Program Verification: Lecture 2

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Equational Theories

Theories in equational logic are called equational theories. In Computer Science they are sometimes referred to as algebraic specifications.

An equational theory is a pair (Σ, E), where:

- Σ, called the signature, describes the syntax of the theory, that is, what types of data and what operation symbols (function symbols) are involved;
- E is a set of equations between expressions (called terms) in the syntax of Σ.

Unsorted, Many-Sorted, and Order-Sorted Signatures

Our syntax Σ can be more or less expressive, depending on how many types (called sorts) of data it allows, and what relationships between types it supports:

- unsorted (or single-sorted) signatures have only one sort, and operation symbols on it;
- many-sorted signatures allow different sorts, such as `Integer`, `Bool`, `List`, etc., and operation symbols relating these sorts;
- order-sorted signatures are many-sorted signatures that, in addition, allow inclusion relations between sorts, such as `Natural < Integer < Rational`.

Maude Functional Modules

Maude functional modules are equational theories (Σ, E), declared with syntax

$$\texttt{fmod}\ (\Sigma, E)\ \texttt{endfm}$$

Such theories can be unsorted, many-sorted, or order-sorted, or even more general membership equational theories (see §4.1–4.2 of "All about Maude").

In what follows we will see examples of unsorted, many-sorted and order-sorted equational theories (Σ, E) expressed as Maude functional modules, and of how one can use such theories as functional programs by computing with the equations E.

Unsorted Functional Modules

```
*** prefix syntax

fmod NAT-PREFIX is
  sort Natural .
  op 0 : -> Natural [ctor] .
  op s : Natural -> Natural [ctor] .
  op + : Natural Natural -> Natural .
  vars N M : Natural .
  eq +(N,0) = N .
  eq +(N,s(M)) = s(+(N,M)) .
endfm

Maude> red +(s(s(0)),s(s(0))) .
reduce in NAT-PREFIX : +(s(s(0)), s(s(0))) .
rewrites: 3 in -10ms cpu (0ms real) (~ rewrites/second)
result Natural: s(s(s(s(0))))
Maude>
```

Unsorted Functional Modules (II)

```
fmod NAT-MIXFIX is                               *** mixfix syntax
  sort Natural .
  op 0 : -> Natural [ctor] .
  op s_ : Natural -> Natural [ctor] .
  op _+_ : Natural Natural -> Natural .
  op _*_ : Natural Natural -> Natural .
  vars N M : Natural .
  eq N + 0 = N .
  eq N + s M = s(N + M) .
  eq N * 0 = 0 .
  eq N * s M = N + (N * M) .
endfm

Maude> red (s s 0) + (s s 0) .
reduce in NAT-MIXFIX : s s 0 + s s 0 .
rewrites: 3 in 0ms cpu (0ms real) (~ rewrites/second)
result Natural: s s s s 0
Maude>
```

Many-Sorted Functional Modules

```
fmod NAT-LIST is
  protecting NAT-MIXFIX .
  sort List .
  op nil : -> List [ctor] .
  op _._ : Natural List -> List [ctor] .
  op length : List -> Natural .
  var N : Natural .
  var L : List .
  eq length(nil) = 0 .
  eq length(N . L) = s length(L) .
endfm

Maude> red length(0 . (s 0 . (s s 0 . (0 . nil)))) .
reduce in NAT-LIST : length(0 . s 0 . s s 0 . 0 . nil) .
rewrites: 5 in 0ms cpu (0ms real) (~ rewrites/second)
result Natural: s s s s 0
Maude>
```

Many-Sorted Signatures

The full signature Σ of the `NAT-LIST` example, that imports `NAT-MIXFIX`, is then,

```
sorts Natural List .
op 0 : -> Natural .
op s_ : Natural -> Natural .
op _+_ : Natural Natural -> Natural .
op _*_ : Natural Natural -> Natural .
op nil : -> List .
op _._ : Natural List -> List .
op length : List -> Natural .
```

Many-Sorted Signatures as Labeled Multigraphs

A many-sorted signature is just a labeled multigraph, whose nodes are called sorts, whose labels are called function symbols, and whose labeled multiedges are called the typings of the function symbols.

Definition. A labeled multigraph, [also called a many-sorted signature] is a triple $\Sigma = (S, F, G)$, where S is its set of nodes [also called sorts], F is its set of labels [also called function symbols], and G is its labeled multigraph, [also called the typings], which is a set G of triples of the form:

$$G \subseteq S^* \times F \times S$$

where S^* denotes the set of strings on the alphabet S. A triple $(s_1 \ldots s_n, f, s) \in G$ is displayed as $f : s_1 \ldots s_n \to s$, or, [to emphasize f as the label of the multiedge] as $s_1 \ldots s_n \xrightarrow{f} s$.

Many-Sorted Signatures as Labeled Multigraphs (II)

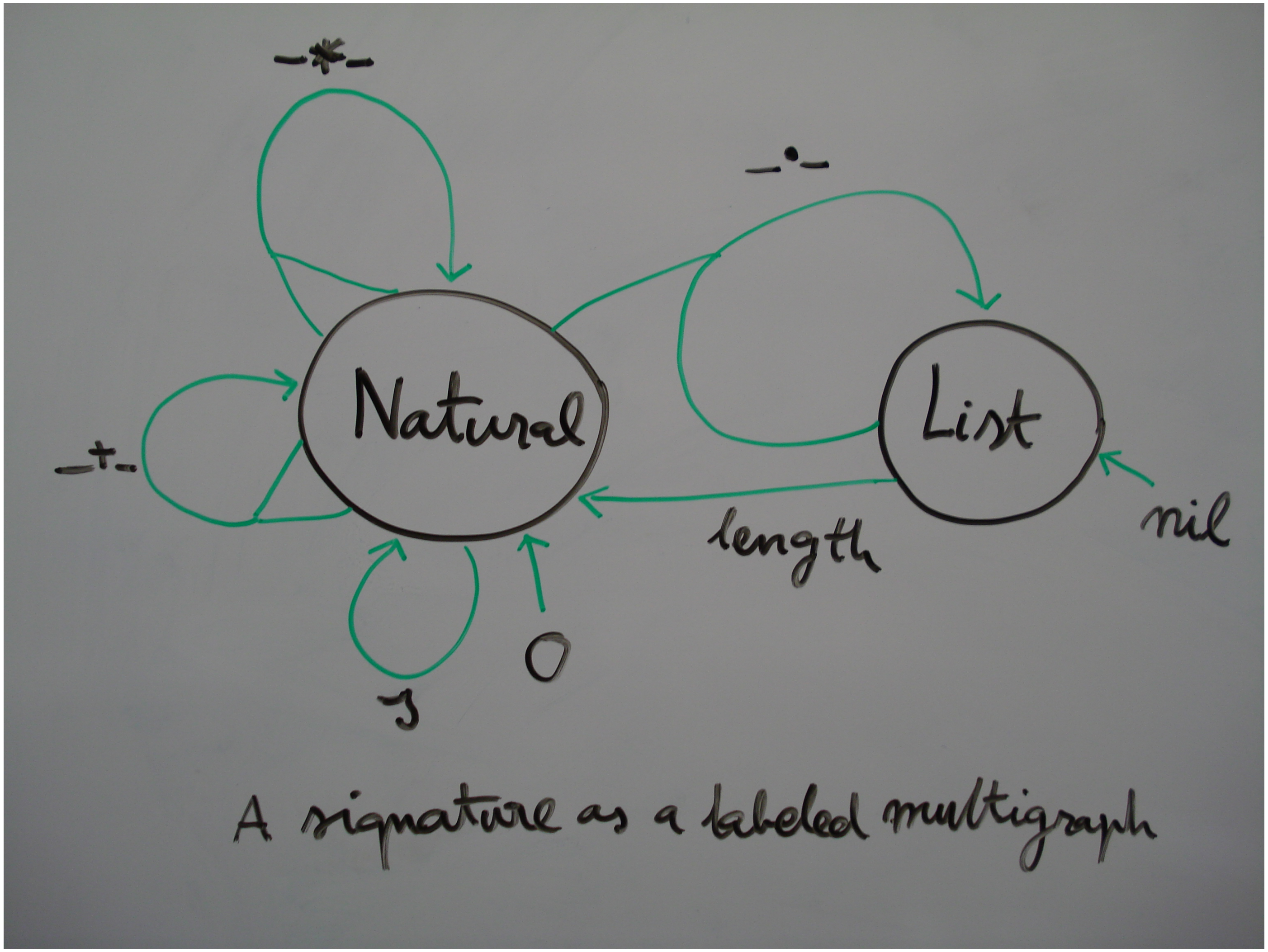
In the signature terminology, we call $f : s_1 \ldots s_n \to s$ a typing of f with input sorts $s_1 \ldots s_n$ and result sort s.

In a typing of the form $a : \epsilon \to s$, we call $a \in F$ a constant symbol of sort s.

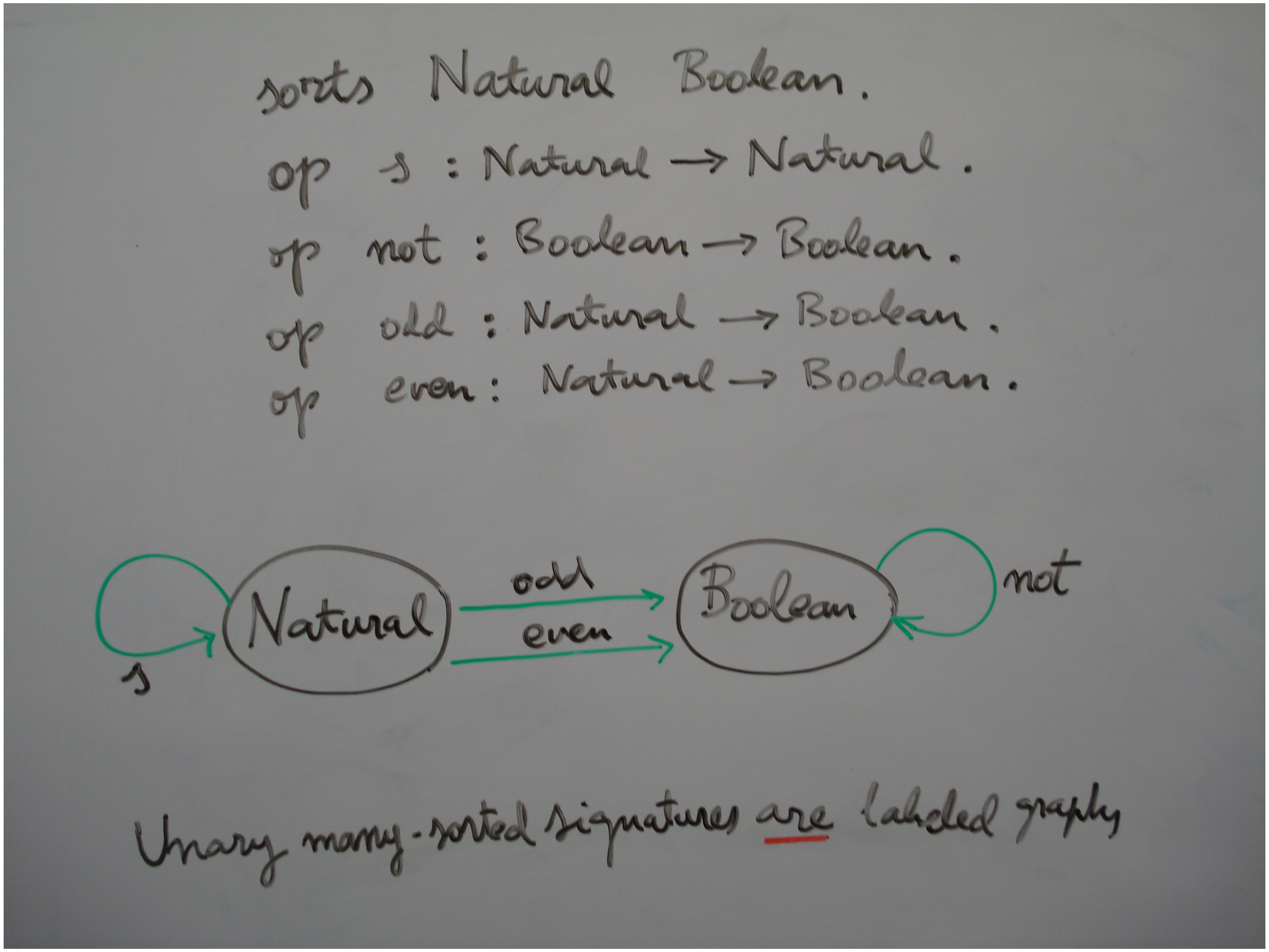
For example, we view an operator declaration like:

```
op _._ : Natural List -> List .
```

as a labeled multiedge having two input nodes and one output node (see picture below).



Of course, when all operations are unary, signatures are exactly labeled graphs (see picture below)



The Need for Order-Sorted Signatures

Many-sorted signatures are still too restrictive. The problem is that some operations are partial, and there is no natural way of defining them in just a many-sorted framework.

Consider for example defining a function `first` that takes the first element of a list of natural numbers, or a predecessor function `p` that assigns to each natural number its predecessor. What can we do? If we define:

```
op first : List -> Natural .
op p_ : Natural -> Natural .
```

we have then the awkward problem of defining the values of `first(nil)` and of `p 0`, which in fact are undefined.

The Need for Order-Sorted Signatures (II)

A much better solution is to recognize that these functions are partial with the typing just given, but become total on appropriate subsorts `NeList < List` of nonempty lists, and `NzNatural < Natural` of nonzero natural numbers. If we define:

```
op s_ : Natural -> NzNatural .
op _._ : Natural List -> NeList .
op first : NeList -> Natural .
op p_ : NzNatural -> Natural .
```

everything is fine. Subsorts also allow us to overload operator symbols. For example, `Natural < Integer`, and

```
op _+_ : Natural Natural -> Natural .
op _+_ : Integer Integer -> Integer .
```

Order-Sorted Functional Modules

```
fmod NATURAL is
  sorts Natural NzNatural .
  subsorts NzNatural < Natural .
  op 0 : -> Natural [ctor] .
  op s_ : Natural -> NzNatural [ctor] .
  op p_ : NzNatural -> Natural .
  op _+_ : Natural Natural -> Natural .
  op _+_ : NzNatural NzNatural -> NzNatural .
  vars N M : Natural .
  eq p s N = N .
  eq N + 0 = N .
  eq N + s M = s(N + M) .
endfm

Maude> red p((s s 0) + (s s 0)) .
reduce in NATURAL : p (s s 0 + s s 0) .
rewrites: 4 in 0ms cpu (0ms real) (~ rewrites/second)
result NzNatural: s s s 0
```

Order-Sorted Functional Modules (II)

```
fmod NAT-LIST-II is
  protecting NATURAL .
  sorts NeList List .
  subsorts NeList < List .
  op nil : -> List [ctor] .
  op _._ : Natural List -> NeList [ctor] .
  op length : List -> Natural .
  op first : NeList -> Natural .
  op rest : NeList -> List .
  var N : Natural .
  var L : List .
  eq length(nil) = 0 .
  eq length(N . L) = s length(L) .
  eq first(N . L) = N .
  eq rest(N . L) = L .
endfm
```

Order-Sorted Signatures Mathematically

An order-sorted signature Σ is a triple $\Sigma = ((S, <), F, G)$, where (S, F, G) is a many-sorted signature, and where $<$ is a partial order relation on the set S of sorts called subsort inclusion.

That is, $<$ is a binary relation on S that is:

- irreflexive: $\neg(x < x)$
- transitive: $x < y$ and $y < z$ imply $x < z$

Any such relation $<$ has an associated $\leq$ relation that is reflexive, antisymmetric, and transitive. We will move back and forth between $<$ and $\leq$ (see STACS 7.4).

Note: Unless specified otherwise, by a signature we will always mean an order-sorted signature.

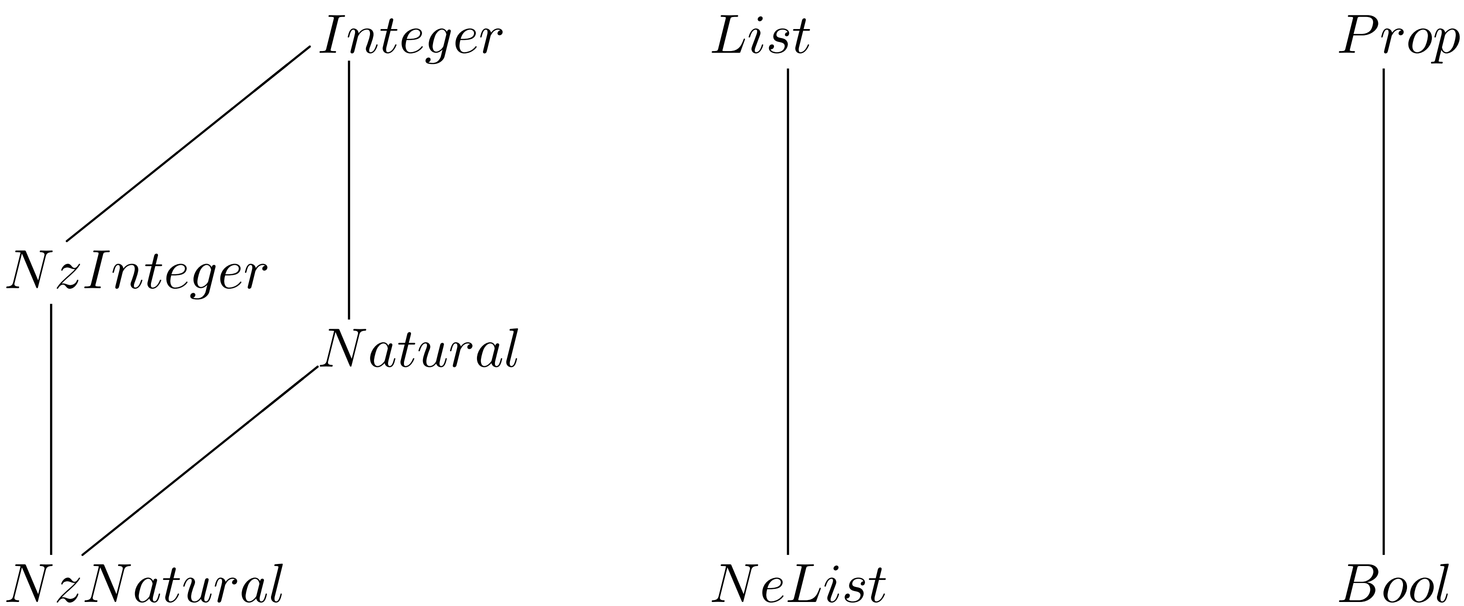
Connected Components of the Poset of Sorts

Given a signature Σ, we can define an equivalence relation (see STACS 7.6) $\equiv_{\leq}$ between sorts $s, s' \in S$ as the smallest relation such that:

- if $s \leq s'$ or $s' \leq s$ then $s \equiv_{\leq} s'$
- if $s \equiv_{\leq} s'$ and $s' \equiv_{\leq} s''$ then $s \equiv_{\leq} s''$

We call the equivalence classes modulo $\equiv_{\leq}$ the connected components of the poset order $(S, \leq)$. Intuitively, when we view the poset as a directed acyclic graph, they are the connected components of the graph (see STACS 7.6, Exercise 68).

Connected Components Example



$$S/\equiv_{\leq} = \{\{NzNatural, Natural, NzInteger, Integer\}, \{Nelist, List\}, \{Bool, Prop\}\}$$

Subsort vs. Ad-hoc Overloading

In general, the same operator name may have different declarations in the same signature Σ. For example, in the NATURAL module we have,

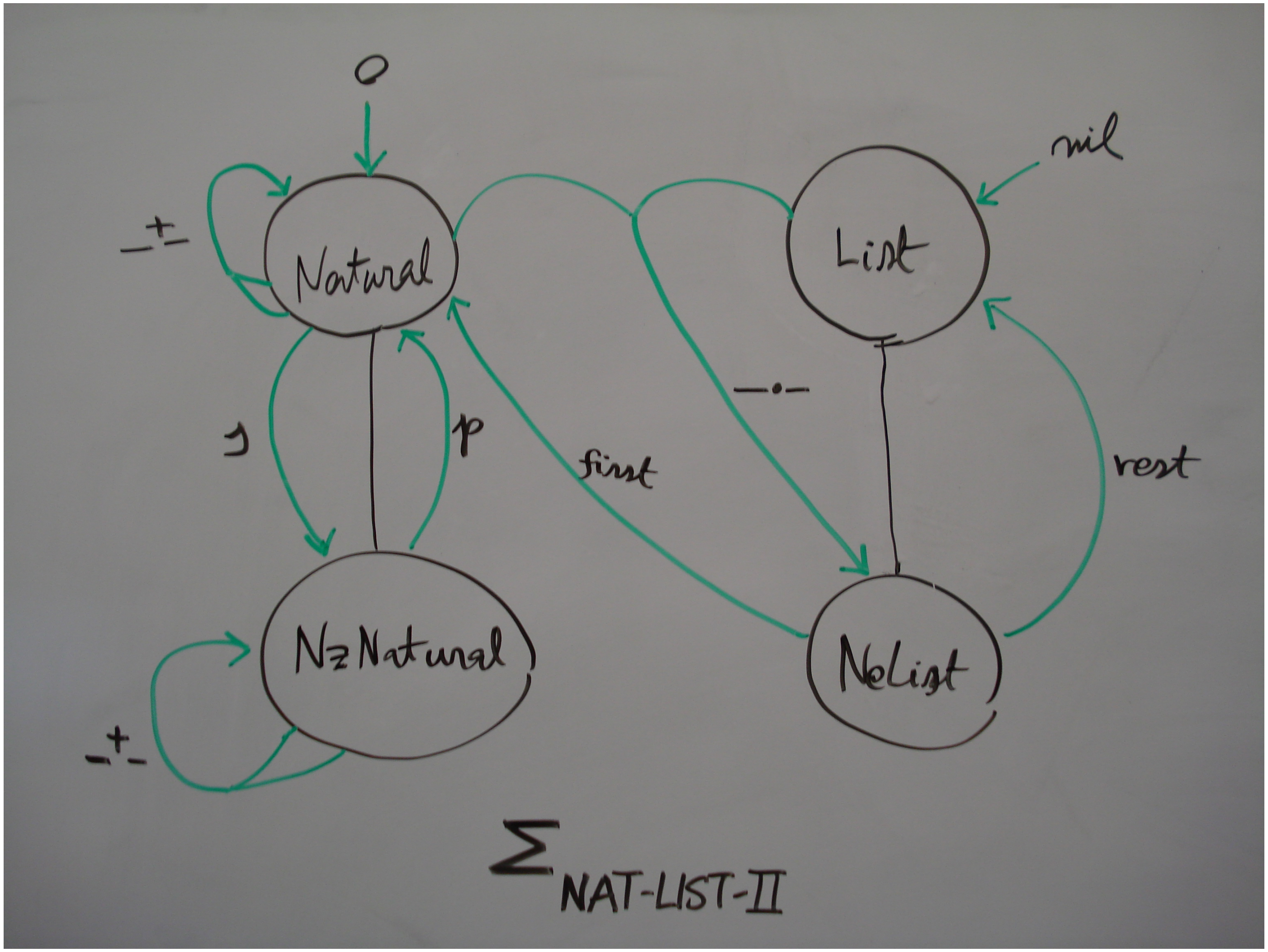
```
op _+_ : Natural Natural -> Natural .
op _+_ : NzNatural NzNatural -> NzNatural .
```

When we have two operator declarations, $f : s_1 \ldots s_n \longrightarrow s$, and $f : s'_1 \ldots s'_n \longrightarrow s'$, then: (1) if $s_i \equiv_{\leq} s'_i$, $1 \leq i \leq n$ and $s \equiv_{\leq} s'$, we call them subsort overloaded; (2) otherwise, e.g, `_+_` for `Natural` and for exclusive or in `Bool`, we call them ad-hoc overloaded.

Order-Sorted Signatures as Labelled Multigraphs

Since an order-sorted signature is a many-sorted signature whose set of nodes is a poset, we can describe them graphically as labeled multigraphs whose set of nodes is a poset.

We can picture subsort inclusions as usual for partial orders, and operators, as before, as labeled multiedges in the multigraph. For example, the order-sorted signature of the module `NAT-LIST-II` is depicted this way in Picture 2.3.


0
nil
_+_
Natural
List
s
p
_._
first
rest
NzNatural
NeList
_+_
Σ NAT-LIST-II

Exercises

Ex.2.1. Define in Maude the following functions on the naturals:

- $>$ and $\geq$ as Boolean-valued binary functions importing the built-in module `BOOL` with single sort `Bool`.
- max and min, that yield the maximum, resp. minimum, of two numbers,
- even and odd as Boolean-valued functions on the naturals,
- factorial, the factorial function.

Exercises (II)

Ex.2.2. Define in Maude the following functions on list of natural numbers:

- append and reverse, which appends two lists, resp. reverses the list,
- max and min that computes the biggest (resp. smallest) number in the list,
- get.even, which extracts the lists of even numbers of a list,
- odd.even, which, given a list, produces a pair of list: the first the sublist of its odd numbers and the second the sublist of its even numbers.

Exercises (III)

Ex.2.3. Given a poset $(S, \leq)$, prove that the smallest equivalence relation $\equiv_{\leq}$ containing $\leq$ is the relation $(\leq \cup \geq)^+$, where, as explained in STACS, given a binary relation R, the relation R^+ denotes its transitive closure.