functional scala 2024
Presents

Recognizing Regular Patterns in Heterogeneous Sequences

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Overview

History

Publication History

- Regular Type Expressions (RTEs) introduced at ELS 2016 (European Lisp Symposium), implemented in Common Lisp.
  `https://www.lrde.epita.fr/wiki/Publications/newton.16.els`
- See PhD Thesis 2018 for theoretical, implementation, and performance details
  `https://www.lrde.epita.fr/wiki/Publications/newton.18.phd`
- RTE Available:

Scala	`https://github.com/jimka2001/scala-rte`
Clojure	`https://github.com/jimka2001/clojure-rte`
Python	`https://github.com/jimka2001/python-rte`
Common Lisp	`https://github.com/jimka2001/cl-rte`

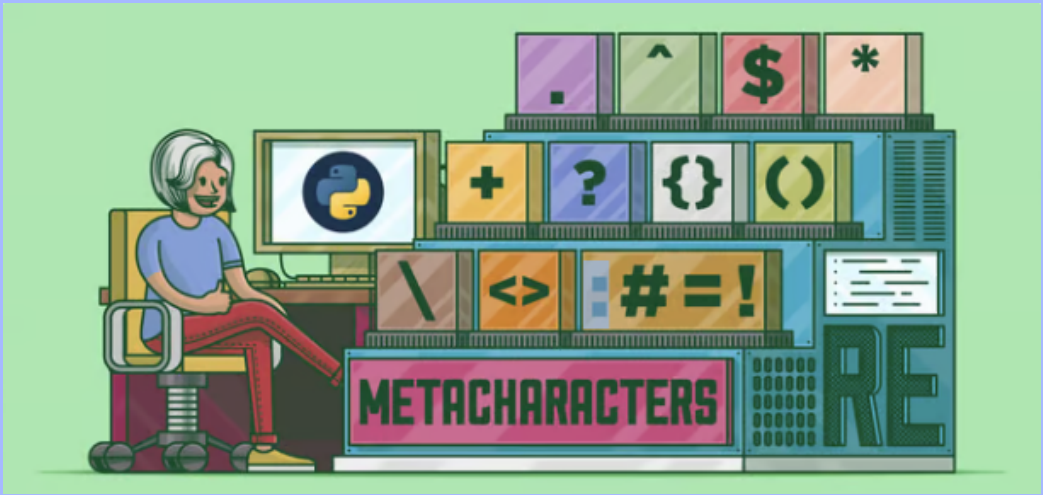
- PADL 2025, Practical Aspects of Declarative Languages:
  Type-Checking Heterogeneous Sequences in a Simple Embeddable Type System

Goal

- Efficiently recognize *regular patterns* in mixed-type sequences.
- Supported in Scala as `Seq[Any]`.

Example

Regular Type Expressions (RTEs)



Regular Type Expressions (RTEs)

We'd like to recognize sequences with *regular patterns*.

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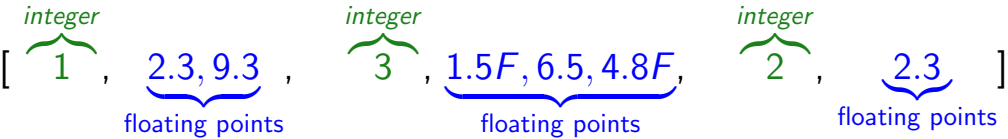

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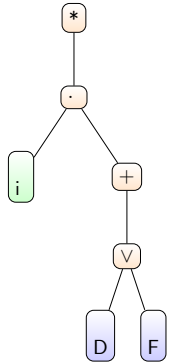
String-based regular expressions

- Match strings like: `"iDDiFDFiD"`,
- ... we use surface syntax: `"(i(D|F)+)*"`.
- ... representing expression: $(i \cdot (D \vee F)^{+})^{*}$,



Abstract Syntax Tree (AST)

Regular Type Expressions (RTEs)

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We propose Rational Type Expressions (RTEs)

- Rational type expression: (Int $\cdot$ (Double $\cup$ Float)$^+$)*
- *Challenge №1:* We need a surface syntax (and AST) for Scala.

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```
[13 2.0 6.0 4 "a" "an" "the" -5 2.0 3.0 4.0 7 8.0]
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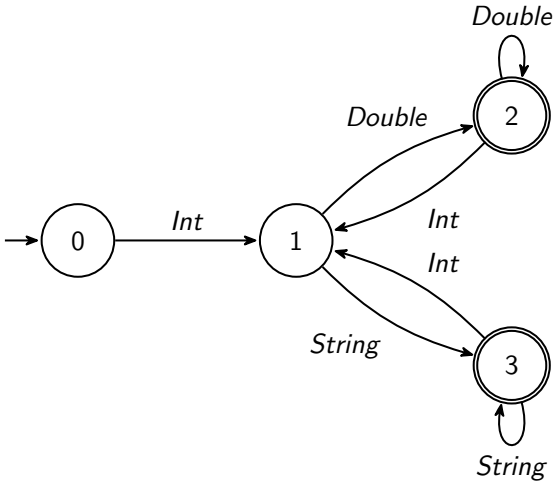
Does the sequence match the pattern?
$(Int \cdot (Double^+ \ \vee String^+))^+$

We construct a finite automaton (DFA).

Challenge #2: How to construct a finite automaton from an RTE?



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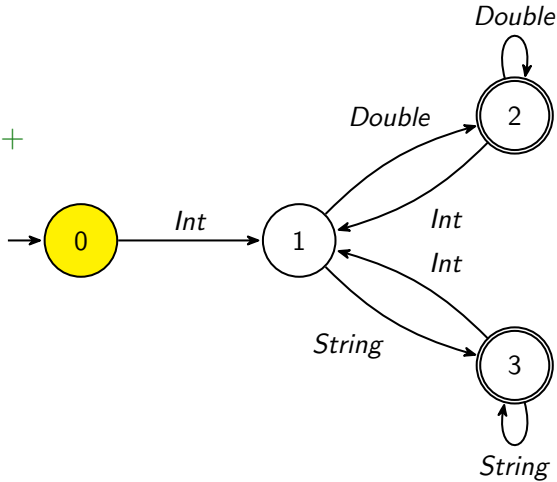

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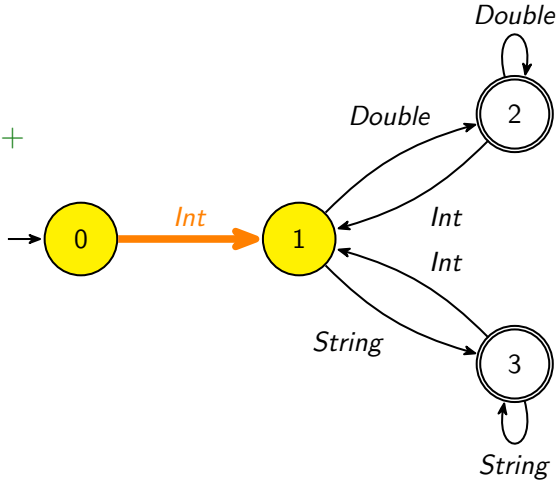

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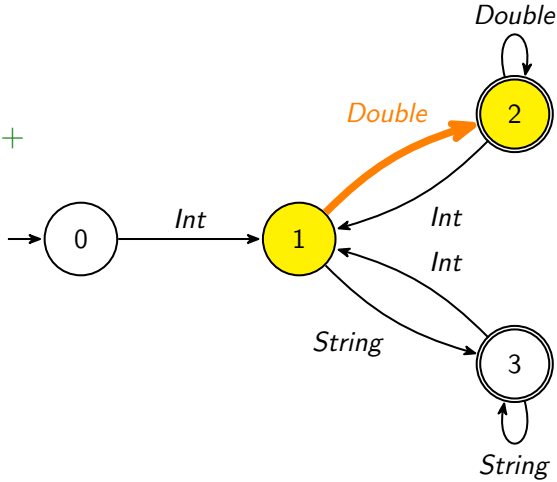

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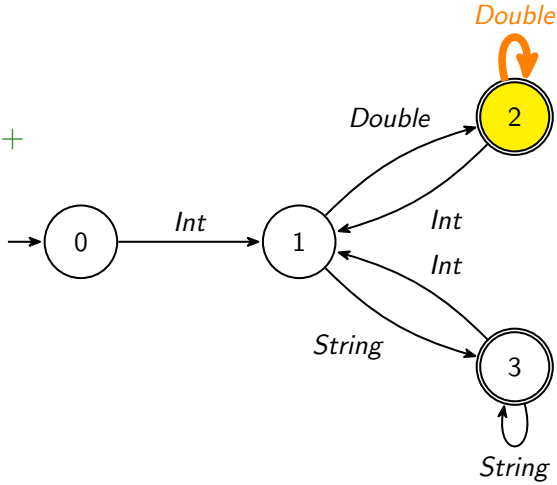

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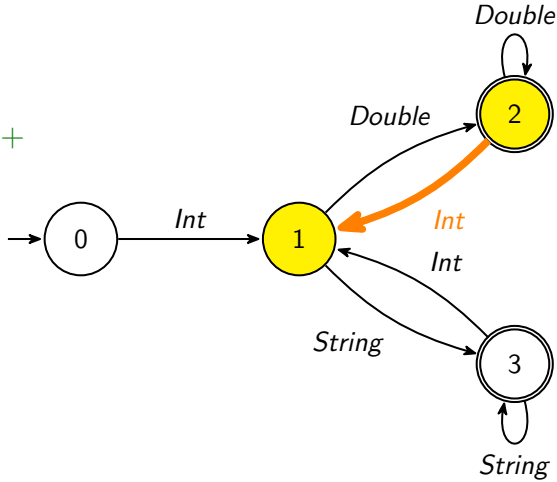

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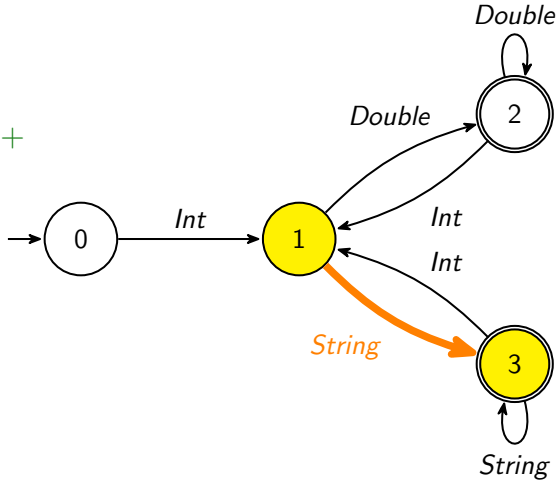

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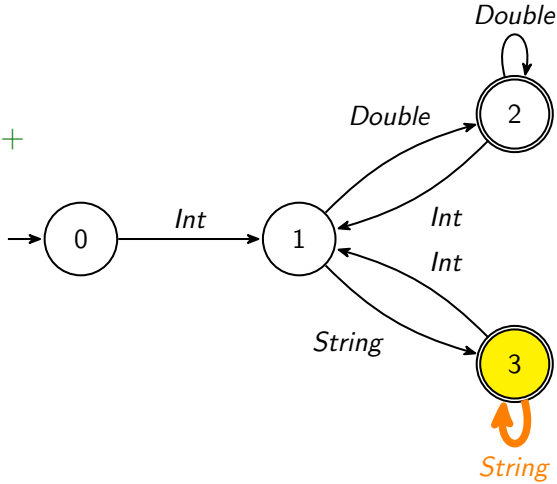

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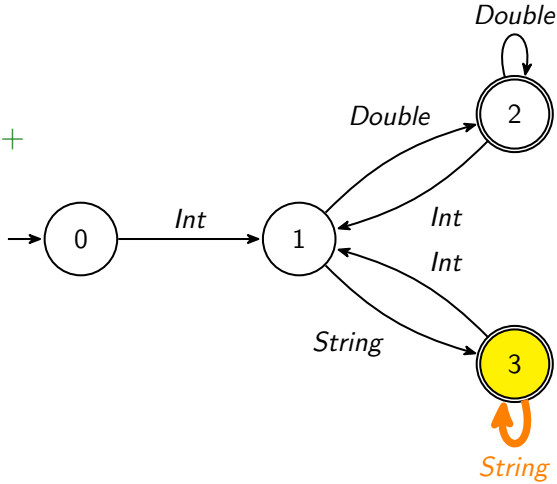

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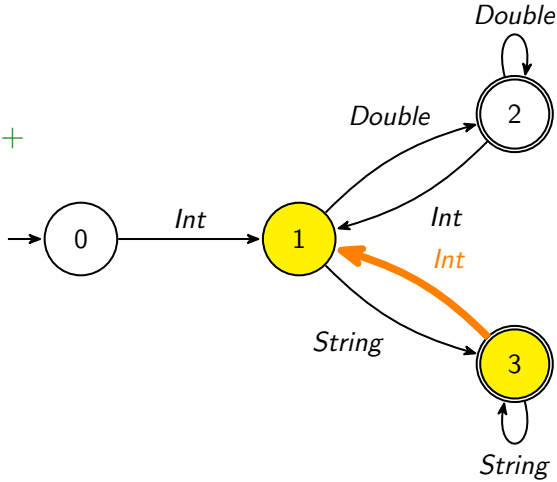

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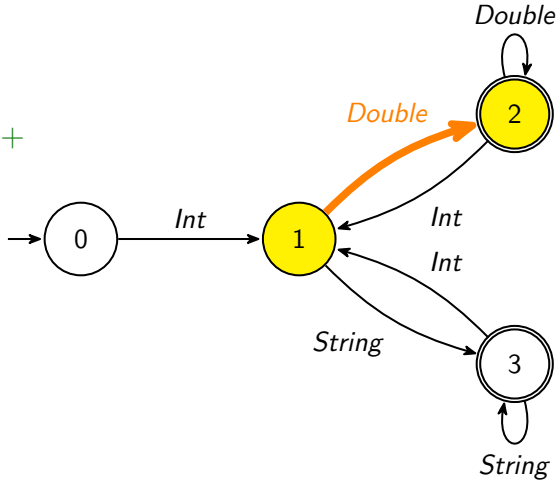

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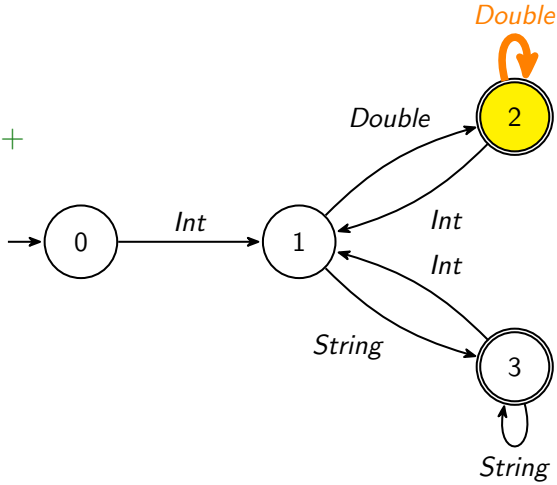

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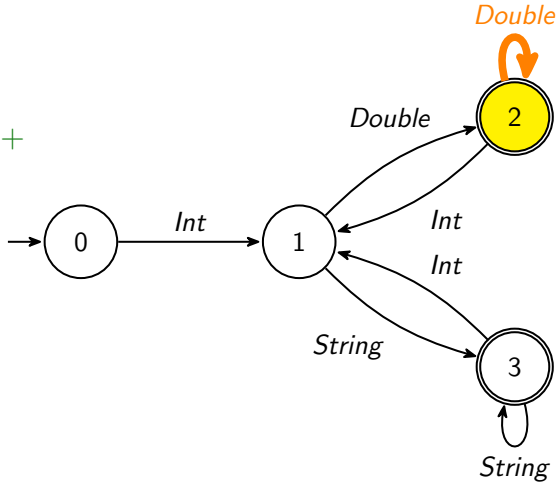

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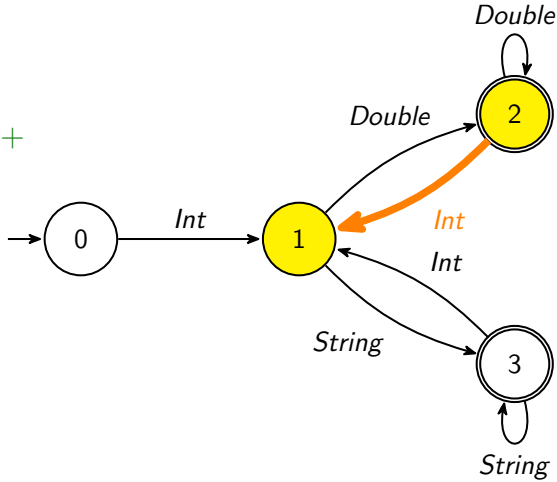

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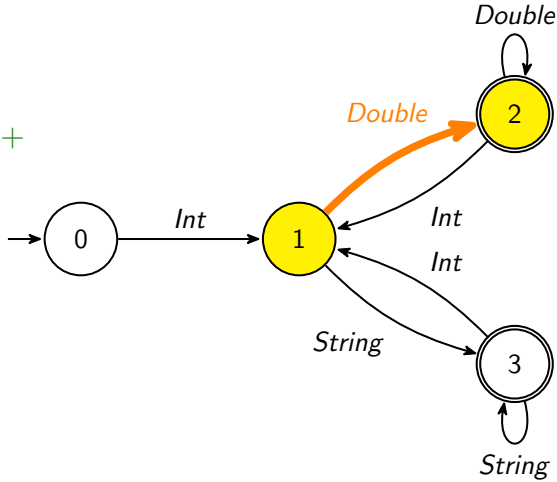

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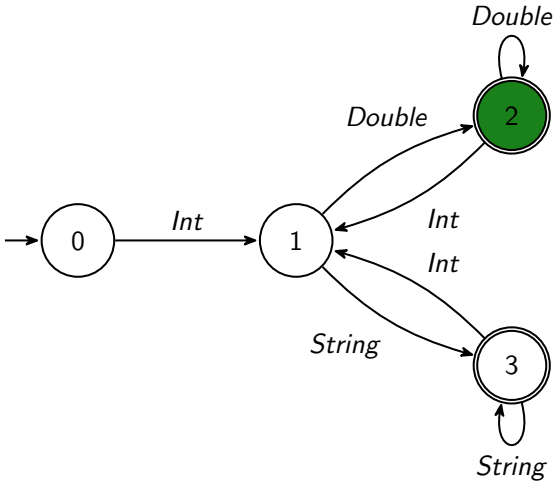
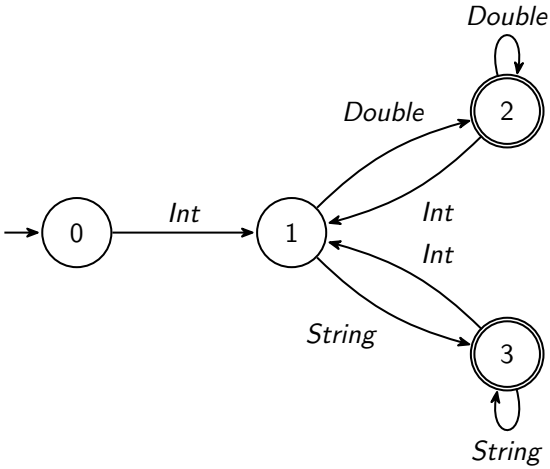


Yes, it's a match!

Example 1: How does a pattern predicate work?

Decision procedure is $O(n)$, *independent of syntactical complexity* of the RTE.

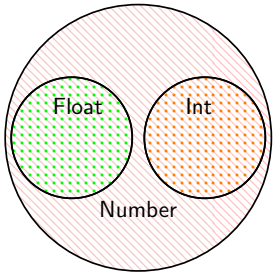


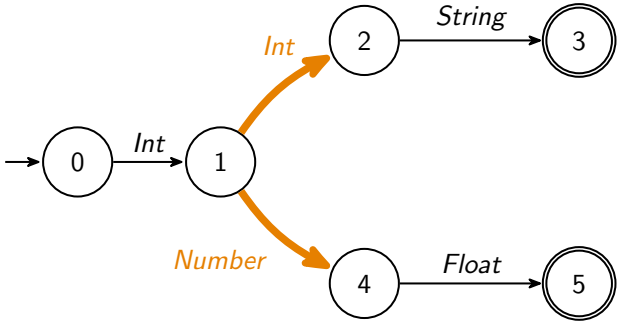
Deterministic (DFA) vs Non-deterministic (NFA)

Suppose sequence = `[2, 3, 5.6F]`

$Int \subseteq Number$

$Int \cap Number \neq \emptyset$





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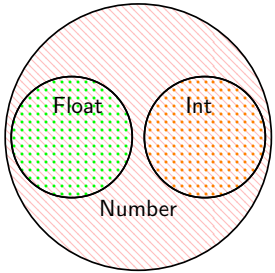

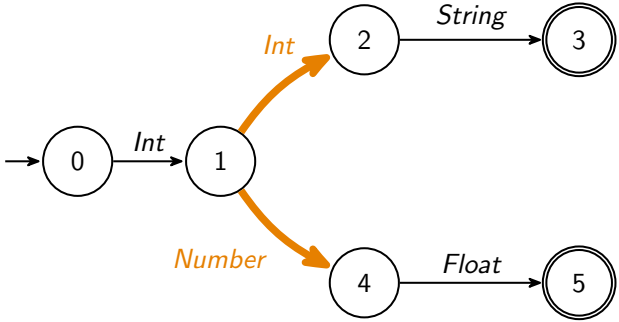

Backtracking?

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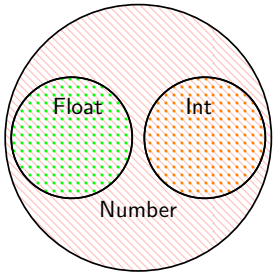

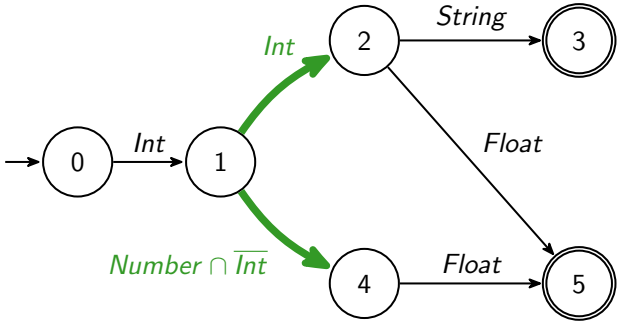

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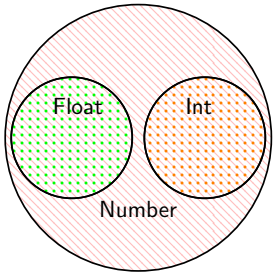

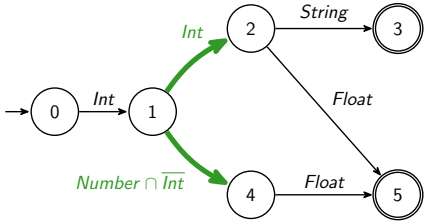

Challenge №3: How to support $Int \cap \overline{Number}$ in Scala?

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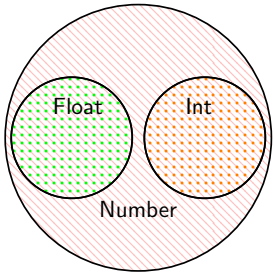

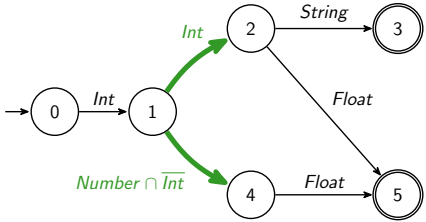

Challenge №3: How to support $Int \cap \overline{Number}$ in Scala?

Challenge №4: How to partition types?

E.g., type decomposition

$\{String, Int, Number\} \rightarrow \{String, Int, Number \cap \overline{Int}\}$

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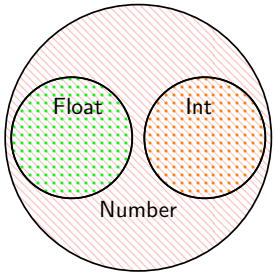
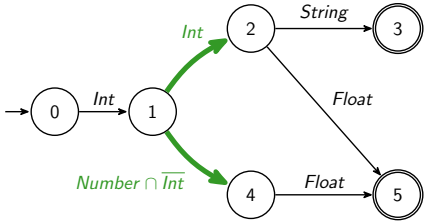




Challenge №3: How to support $Int \cap \overline{Number}$ in Scala?

Challenge №4: How to partition types?

Challenge №5: How to avoid duplicate type checks?

Challenges of the Project

- *Challenge № 1:* RTE Representation: Representing an RTE in Scala?
- *Challenge № 2:* DFA Construction: Constructing from RTE?
- *Challenge № 3:* Type Lattice: Union, intersection, complement types?
- *Challenge № 4:* Determinism: Type partitioning?
- *Challenge № 5:* Efficiency: Avoiding redundant type checks at run-time?

Challenge №1: RTE Representation

How to represent an RTE in Scala?

- Surface syntax: declarative, expressive, composable
- Programmatic interface: reflective, algebraic manipulation

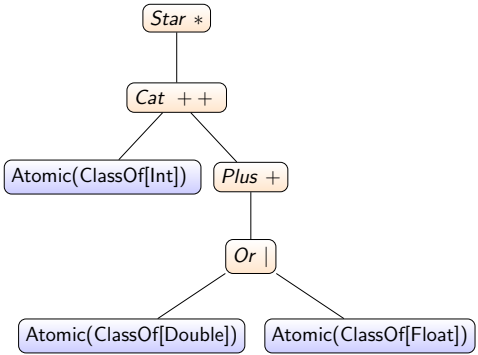
RTEs

What are Regular Type Expressions?

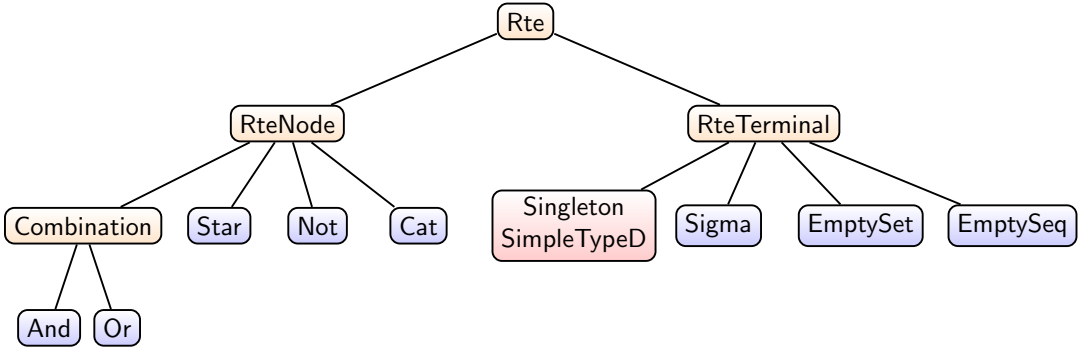
- Mathematical notation:
  $(Int \cdot (Double \cup Float)^{+})^{*}$
- Scala notation: AST

```
1  val I:Rte = Atomic(classOf[Int])
2  val F:Rte = Atomic(classOf[Float])
3  val D:Rte = Atomic(classOf[Double])
4
5  val re:Rte = (I ++ (D | F).+ ).*
```

- Leaf nodes interface to Scala Type System



`Rte` class quasi-ADT, Algebraic Data Type



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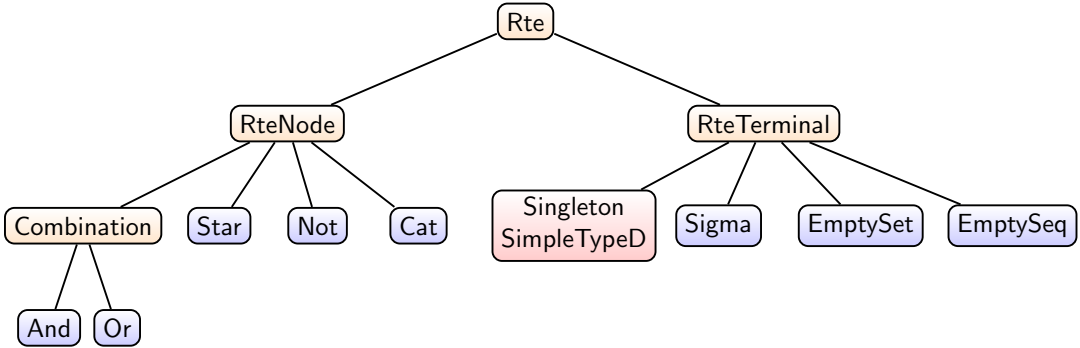


More on `SimpleTypeD` later ...

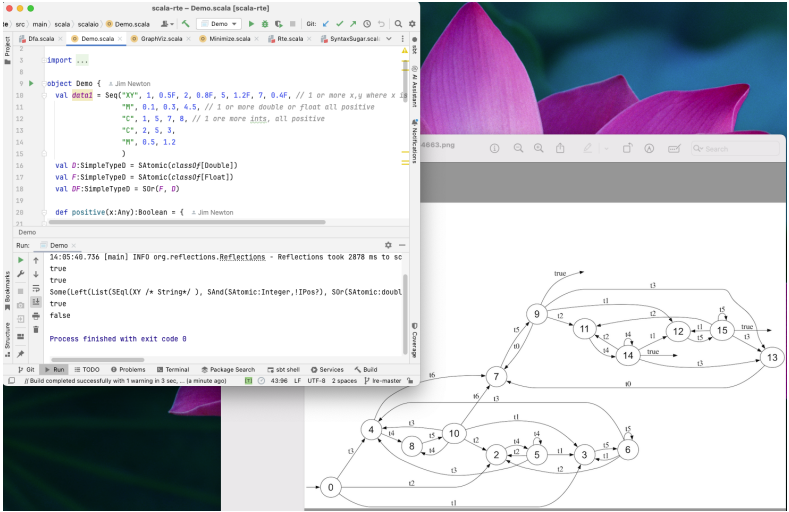
Challenge №2: DFA Construction

Given an RTE, generate a finite automaton.

- Well-known techniques exists to construct DFAs from RE
  - Brzozowski Derivative
- Adapt them to work with RTEs
- Enforce determinism

Demo

Sample Flow



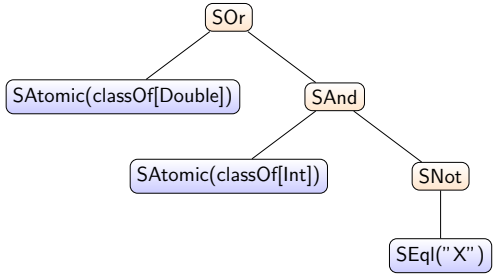
Challenge №3: Type Lattice

How to support types like $Int \cap \overline{Number}$ in Scala?

- Support *complemented type lattice*
- Embed a dynamic type system into an existing programming language.
- Answer type membership and subtype questions.

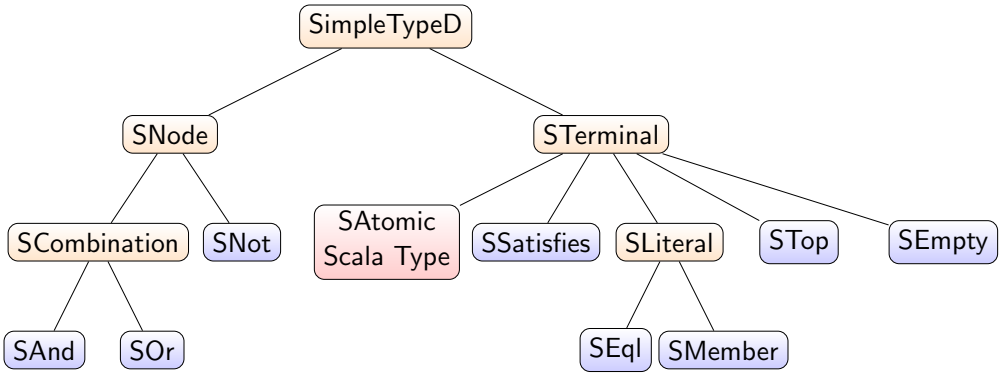
Example `SimpleTypeD` Expression Tree: AST

```
1 val Int     = SAtomic(classOf[Int])
2 val Double = SAtomic(classOf[Double])
3 val td:SimpleTypeD = SOr(Double, SAnd(Int, SNot(SEql("X"))))
```



- A type designator is an expression tree (AST).
- Leaf nodes interface to Scala classes via `SAtomic(...)`.
- ... and to literal Scala values via `SEql(...)`
- ... and to predicate functions via `SSatisfies(...)`

`SimpleTypeD` class quasi-ADT



Type Membership Predicate

Boolean type membership question is *always answerable*.

```
SAtomic(classOf[Int]).typep(-42) // returns true

// returns true
(SAtomic(classOf[String]) || SAtomic(classOf[Int])).typep(7)


// define predicate
def oddp(a:Any):Boolean = {
  a match
    case a:Int => a % 2 != 0
    case _ => false
}

SSatisfies(oddp).typep(36) // returns false
```

Subtype Predicate

Semi-Boolean Subtype predicate *sometimes unanswerable*.

```
val Str:SimpleTypeD = SAtomic(classOf[String])
val Int:SimpleTypeD = SAtomic(classOf[Int])
val Num:SimpleTypeD = SAtomic(classOf[Number])
val odd:SimpleTypeD = SSatisfies(oddp, "oddp")

Str.subtypep(Int) // returns Some(false)
Int.subtypep(Num) // returns Some(true)
SSatisfies(oddp).subtypep(Int) // returns None
```

Unanswerable because:

- Impossible to compute, *e.g.* `SSatisfies`.
- Code is incomplete.
- JVM supports run-time loaded classes.
- Limitations of support libraries (discussed later).

Simple Embedded Type System: SETS

At the point, *what have we done*?

- Wrapped the Scala type system
- ... with a simple type system
- ... which supports a complemented type lattice
- ... with membership Boolean predicate
- ... with subtype semi-Boolean predicate
- ... which supports reflection

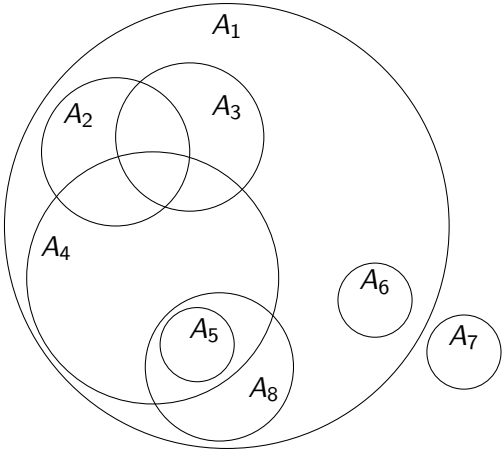
Cf: *A Portable, Simple, Embeddable Type System* [Newton, Pommellet] 2021 ELS

Challenge №4: Deterministic State Machines

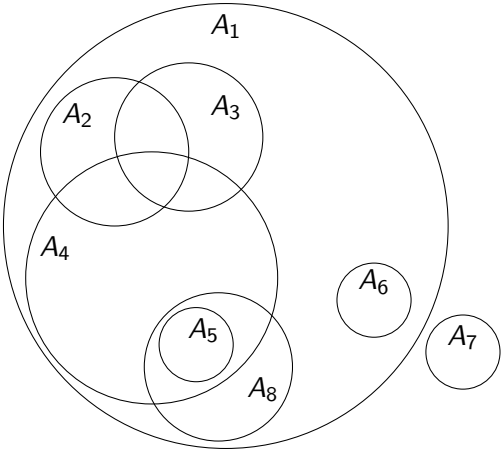
How to assure DFAs are deterministic by construction?

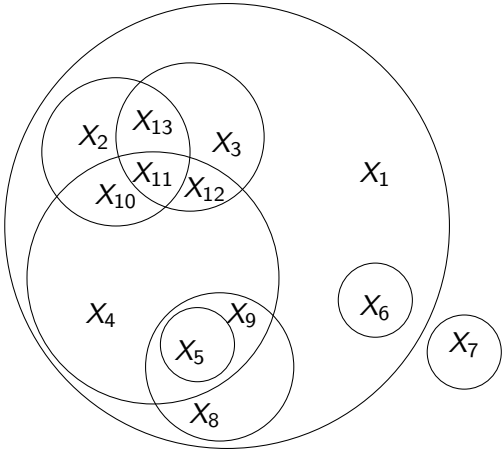
- Compute a partition of a given set of type designators,
- ... even (especially) when subtype relation is unknown.

MDTD: Maximal Disjoint Type Decomposition

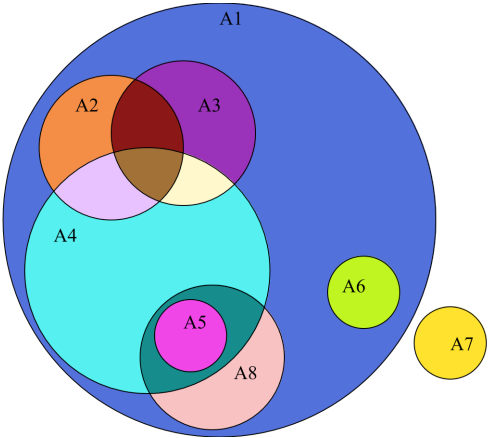


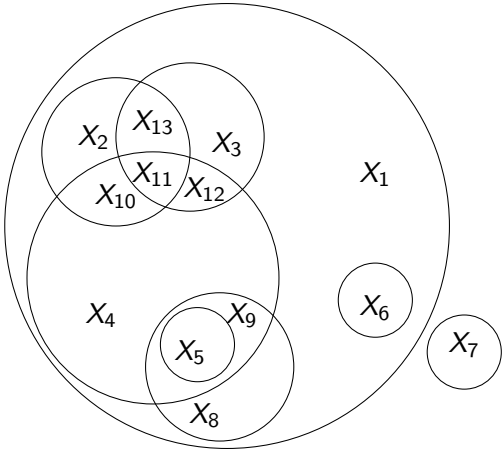
MDTD: Maximal Disjoint Type Decomposition



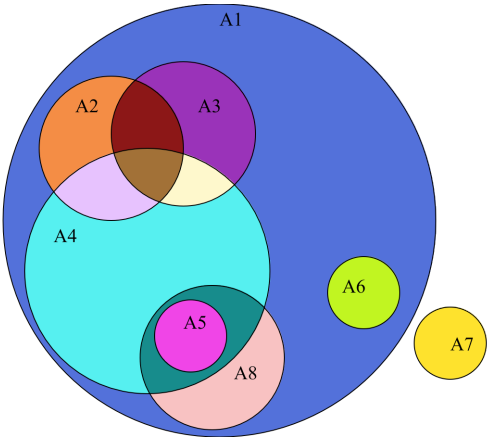


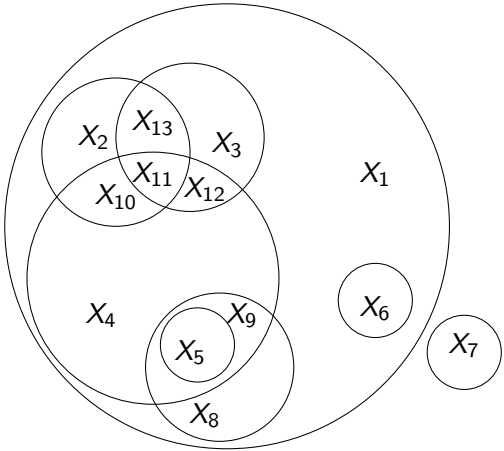
MDTD: Maximal Disjoint Type Decomposition





MDTD: Maximal Disjoint Type Decomposition



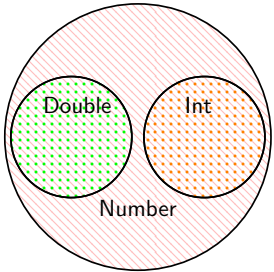


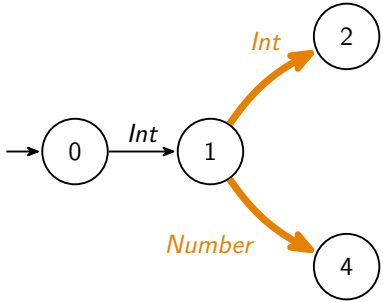
Cf: *An Elegant and Fast Algorithm for Partitioning Types* [Newton] 2023 ELS

Non-determinism by subtype

$Int \subseteq Number$

$Int \cap Number \neq \emptyset$





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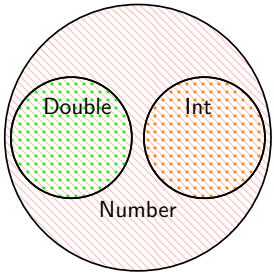

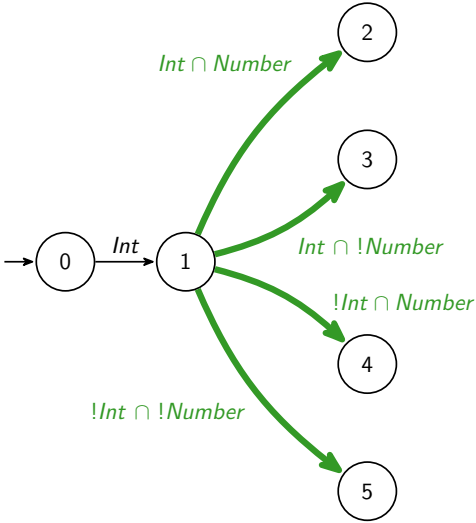

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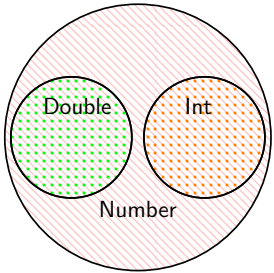
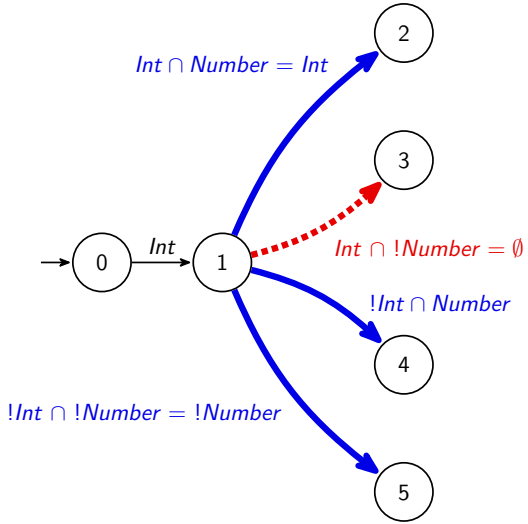


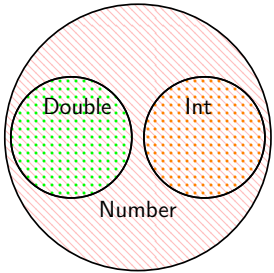


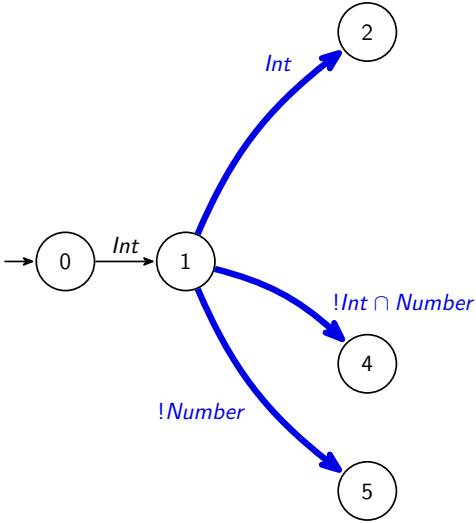
We can *decide* that state ③ is unreachable.

Non-determinism by subtype

$Int \subseteq Number$

$Int \cap Number \neq \emptyset$



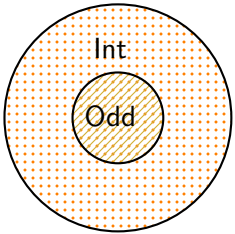


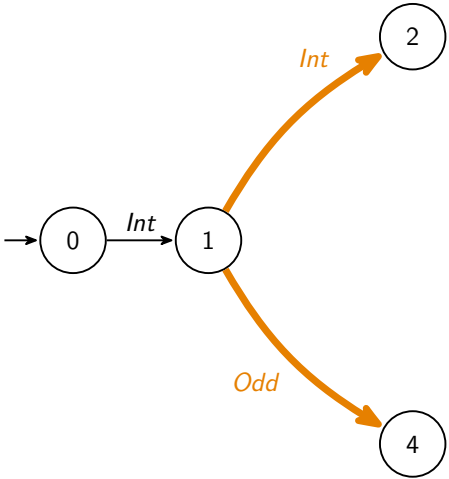
We can *decide* that state ③ is unreachable.

Non-determinism by `SSatisfies`

$Odd \subseteq Int$ unknown

$Odd \cap !Int = \emptyset$ unknown





Non-determinism by `SSatisfies`

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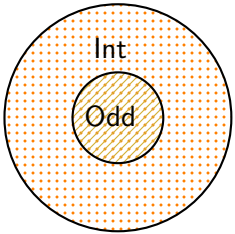

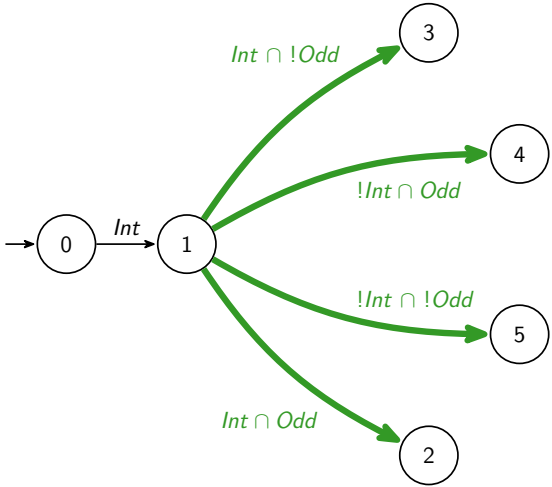

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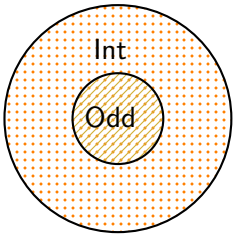
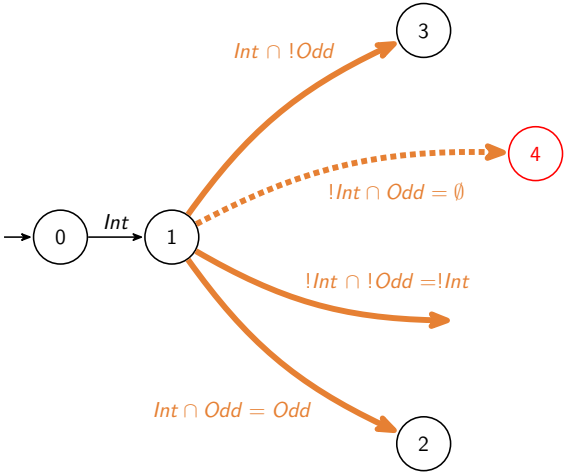
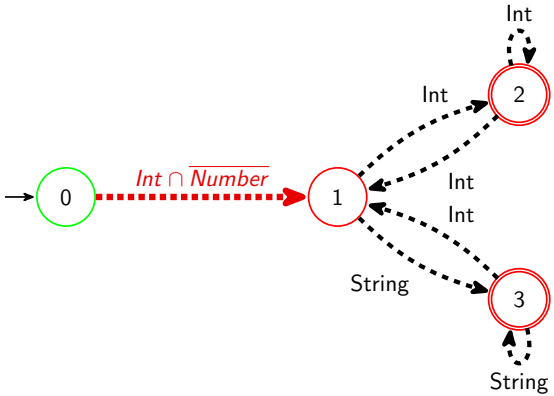




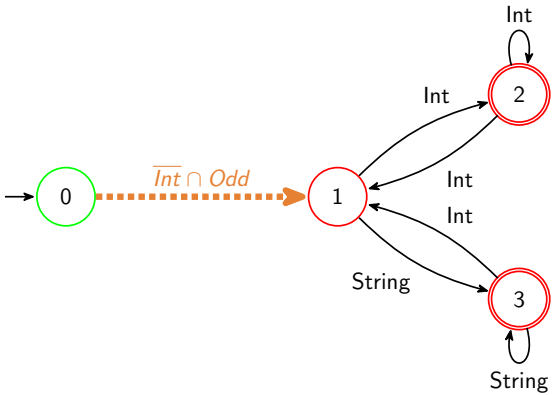
Unreachable state ④, but *undecidable*.

Unsatisfiable Transitions



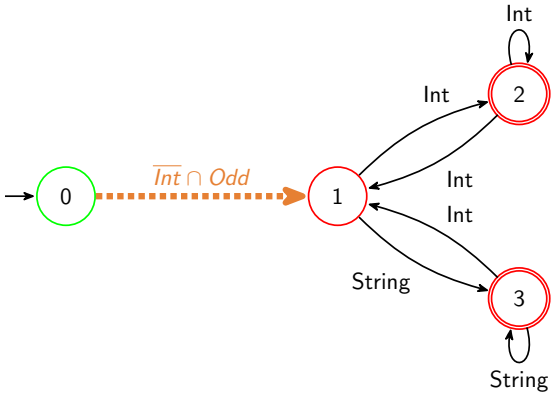
- If we determine a type is empty, then the transition is *unsatisfiable*.
- Thus we *can eliminate* the transition and unreachable states.

Indeterminate Transitions



- If we cannot determine a type is empty, the transition may *still be unsatisfiable*.
- However, we *cannot eliminate* the transition and unreachable states.

Indeterminate Transitions



- We *can always* determine *type membership*.
- DFAs with indeterminate transitions *correctly* match sequences in $O(n)$.

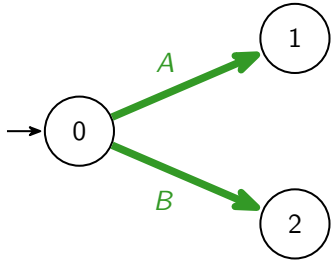
Determining whether two classes are disjoint

```
final class A() {}
final class B() {}

class C() {}
trait D() {}

abstract class E() {}
trait F {}

class G() extends E with F {}
```



$$A \cap B = \emptyset$$

Both are `final`; they have no common *inhabited* subclass.

Determining whether two classes are disjoint

```
final class A() {}
final class B() {}

class C() {}
trait D() {}

abstract class E() {}
trait F {}

class G() extends E with F {}
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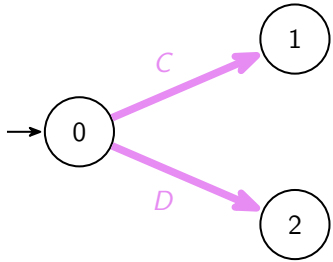


$$C \cap D = \textit{unknown}$$

Is there a class *somewhere* which inherits from both?

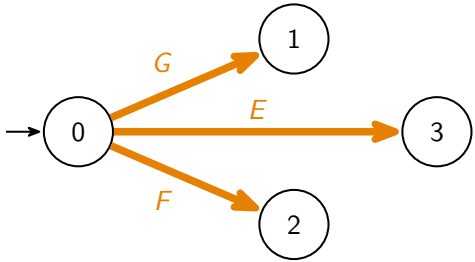
Determining whether two classes are disjoint

```
final class A() {}
final class B() {}

class C() {}
trait D() {}

abstract class E() {}
trait F {}

class G() extends E with F {}
```



$$G \subset E \implies G \cap E \neq \emptyset$$

Explicit subtype relation.

Determining whether two classes are disjoint

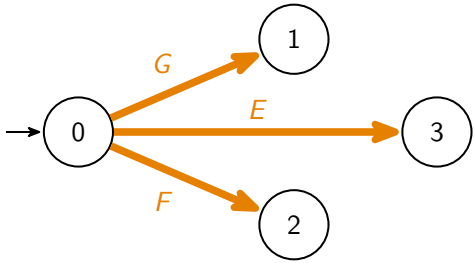
```
final class A() {}
final class B() {}

class C() {}
trait D() {}

abstract class E() {}
trait F {}

class G() extends E with F {}
```

G inherits from E and F.



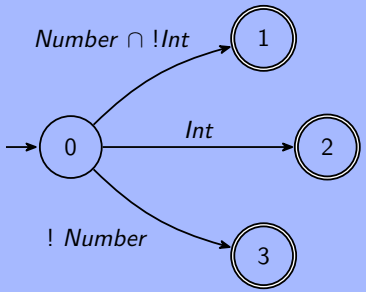
$$E \cap F \neq \emptyset$$

Determining whether two classes are disjoint: Caveats

- If *currently* no subclass exists, JVM might *later* run-time load `subclass.jar`
- With Java $> 8.x$, Scala cannot dependably compute list of subclasses.
- Library `github.com/ronmamo/reflections` no longer maintained.
  - `https://github.com/ronmamo/reflections/issues/324`
  - `https://users.scala-lang.org/t/help-with-org-reflections-api`
  - `https://stackoverflow.com/questions/52879584`

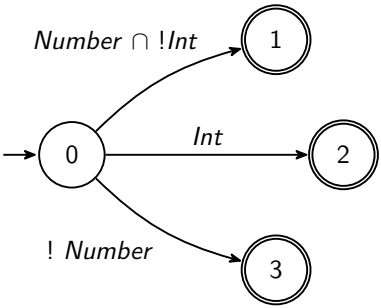
Challenge №5: Redundant Type Check

Select correct transition, avoiding *redundant type checks*.



Sequential Type Check

A DFA state may have several *disjoint* transitions, each with its own type label.

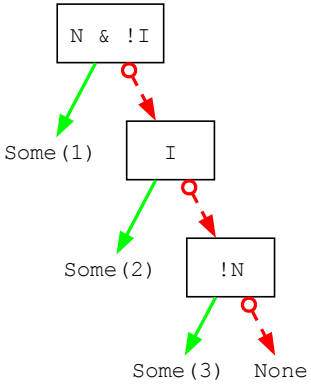



```
1  val N = SAtomic(classOf[Number])
2  val I = SAtomic(classOf[Int])
3
4  if (N & !I).typep(x)
5    Some(1)
6  else if I.typep(x)
7    Some(2)
8  else if (!N).typep(x)
9    Some(3)
10 else
11   None
```

Some types may be checked multiple times. We can rewrite the code to *eliminate redundant checks*.

Decision Tree Structure

We programmatically manipulate `if then ... else ...` using a lazy decision tree.

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1  val N = SAtomic(classOf[Number])
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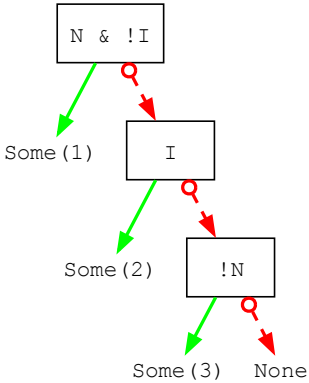
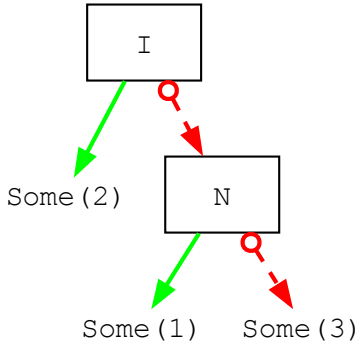
7    Some(2)
8  else if (!N).typep(x)
9    Some(3)
10 else
11   None
```

Decision Tree, Before and After

Viewing the decision tree before/after

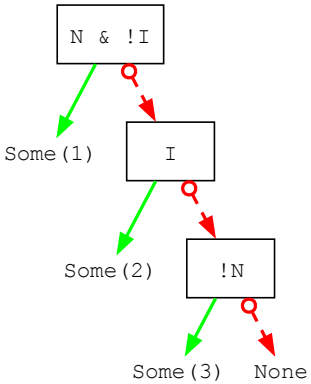
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$





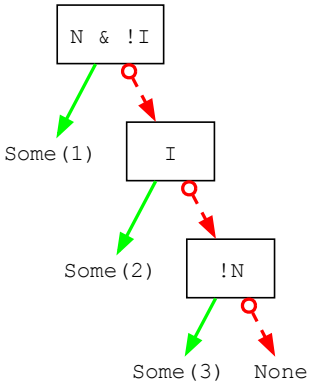
Rewrite: 1 → 2 → 3 → 4 → 5 → 6 → 7 → 8 → 9

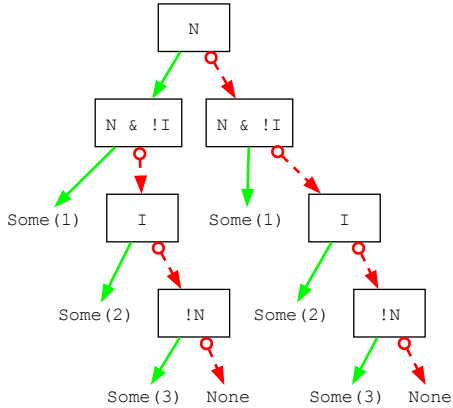
Duplicate tree, and introduce `if N.typep(x) then ... else ...`



Rewrite: 1 → 2 → 3 → 4 → 5 → 6 → 7 → 8 → 9

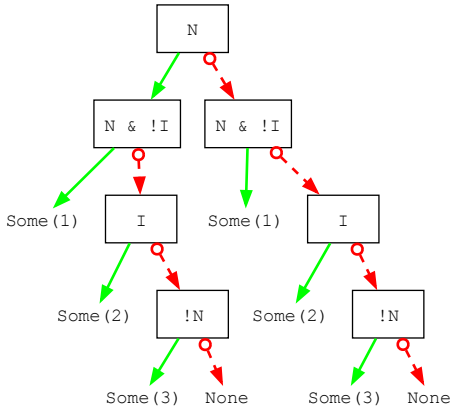
Duplicate tree, and introduce `if N.typep(x) then ... else ...`





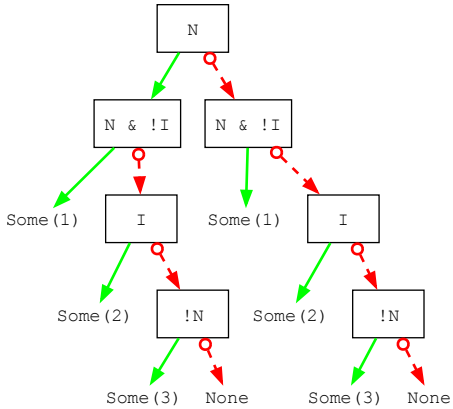
Rewrite: 1 → 2 → 3 → 4 → 5 → 6 → 7 → 8 → 9

Duplicate tree, and introduce `if N.typep(x) then ... else ...`



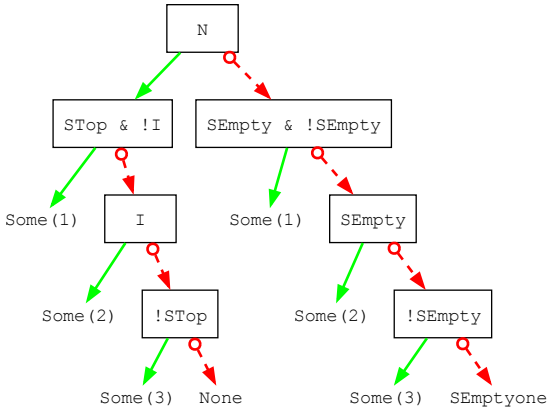
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

In `then` part: Supertypes of `N` $\to$ `STop`. In `else` part: Subtypes of `N` $\to$ `SEmpty`.



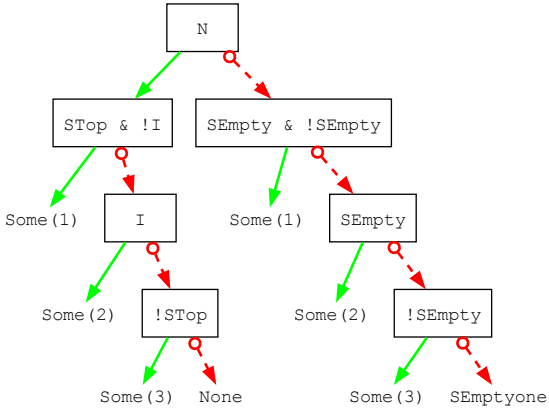
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

In `then` part: Supertypes of `N` $\to$ `STop`. In `else` part: Subtypes of `N` $\to$ `SEmpty`.



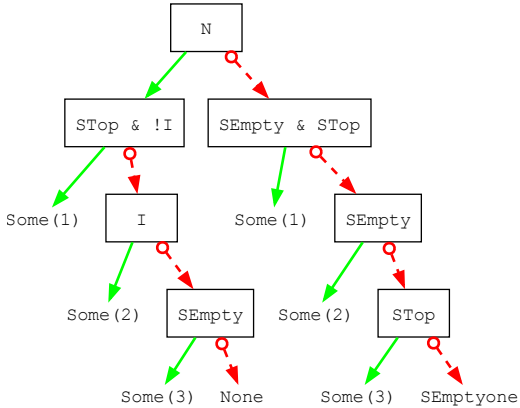
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

`!STop → SEmpty` `!SEmpty → STop`



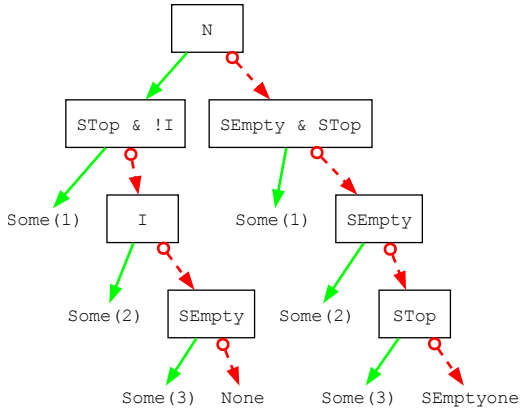
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

`!STop → SEmpty` `!SEmpty → STop`



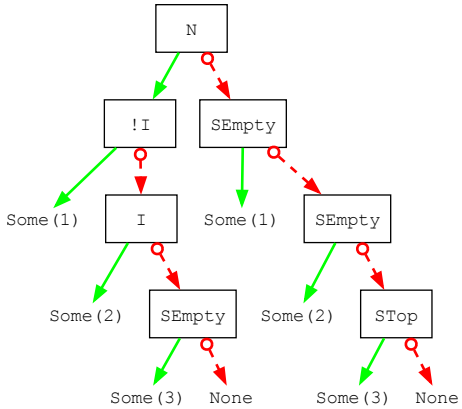
Rewrite: $1 \to 2 \to 3 \to \boxed{4} \to 5 \to 6 \to 7 \to 8 \to 9$

`(STop & x)` $\to$ `x` `(SEmpty & x)` $\to$ `SEmpty`



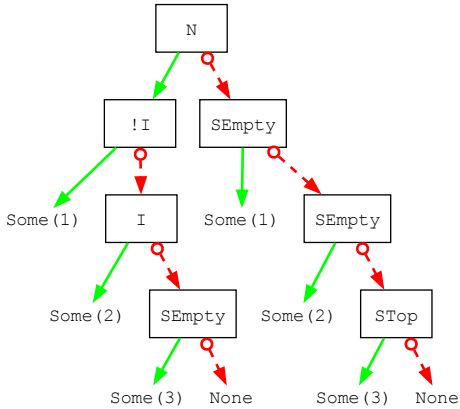
Rewrite: $1 \to 2 \to 3 \to \boxed{4} \to 5 \to 6 \to 7 \to 8 \to 9$

`(STop & x)` $\to$ `x` `(SEmpty & x)` $\to$ `SEmpty`



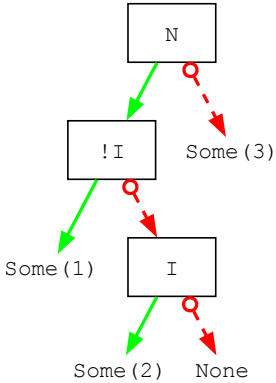
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

Replace `STop` with `then` branch. Replace `SEmpty` with `else` branch.



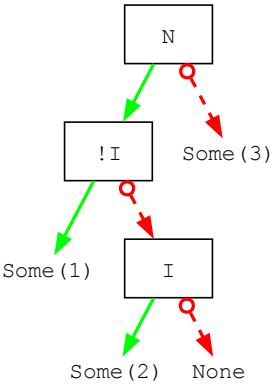
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

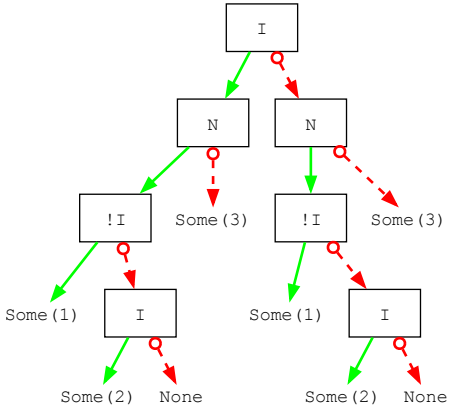
Replace `STop` with `then` branch. Replace `SEmpty` with `else` branch.



Rewrite: $1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9$

Duplicate tree, and introduce `if I.typep(x) then ... else ...`





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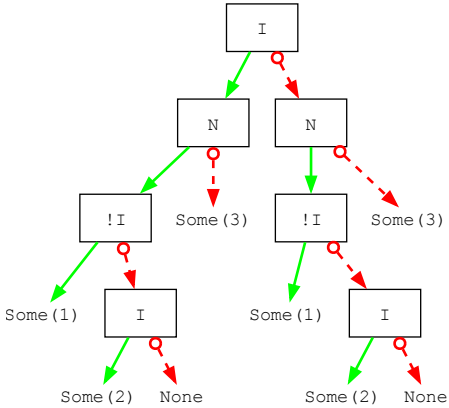
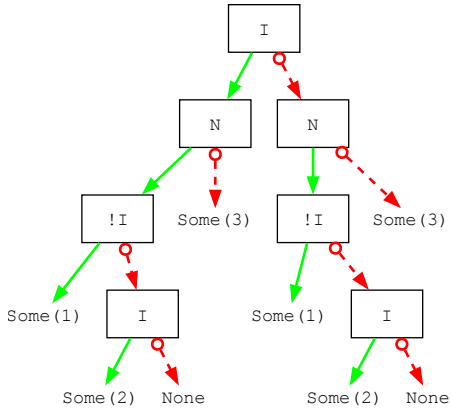


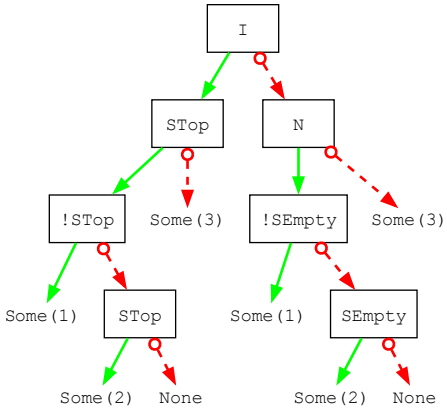
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

In `then` part: Supertypes of `I` $\to$ `STop`. In `else` part: Subtypes of `I` $\to$ `SEmpty`.



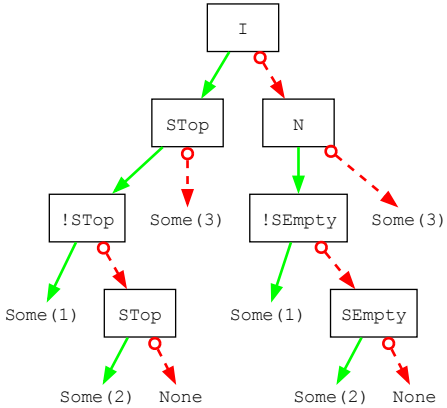
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

In `then` part: Supertypes of `I → STop`. In `else` part: Subtypes of `I → SEmpty`.



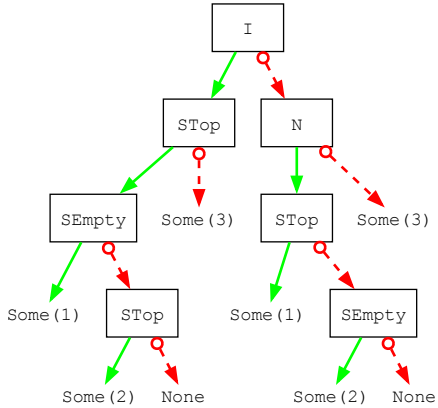
Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

`!STop → SEmpty` `!SEmpty → STop`



Rewrite: $1 \to 2 \to 3 \to 4 \to 5 \to 6 \to 7 \to 8 \to 9$

`!STop → SEmpty` `!SEmpty → STop`



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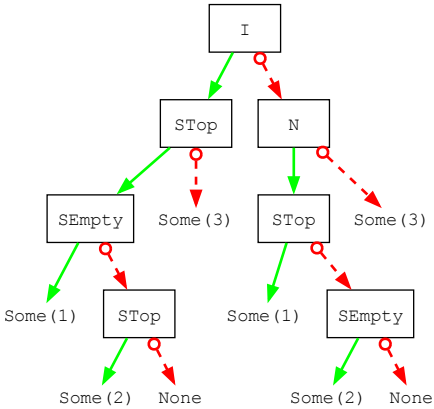

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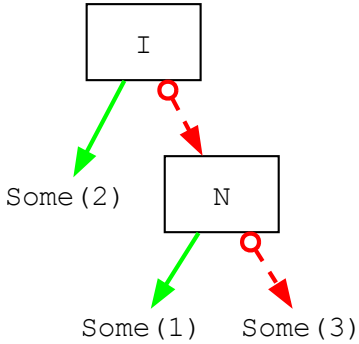

Rewrite: Summary

Code has been rewritten so that *any type check occurs no more than once*.

```
val N = SAtomic(classOf[Number])
val I = SAtomic(classOf[Int])

if (N & !I).typep(x)
  Some(1)
else if I.typep(x)
  Some(2)
else if (!N).typep(x)
  Some(3)
else
  None
```

```
1 if I.typep(x)
2   Some(2)
3 else if N.typep(x)
4     Some(1)
5 else
6   Some(3)
```

And it is clear the code never returns `None`.

Summary: Challenges of the Project

- *Challenge № 1:* RTE Representation: Representing an RTE in Scala?
- *Challenge № 2:* DFA Construction: Constructing from RTE?
- *Challenge № 3:* Type Lattice: Union, intersection, complement types?
- *Challenge № 4:* Determinism: Type partitioning?
- *Challenge № 5:* Efficiency: Avoiding redundant type checks at run-time?

Perspectives

- Open/Closed world-view of Java types/classes
- Publish a summary of our techniques and results (PADL 2025).
- Move away from Scala 2
- Find replacement (or fix) for abandoned library: `github.com/ronmamo/reflections`

Conclusion

- Efficient pattern recognition for heterogeneous sequences for Scala
- Available here:

Scala	`https://github.com/jimka2001/scala-rte`
Clojure	`https://github.com/jimka2001/clojure-rte`
Python	`https://github.com/jimka2001/python-rte`
Common Lisp	`https://github.com/jimka2001/cl-rte`

- *Critical Feedback Welcome!*
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THANK YOU

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