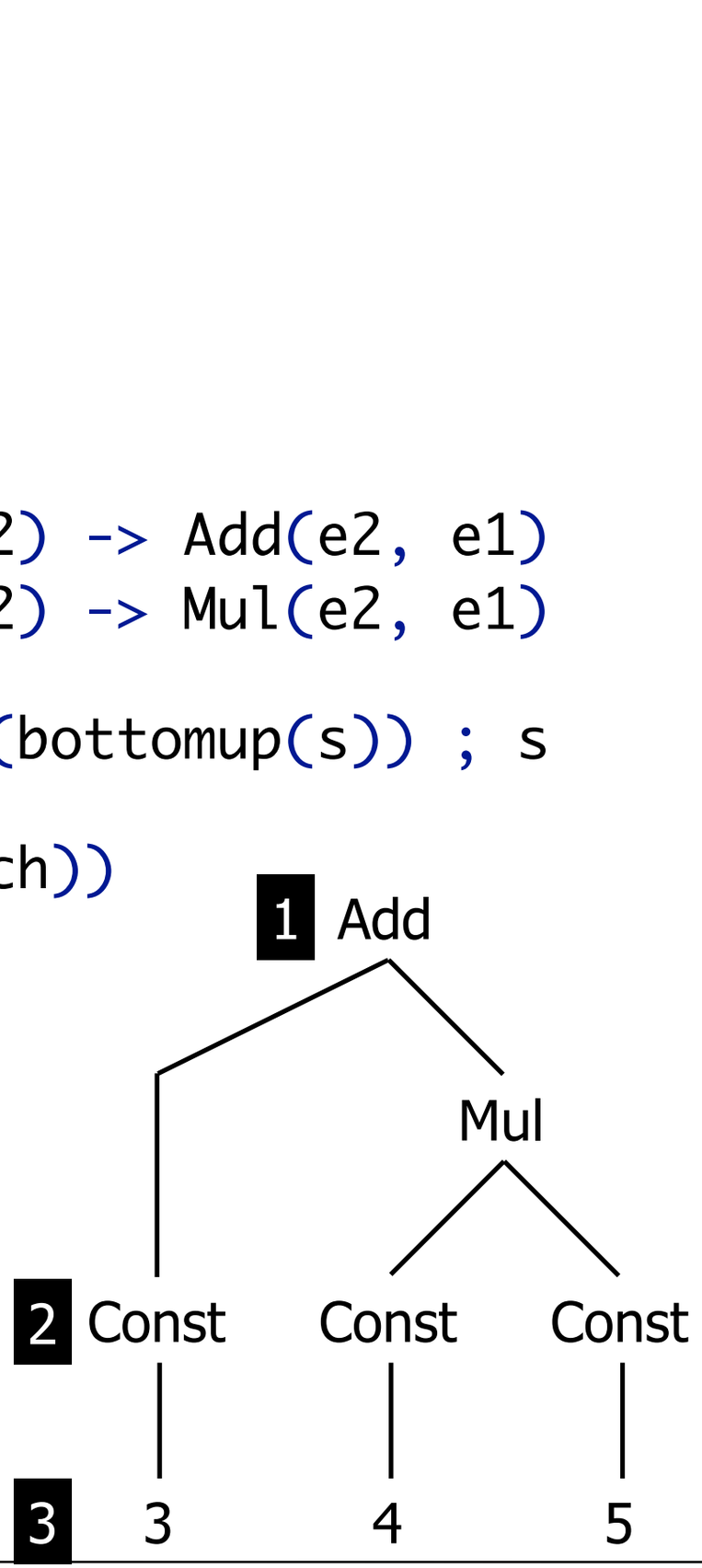

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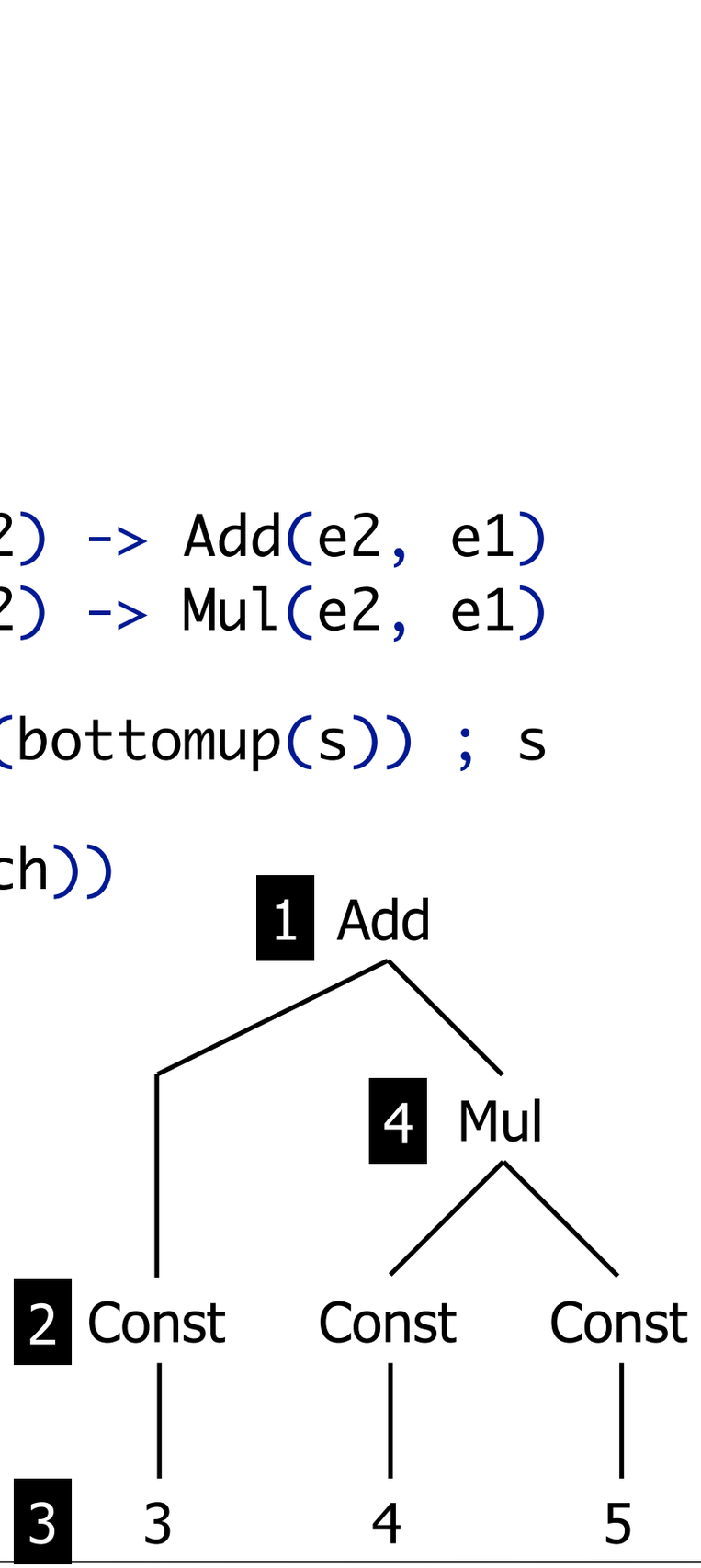

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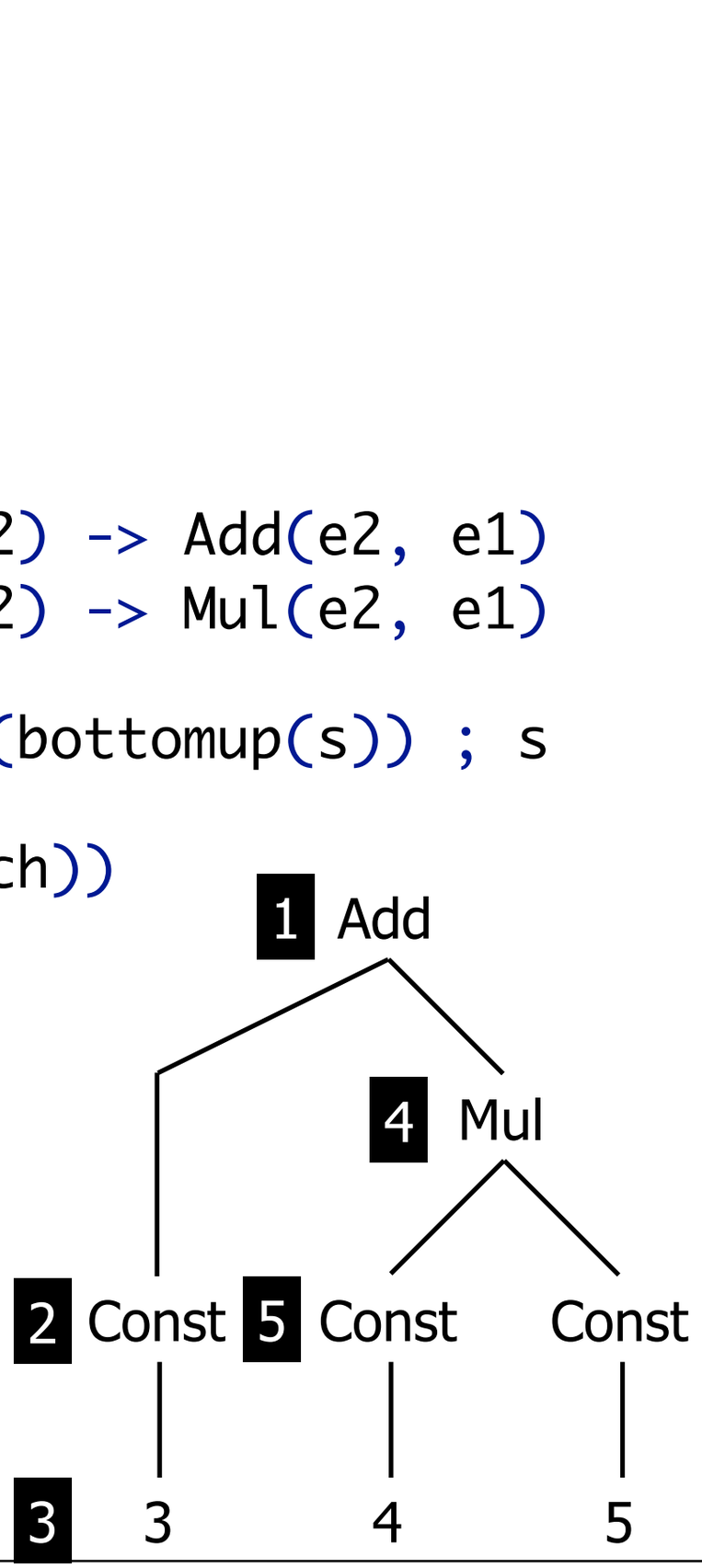

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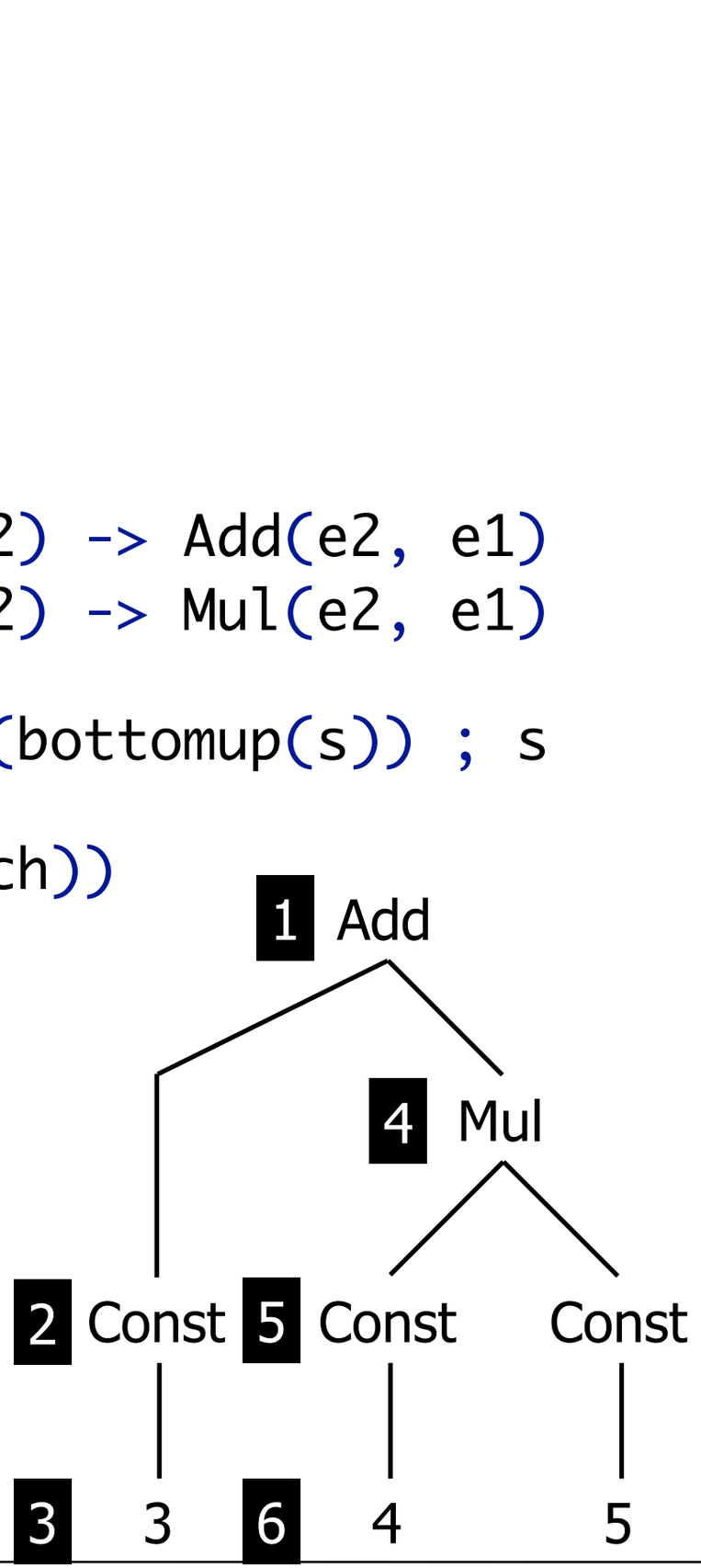

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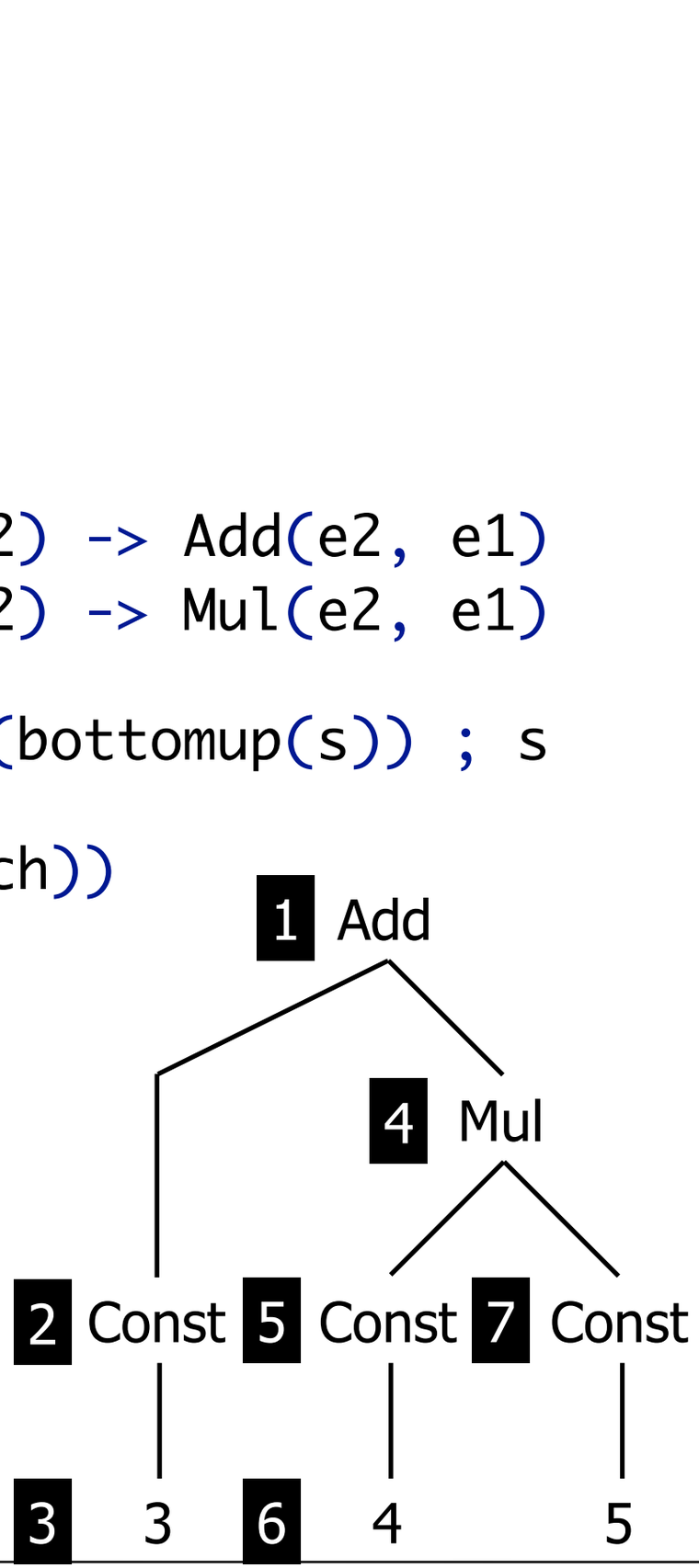

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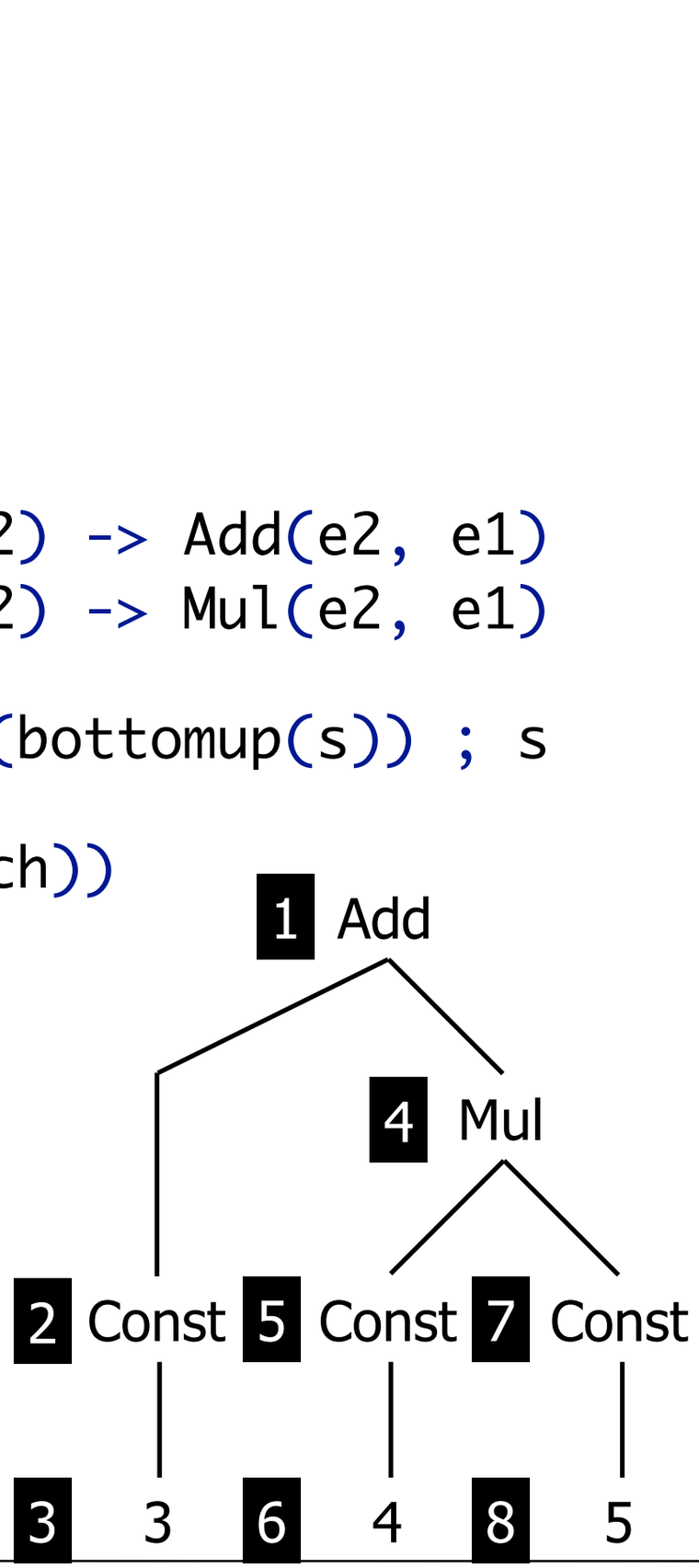

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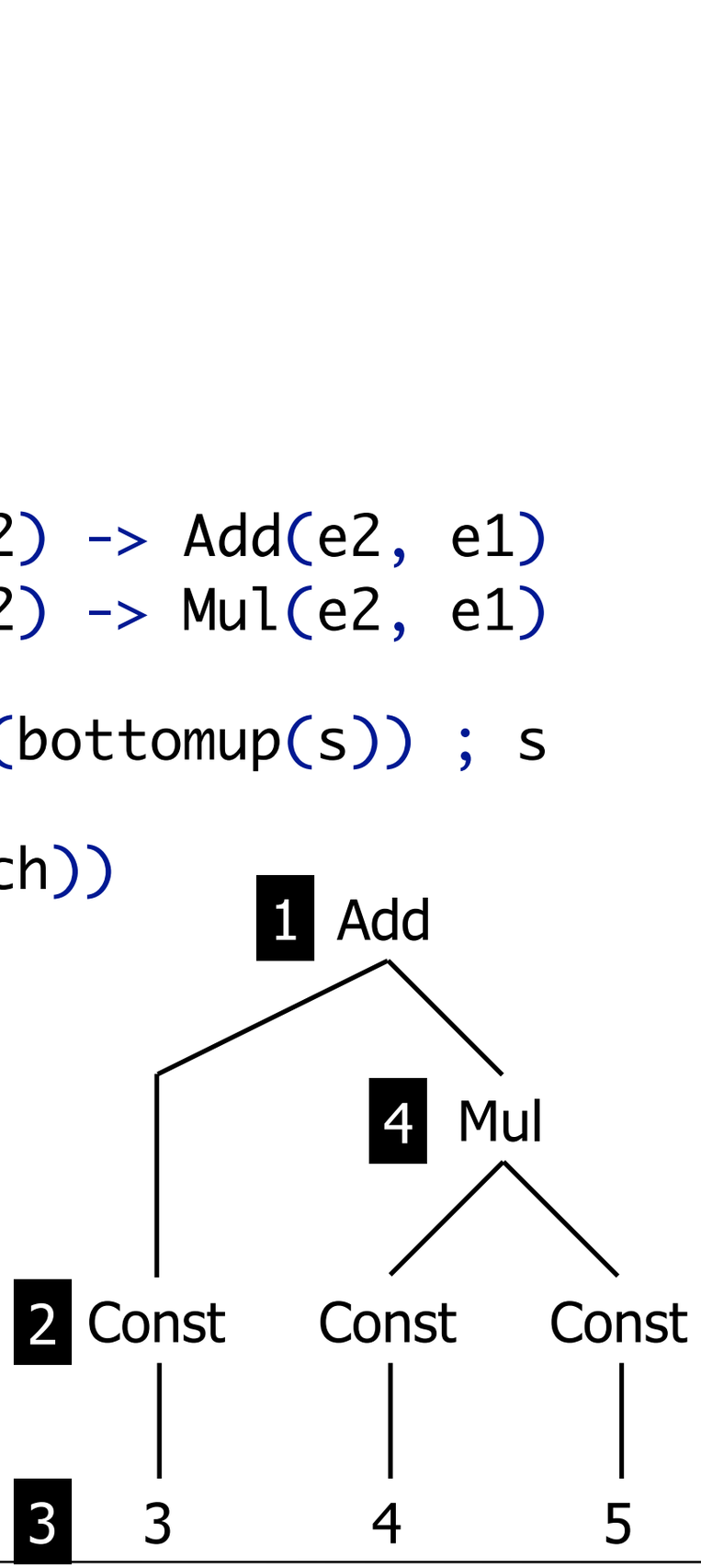

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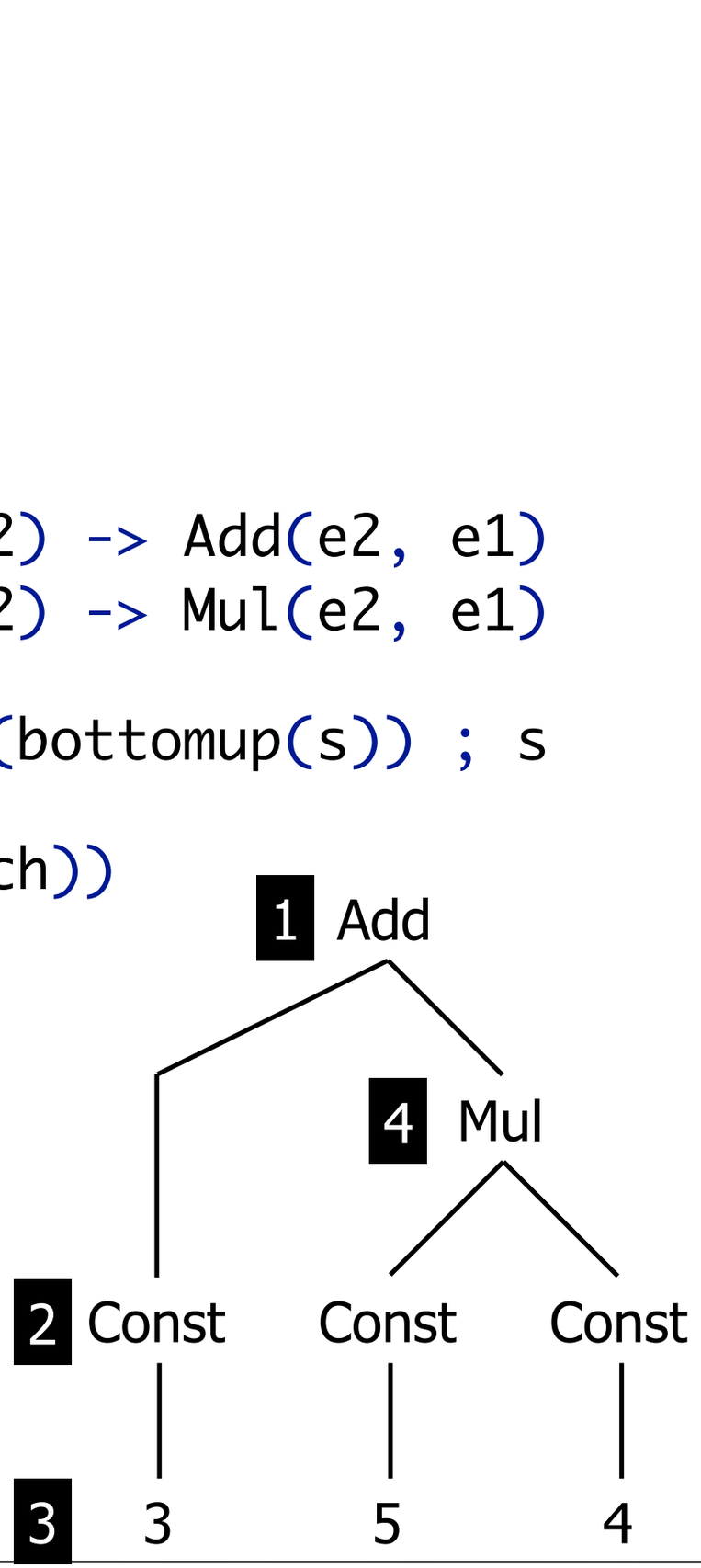

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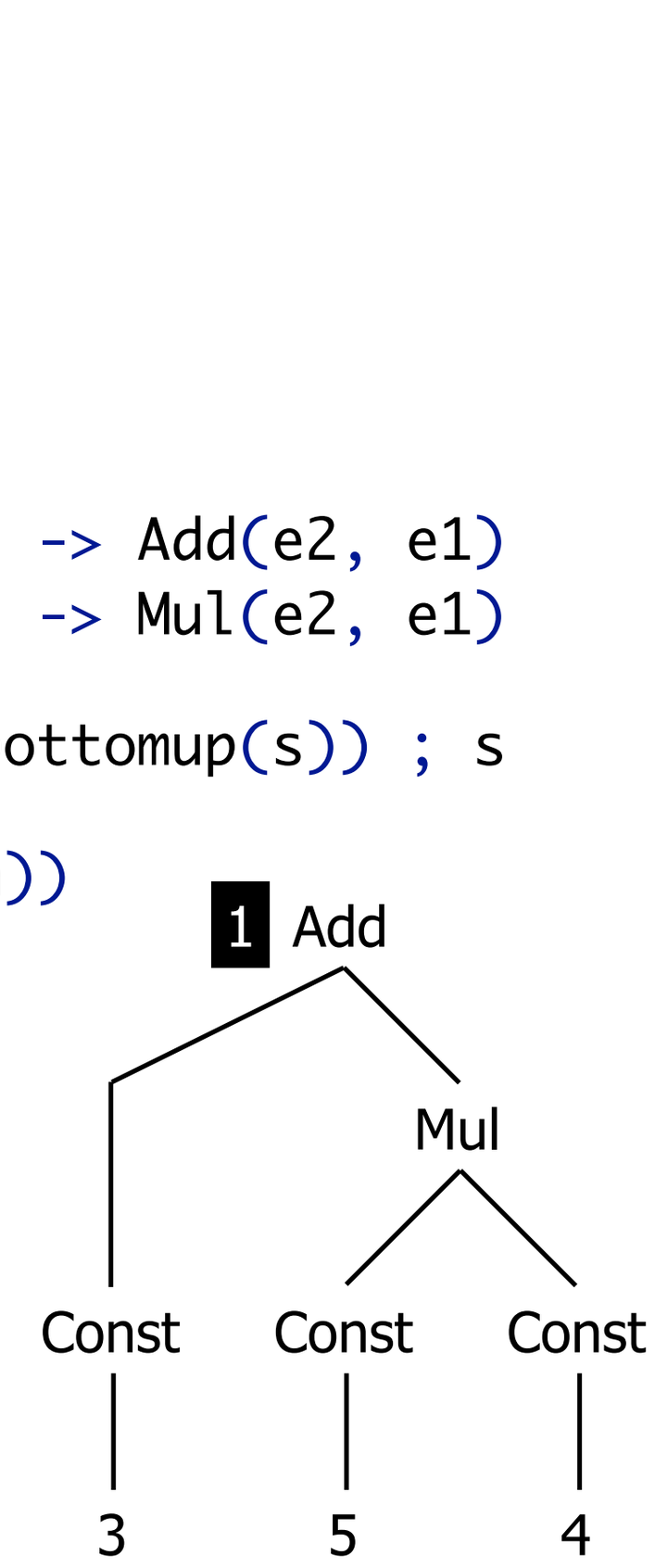

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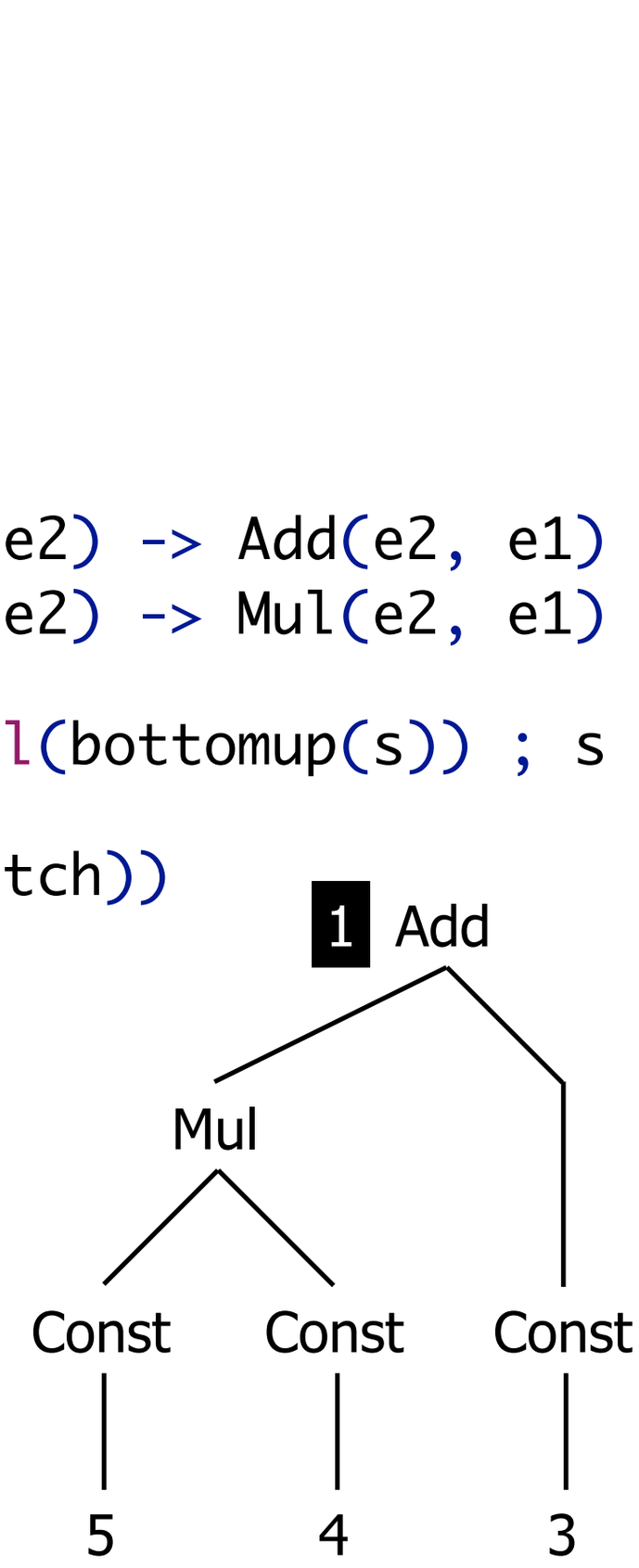

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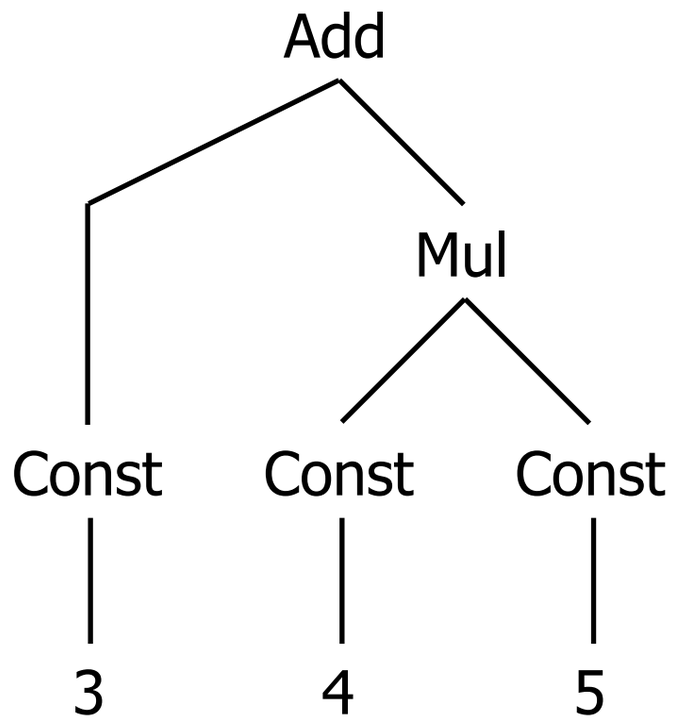

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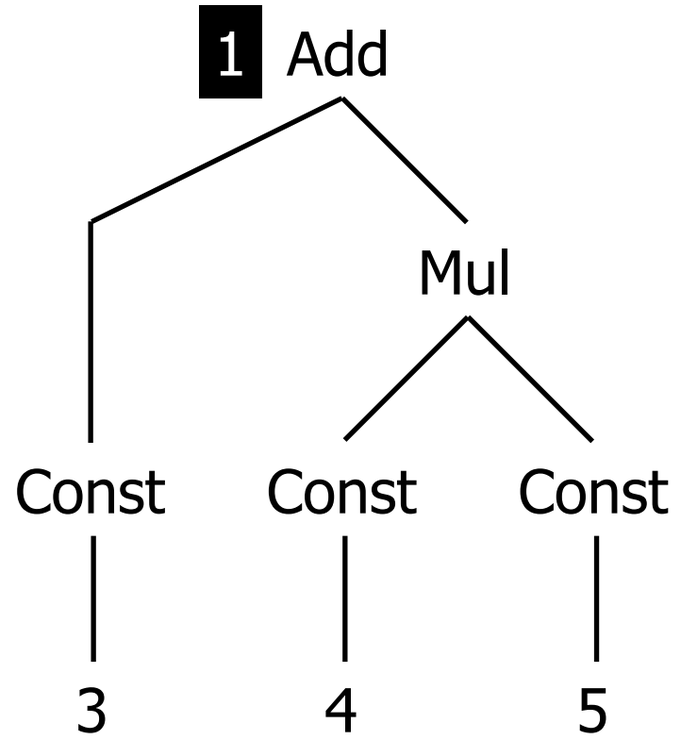

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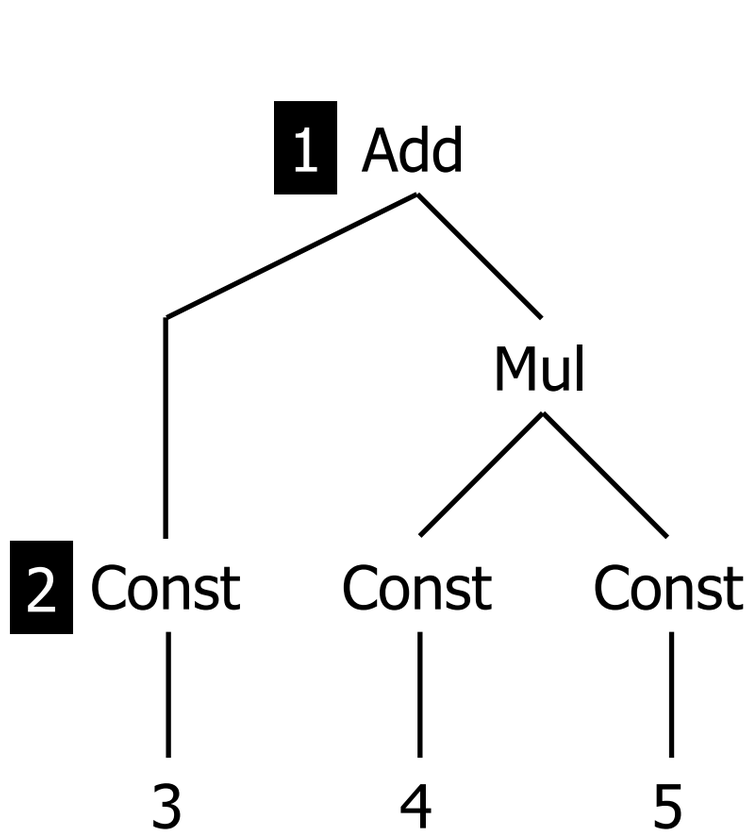

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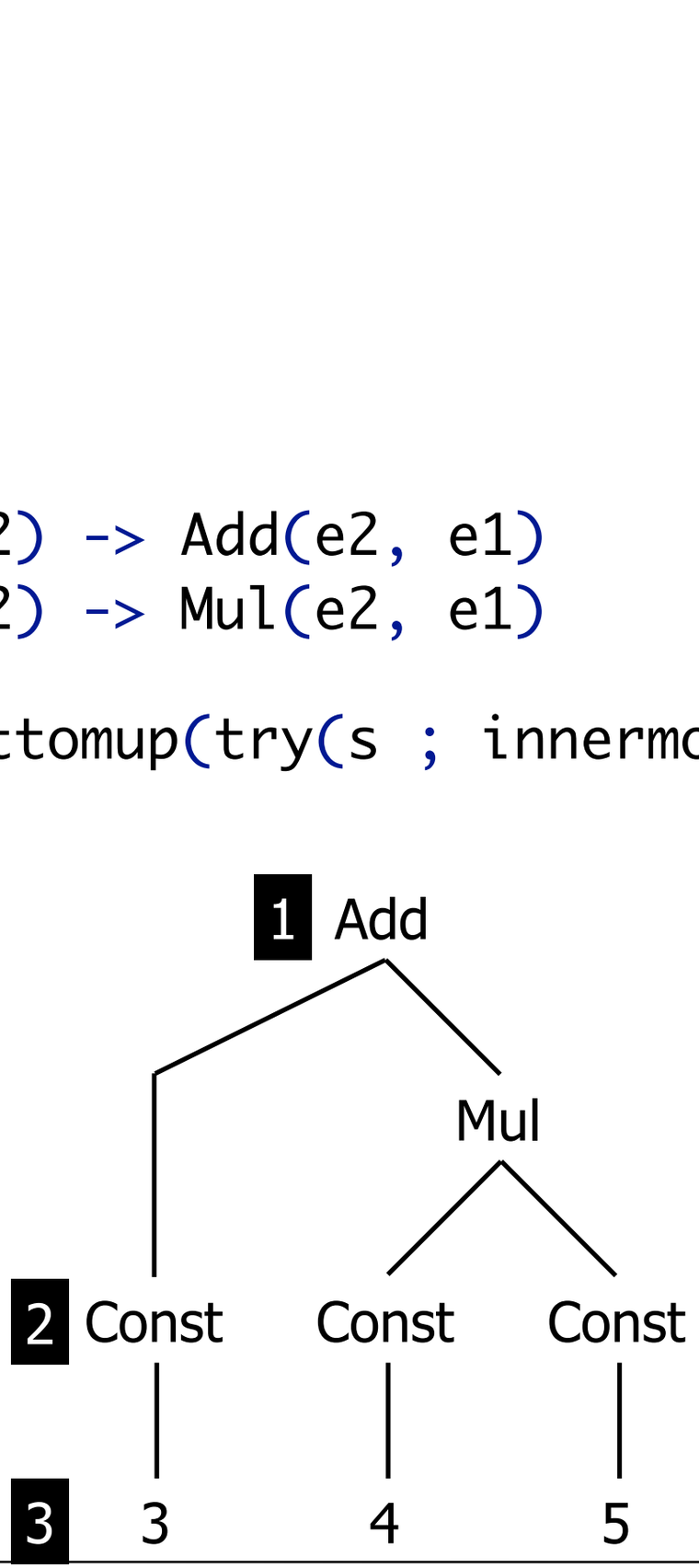

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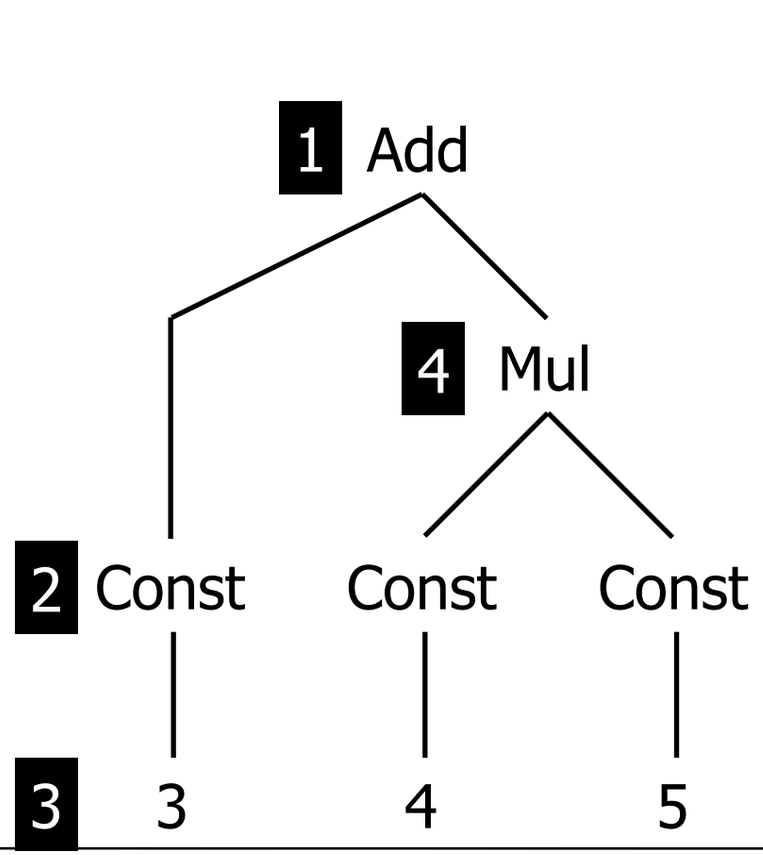

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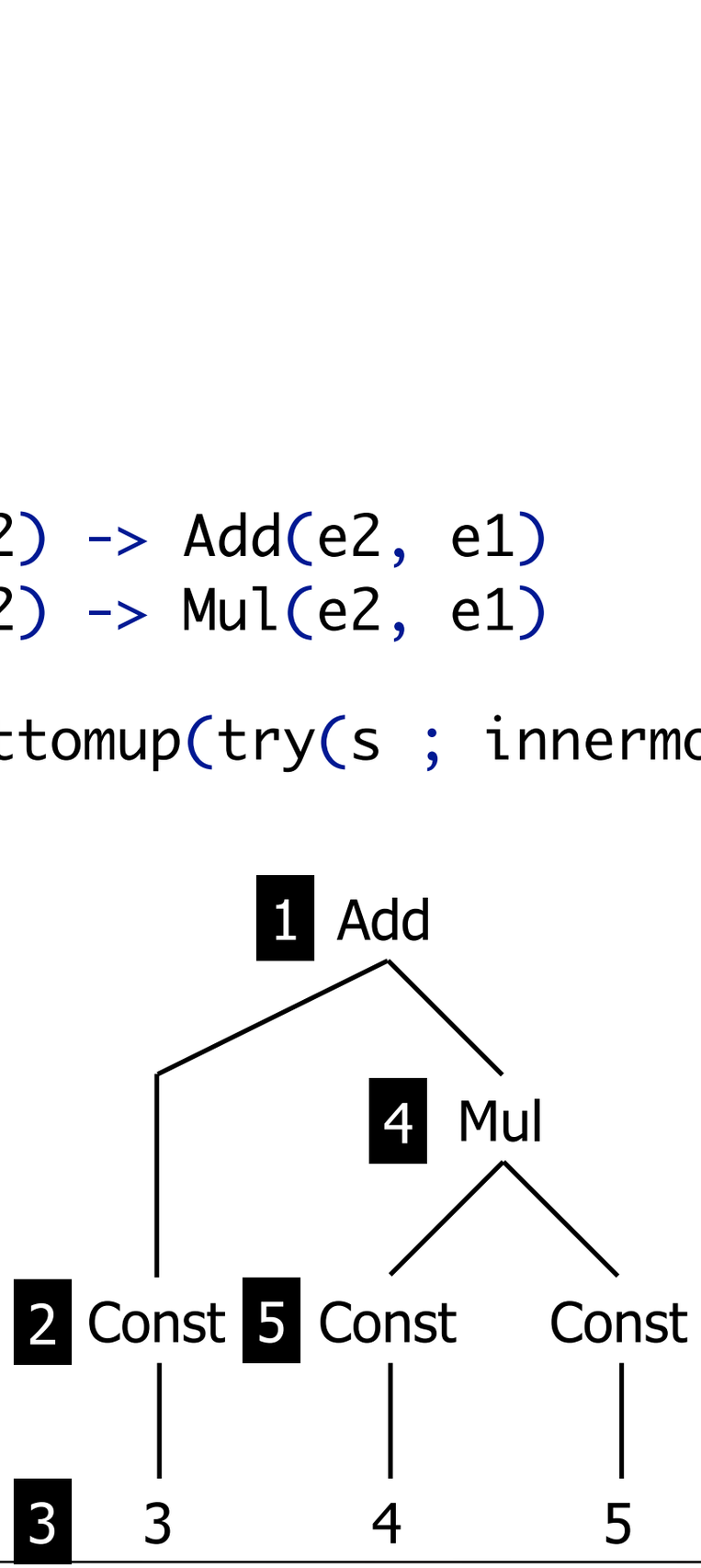

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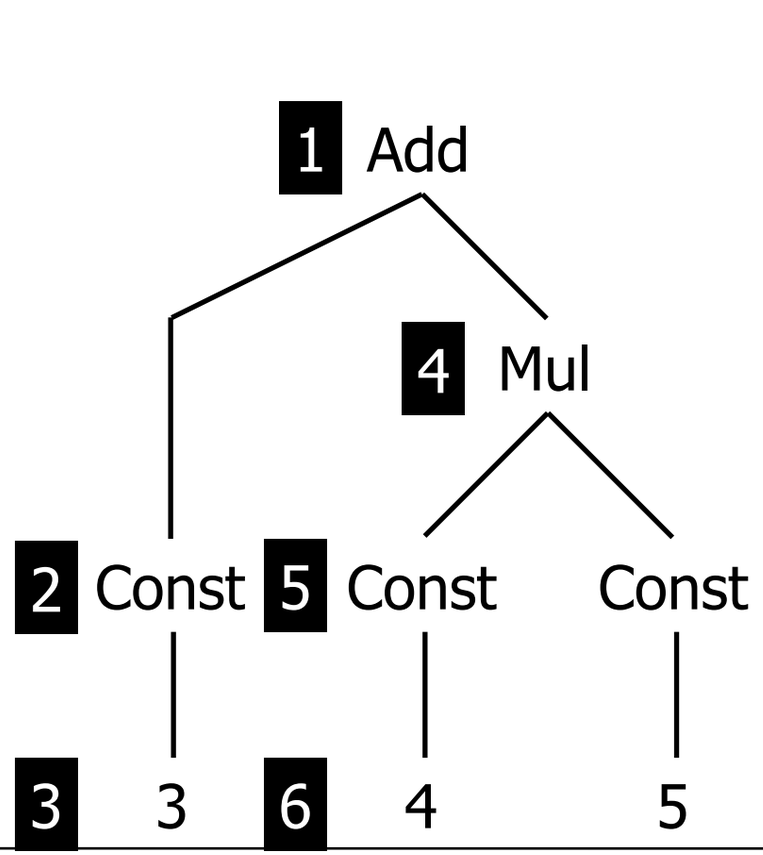

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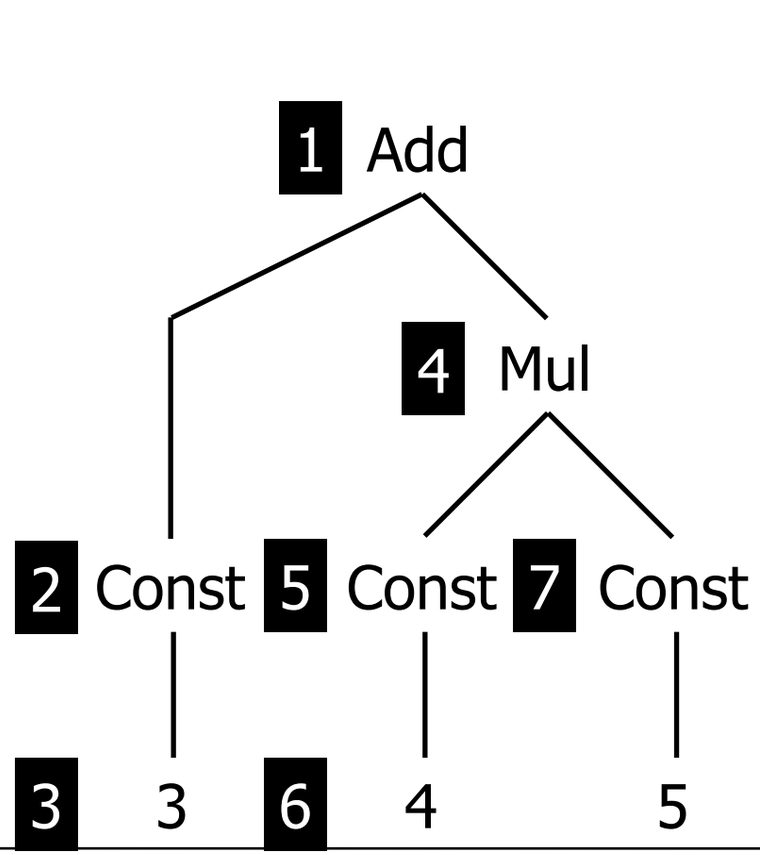

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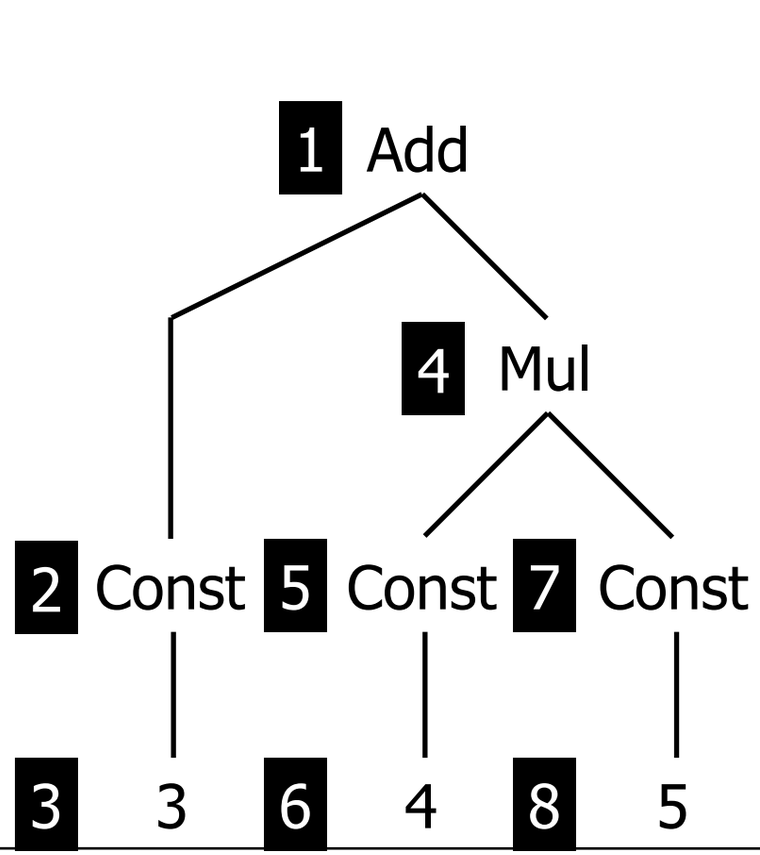

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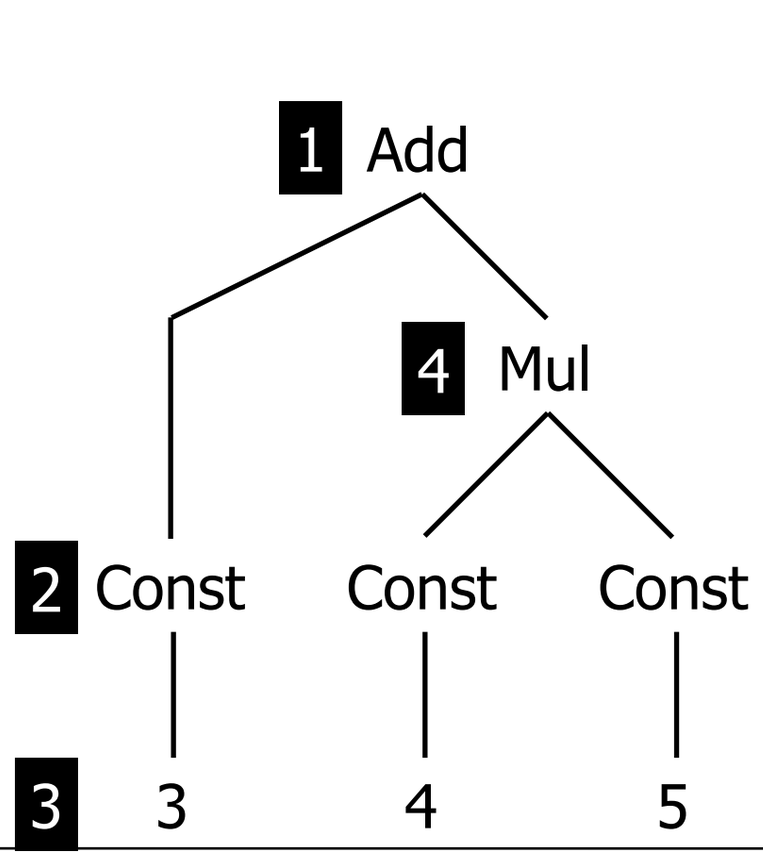

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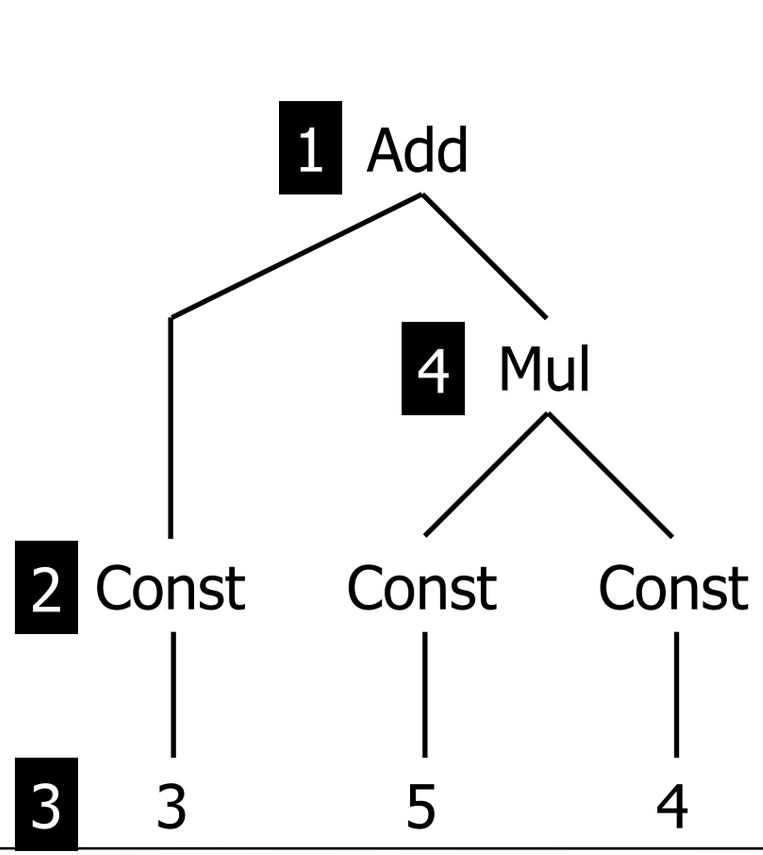

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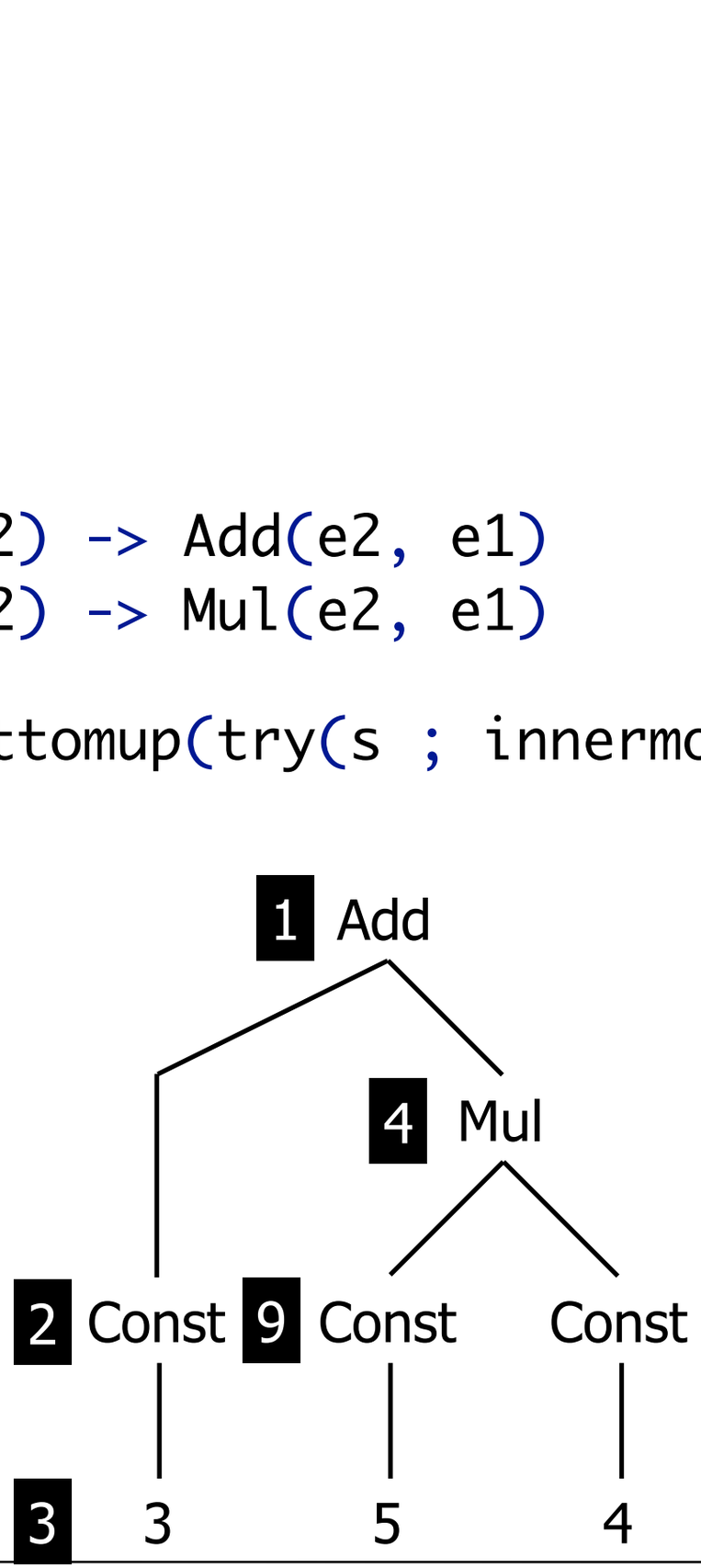

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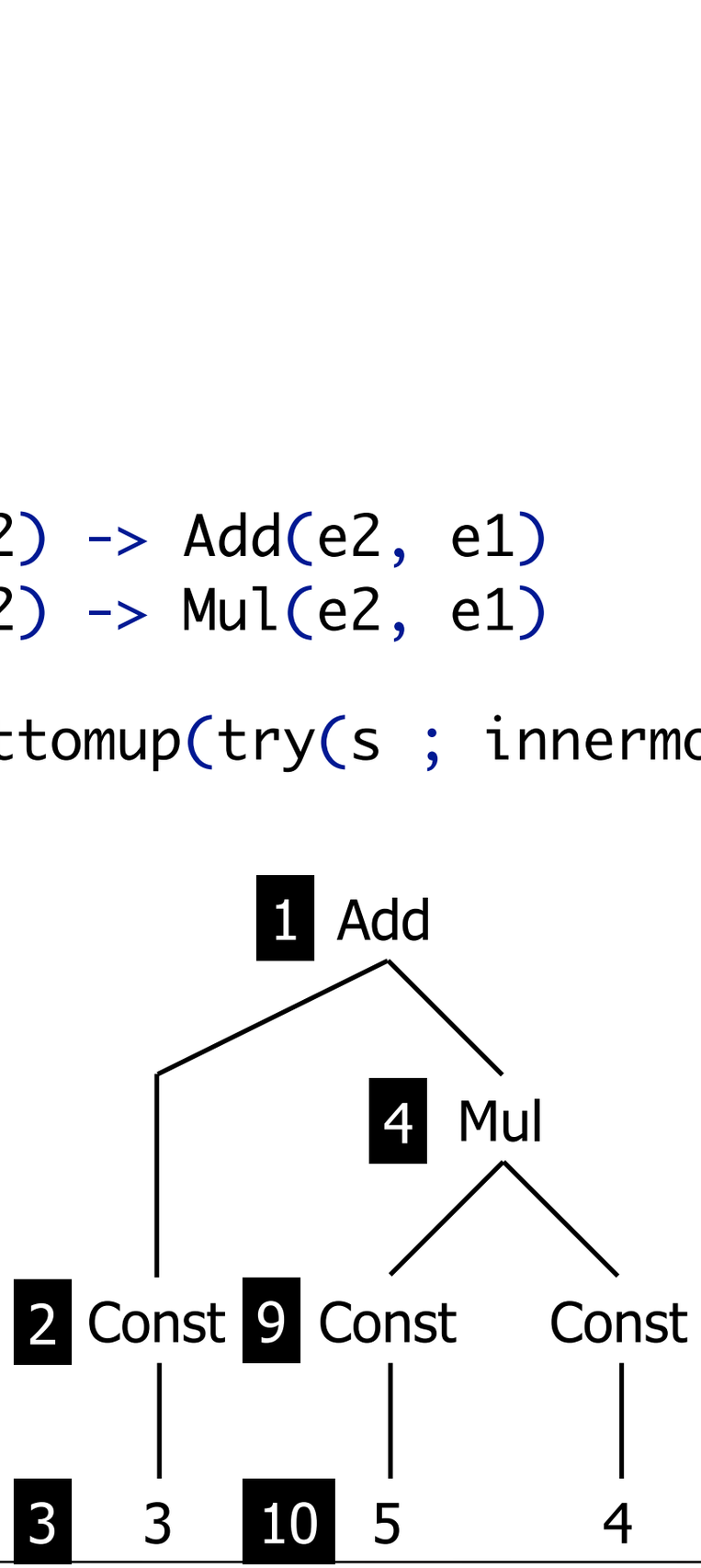

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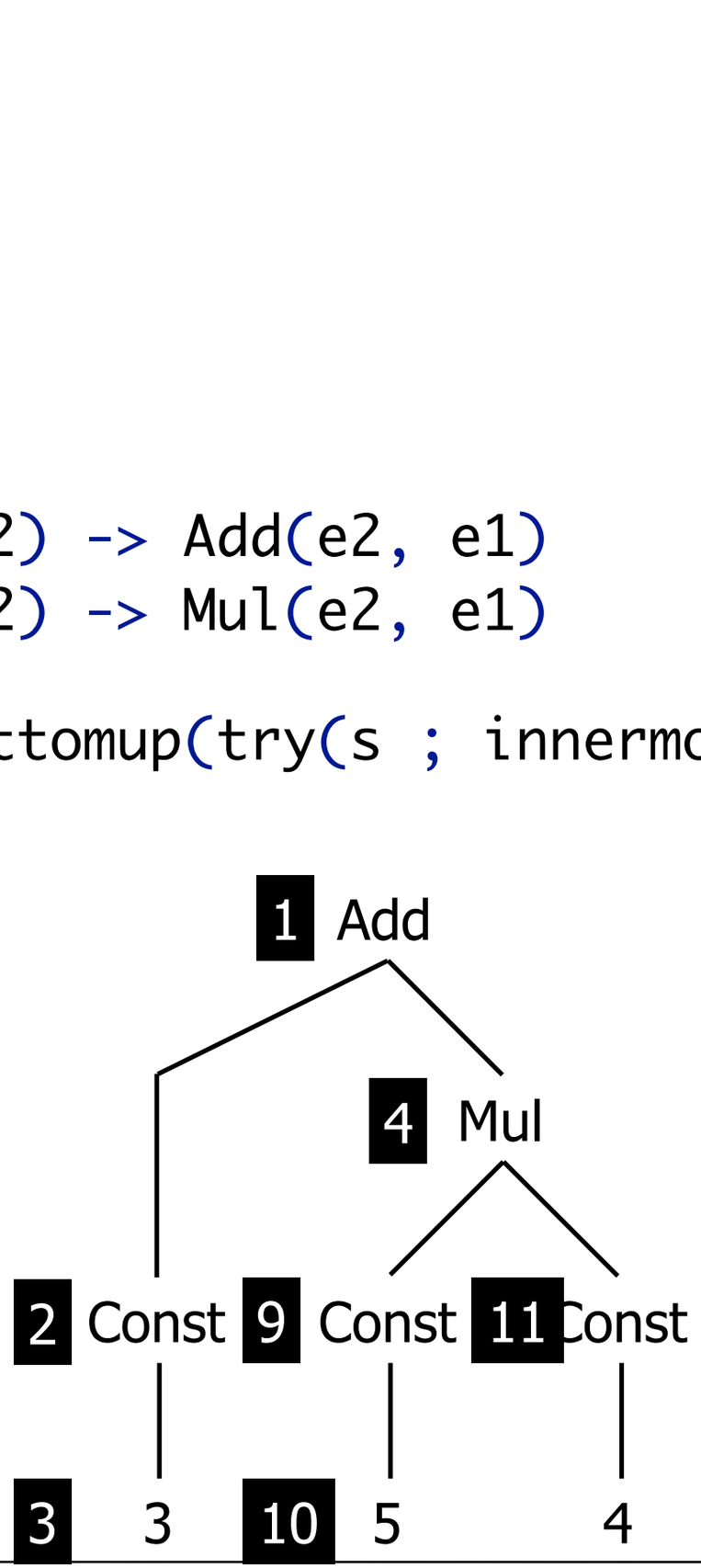

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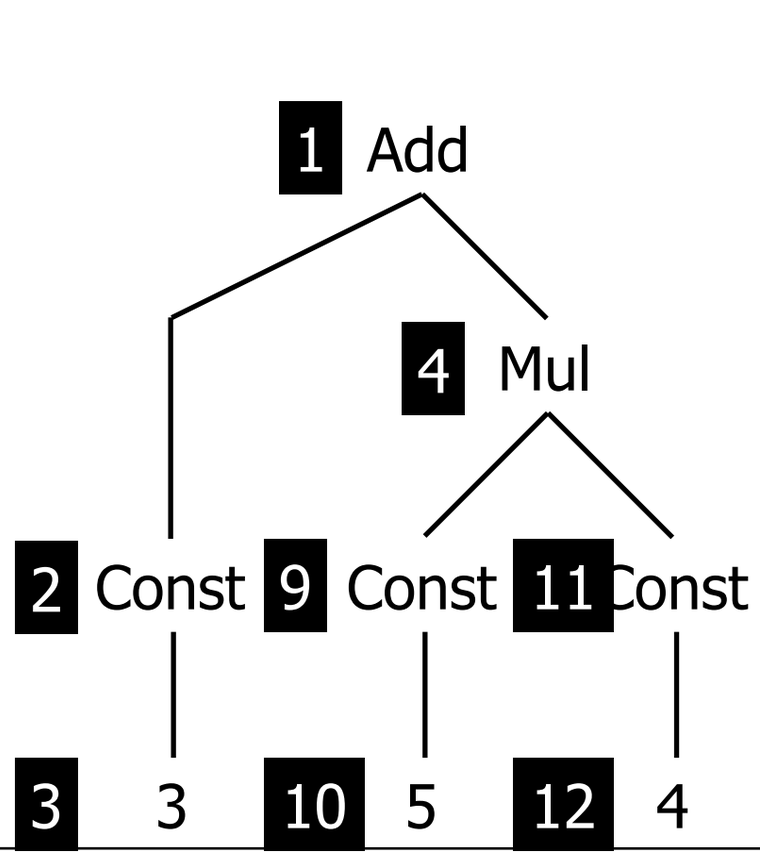

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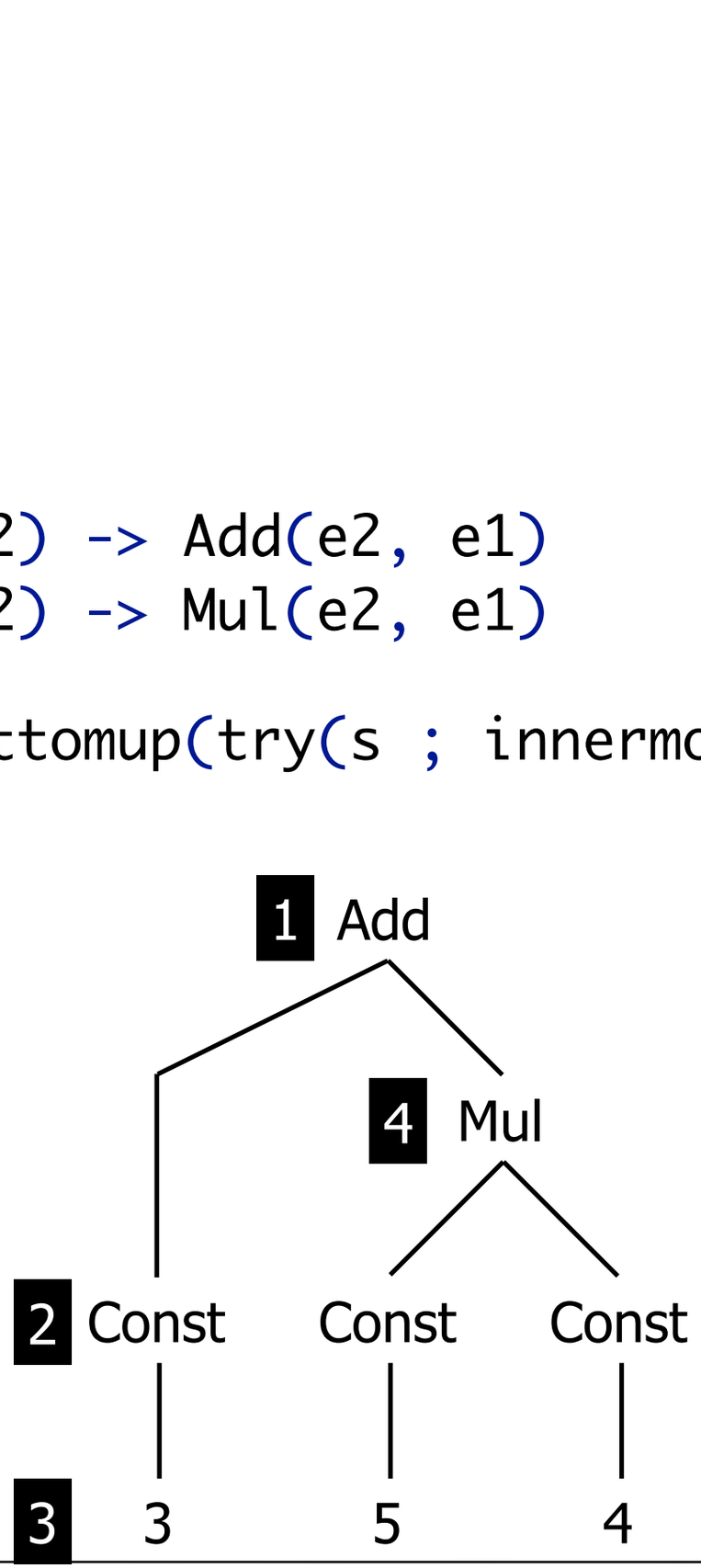

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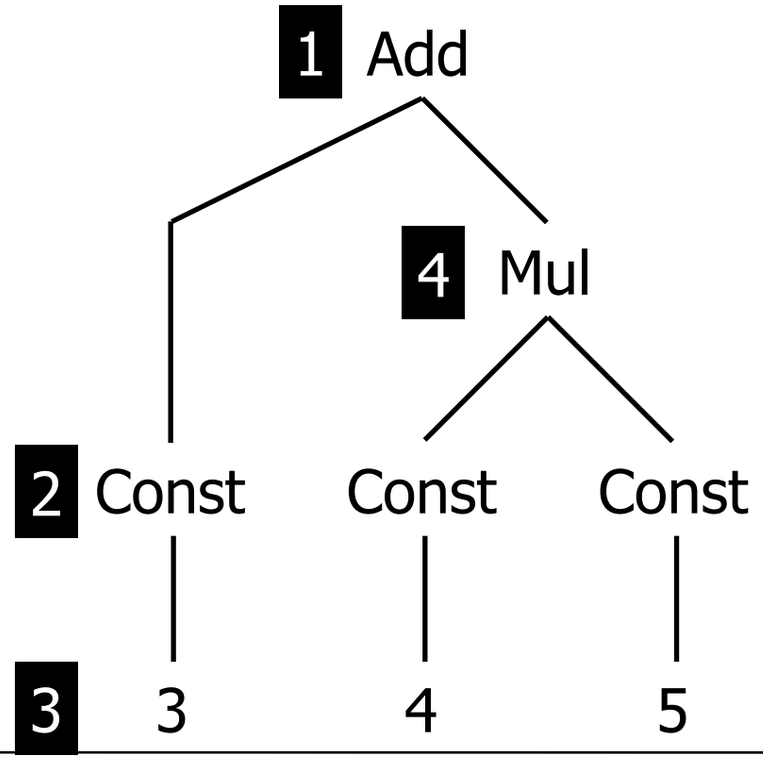

Summary
lessons learned

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How do you define AST transformations in Stratego?

- signatures
- rewrite rules
- rewrite strategies
- strategy combinators

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- signatures
- rewrite rules
- rewrite strategies
- strategy combinators

What kind of strategies can you find in the Stratego library?

- arithmetics
- map, zip, foldr
- generic traversals

Literature

learn more

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Spoofax

Lennart C. L. Kats, Eelco Visser: The Spoofax Language Workbench. Rules for Declarative Specification of Languages and IDEs. OOPSLA 2010

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Stratego

Martin Bravenboer, Karl Trygve Kalleberg, Rob Vermaas, Eelco Visser: Stratego/XT 0.17. A language and toolset for program transformation. Science of Computer Programming, 72(1-2), 2008.

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