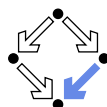


Loose Specifications

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1. General Remarks

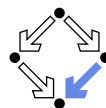
2. Loose Specifications

3. Loose Specifications with Constructors

4. Loose Specifications with Free Constructors

5. Summary

Specifications

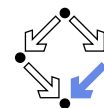


We will introduce various flavors of specifications of ADTs.

- **Specification semantics:** $sp \rightarrow \mathcal{M}(sp)$.
 - Specification sp .
 - Its meaning $\mathcal{M}(sp)$ (an abstract datatype).
- sp is an **adequate specification of an ADT** \mathcal{C} :
 - $\mathcal{C} \subseteq \mathcal{M}(sp)$.
- sp is a **strictly adequate specification of an ADT** \mathcal{C} :
 - $\mathcal{C} = \mathcal{M}(sp)$.
- sp is a **(strictly) adequate specification of an algebra** A :
 - sp is (strictly) adequate specification of the monomorphic ADT $[A]$.
- sp is **polymorphic (monomorphic)**:
 - sp defines a polymorphic (monomorphic) ADT.

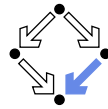
General notions independent of the kind of specification.

Properties of Specifications

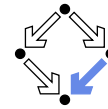


- Is the specification inconsistent?
 - Is the specified ADT empty (i.e. does not contain any algebras)?
- Is the specification monomorphic?
 - Are all algebras of the specified ADT isomorphic?
- Are two specifications equivalent?
 - Do they specify the same ADT?
- Does the specification (strictly) adequately describe a given ADT?
 - Assumes that the ADT is mathematically defined by other means.
 - But specification itself is typically the *only* definition of the ADT.
 - Then no mathematical proof of adequacy is possible.
 - Nevertheless, by “executing the specifications” (mechanically evaluating ground terms), we may investigate the properties of the specified ADT to increase our confidence in its adequacy.

All these questions now have a precise meaning.



1. General Remarks
2. Loose Specifications
3. Loose Specifications with Constructors
4. Loose Specifications with Free Constructors
5. Summary

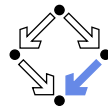


Loose Specifications

Take logic L .

- Loose specification $sp = (\Sigma, \Phi)$ in L :
 - Signature Σ , set of formulas $\Phi \subseteq L(\Sigma)$.
- Semantics $\mathcal{M}(sp) = Mod_{\Sigma}(\Phi)$.
 - All Σ -algebras are candidates for the specified ADT.
 - $Mod_{\Sigma}(\Phi) = Mod_{Alg(\Sigma), \Sigma}(\Phi)$.

A loose specification specifies as the abstract datatype the class of all models of its formula set.

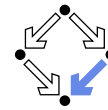


Concrete Syntax

```
loose spec
  sorts sort ...
  opns operation ...
  vars variable: sort ...
  axioms formula ...
endspec
```

- Signature $\Sigma = (\{sort, \dots\}, \{operation, \dots\})$.
- Set of formulas $\Phi = \{(\forall variable : sort, \dots . formula), \dots\}$.

We will only use the concrete syntax to define specifications.

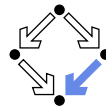


Example

```
loose spec
  sorts el, bool, list
  opns
    True :→ bool
    False :→ bool
    [ ] :→ list
    Add : el × list → list
    _ . _ : list × list → list
  vars l, m : list, e : el
  axioms
    [ ].l = l
    Add(e, l).m = Add(e, l.m)
endspec
```

Adequate specification of the “classical” list algebra in EL .

Strict Adequacy

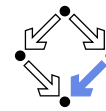


Not a *strictly* adequate specification of the “classical” list algebra.

- Carrier set for *bool* may be a singleton.
PL: **axiom** $\neg(True = False)$
- Carrier set for *list* may be a singleton.
PL: **axiom** $\forall e : el, l : list . \neg([] = Add(e, l))$
- Size of lists may be bound.
PL: **axiom** $\forall e_1, e_2 : elem, l_1, l_2 : list .$
 $Add(e_1, l_1) = Add(e_2, l_2) \Rightarrow e_1 = e_2 \wedge l_1 = l_2$
- Carrier sets may contain extra values (“junk”).
 - There may a *bool* value different from *True* and *False*.
PL: **axiom** $\forall b : bool . b = True \vee b = False$
 - There may be *list* values different from those that can be constructed by application of $[]$ and *Add*.
 - No axiom can express this in *PL*, a solution will be later presented.

In *PL* (not *EL* or *CEL*), additional axioms may solve *some* problems.

Example



loose spec

sorts *el, bool, list*

opns

True $\rightarrow bool$
False $\rightarrow bool$
 $[] : \rightarrow list$
Add $: el \times list \rightarrow list$
 $_ . _ : list \times list \rightarrow list$

vars *l, m : list, e, e₁, e₂ : el*

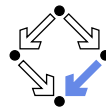
axioms

$\neg(True = False)$
 $\neg([] = Add(e, l))$
 $Add(e_1, l_1) = Add(e_2, l_2) \Rightarrow$
 $e_1 = e_2$
 $[].l = l$
 $Add(e, l).m = Add(e, l.m)$

endspec

More (but still not strictly) adequate specification of the “classical” list algebra in *PL*.

Example



loose spec

sorts *bool, nat*

opns

True $\rightarrow bool$
False $\rightarrow bool$
 $0 : \rightarrow nat$
Succ $: nat \rightarrow nat$
 $_ + _ : nat \times nat \rightarrow nat$
 $_ * _ : nat \times nat \rightarrow nat$
 $_ \leq _ : nat \times nat \rightarrow bool$

vars *m, n : nat, b : bool*

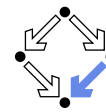
axioms

$\neg(True = False)$
 $b = True \vee b = False$
 $\neg(0 = Succ(n))$
 $Succ(n) = Succ(m) \Rightarrow n = m$
 $(0 \leq n) = True$
 $(Succ(n) \leq 0) = False$
 $(Succ(n) \leq Succ(m)) = (n \leq m)$
 $n + 0 = n$
 $n + Succ(m) = Succ(n + m)$
 $n * 0 = 0$
 $n * Succ(m) = n + (n * m)$

endspec

Adequate specification of Peano arithmetic in *PL* (not strictly adequate because *nat* may contain junk).

Proving Strategies for Loose Specifications

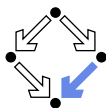


Take loose specification $sp = (\Sigma, \Phi)$ in logic *L* with inference calculus \vdash .

- Prove: $\mathcal{M}(sp) \models \varphi$.
 - Every implementation of the specification *sp* has the property expressed by formula φ .
 - It suffices to prove $\Phi \vdash \varphi$.
 - Formula φ can be derived from the specification axioms Φ .
- Prove: $\mathcal{M}(sp) \subseteq \mathcal{M}(sp')$.
 - Loose specification $sp' = (\Sigma, \Psi)$.
 - Every implementation of the specification *sp* is also an implementation of the specification sp' .
 - It suffices to prove $\Phi \vdash \Psi$.
 - Every axiom $\psi \in \Psi$ can be derived from the axioms Φ .

Straight-forward reduction of semantic questions to proving.

Expressive Power of Loose Specifications

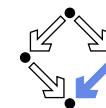


Take loose specification $sp = (\Sigma, \Phi)$ with $\Phi \subseteq L(\Sigma)$.

- **Theorem 1:** $\mathcal{M}(sp) = \text{Mod}_{\Sigma}(Th_L(\mathcal{M}(sp)))$.
 - $Th_L(\mathcal{C}) = \{\phi \in L(\Sigma) \mid \forall A \in \mathcal{C} : A \models_{\Sigma} \phi\}$.
 - The theory of a class of algebras w.r.t. a given logic is the set of all formulas of that logic that are satisfied by every algebra of the class.
 - Thus sp can specify an ADT \mathcal{C} only if $\mathcal{C} = \text{Mod}_{\Sigma}(Th_L(\mathcal{C}))$.
- Example:
 - Signature $\text{NAT} = (\{nat\}, \{0 : \rightarrow nat, s : nat \rightarrow nat\})$.
 - NAT-algebra $N = (\{\mathbb{N}\}, \{0_{\mathbb{N}}, (\lambda x . x + 1)\})$.
 - $[N]$ cannot be specified by any specification sp in $EL(\text{NAT})$.
 - Assume specification sp with $\mathcal{M}(sp) = [N]$.
 - $Th_{EL}([N]) = \{0 = 0, s(0) = s(0), s(s(0)) = s(s(0)), \dots\}$.
 - Take NAT-algebra $A = (\{0, 1\}, 0, \lambda x . 1 - x)$
 - Clearly $A \not\cong N$, thus $A \notin \mathcal{M}(sp)$.
 - But, since $A \models Th_{EL}(\{N\})$, $A \in \text{Mod}_{\Sigma}(Th_{EL}([N]))$, and thus, by Theorem 1, $A \in \mathcal{M}(sp)$.

Algebras can be discriminated only by the expressible formulas.

Expressive Power of Loose Specifications

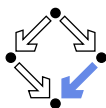


Take loose specification $sp = (\Sigma, \Phi)$ with $\Phi \subseteq L(\Sigma)$.

- **Theorem 2:** If L has a sound and complete calculus and if Φ is recursively enumerable, then $\mathcal{M}(sp)$ is axiomatizable in L .
 - Set S is recursively enumerable, if there is an algorithm that lists all of its elements (running forever, if necessary).
 - A class \mathcal{C} of Σ -algebras is axiomatizable in L , if $Th_L(\mathcal{C})$ is recursively enumerable.
- An ADT whose theory is not recursively enumerable in the given logic, may not be specifiable by a loose specification.
 - Example: Peano arithmetic (natural numbers with addition and multiplication).
 - The theory of peano arithmetic is not recursively enumerable in first-order predicate logic.
 - Gödel's second incompleteness theorem: Peano arithmetic is not axiomatizable in first-order predicate logic.

Not every ADT can be specified by a loose specification.

Expressive Power of Loose Specifications



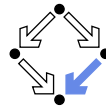
Take loose specification $sp = (\Sigma, \Phi)$ with $\Phi \subseteq L(\Sigma)$.

- **Theorem 3:** If L is EL or CEL , then $\mathcal{M}(sp)$ also contains algebras whose carrier sets are singletons.
 - **Consequence:** No ADT with non-singleton carrier sets can be strictly adequately described by a loose specification in EL or CEL .
 - Cannot prevent "collapse" of the carrier set.
- **Theorem 4:** If L is EL , CEL , or PL and $\mathcal{M}(sp)$ contains an algebra with an infinite carrier set, then $\mathcal{M}(sp)$ also contains algebras whose corresponding carrier sets contain "junk".
 - **Consequence:** No ADT with an infinite carrier set can be strictly adequately described by a loose specification in EL , CEL , or PL .
 - Cannot rule out "extra" values in addition to the desired ones.

We need some more mechanisms for strictly adequate specifications.

1. General Remarks
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Generated Algebras

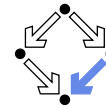


Take signature $\Sigma = (S, \Omega)$, Σ -algebra A .

- Define set of operations $\Omega_c \subseteq \Omega$ (the **constructors**).
 - Restricted signature $\Sigma_c = (S, \Omega_c)$.
- A is **generated by** Ω_c :
 - For each sort $s \in S$ and carrier $a \in A(s)$, there exists a ground term $t \in T_{\Sigma_c, s}$ with $a = A(t)$.
 - Carrier a can be described by a term t that involves only constructors.
 - A is **generated** if it is generated by Ω .
- $Gen(\Sigma, \Omega_c) := \{A \in Alg(\Sigma) \mid A \text{ is generated by } \Omega_c\}$.
 - The set of all Σ -algebras generated by constructors Ω_c .
 - $Gen(\Sigma) := Gen(\Sigma, \Omega)$.

Generated algebra does not contain “junk” in the carrier sets.

Example



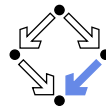
Take signature

$NAT = (\{nat\}, \Omega = \{0 : \rightarrow nat, Succ : nat \rightarrow nat, + : nat \times nat \rightarrow nat\})$.

- Classical NAT-algebra $A = (\mathbb{N}, 0_{\mathbb{N}}, +_{\mathbb{N}})$.
- Constructors $\Omega_c := \{0 : \rightarrow nat, Succ : nat \rightarrow nat\}$.
- A is generated by Ω_c :
 - For every $n \in \mathbb{N}$, $n = A(\underbrace{s(s(s(\dots(s(0))))}_{n \text{ times}}))$.
- A is also generated by Ω .
 - Any superset of a set of constructors is also a set of constructors.

Usually one looks for the minimal set of constructors.

Algebras Generated in Some Sorts

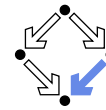


Take signature $\Sigma = (S, \Omega)$, Σ -algebra A .

- Define set of sorts $S_c \subseteq S$ and set of operations $\Omega_c \subseteq \Omega$ (the **constructors**) with target sorts in S_c .
 - Restricted signature $\Sigma_c = (S, \Omega_c)$.
- A is **generated by** Ω_c in S_c :
 - For each sort $s \in S_c$ and carrier $a \in A(s)$, there exists
 - a set X of variables in Σ with $X_s = \emptyset$ for every $s \in S_c$,
 - an assignment $\alpha : X \rightarrow A$,
 - and a term $t \in T_{\Sigma_c(X), s}$
 with $a = A(\alpha)(t)$.
 - Value a can be described by a term t that involves only constructors in the generated sorts and variables in the non-generated sorts.
 - A is **generated in** S_c if it is generated in S_c by Ω .

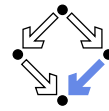
Algebra does not contain “junk” in the carrier sets of the generated sorts.

Example



- Signature $LIST = (S, \Omega)$:
 - $S = \{el, list\}$.
 - $\Omega = \{[] : \rightarrow list, Add : el \times list \rightarrow list, _ \cdot _ : list \times list \rightarrow list\}$.
- LIST-algebra A :
 - $A(el)$... a set of “elements”.
 - $A(list)$... the set of finite lists of elements.
 - $A([])$... the empty list.
 - $A(Add)$ adds an element at the front of the list.
 - $A(\cdot)$ concatenates two lists.
- A is generated by $\Omega_c = \{[], Add\}$ in $S_c = \{list\}$:
 - Take arbitrary $l = [e_1, e_2, \dots, e_n] \in A(list)$.
 - Define $X_{el} := \{x_1, x_2, \dots, x_n\}$.
 - Define $\alpha_{el} := [x_1 \mapsto e_1, x_2 \mapsto e_2, \dots, x_n \mapsto e_n]$.
 - Then $l = A(\alpha)(Add(x_1, Add(x_2, \dots, Add(x_n, []))))$.

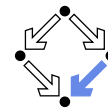
Proofs by Induction



In generated sorts, the principle of structural induction can be applied.

- Take the LIST-algebra A of the previous example.
 - Notation: c_A for $A(c)$.
 - Knowledge: (1) $\forall l \in list_A : []_A \cdot_A l = l$.
 - (2) $\forall e \in el_A, l, r \in list_A :$
 $Add_A(e, l) \cdot_A r = Add_A(e, l \cdot_A r)$.
- Prove: $\forall l \in list_A : l \cdot_A []_A = l$.
- Induction base $l = []_A$:
 - $l \cdot_A []_A = []_A \cdot_A []_A \stackrel{(1)}{=} []_A = l$.
- Induction step $l = Add_A(e, r)$ (for some $e \in el_A, r \in list_A$).
 - Induction Hypothesis (H): $r \cdot_A []_A = r$.
 - $l \cdot_A []_A = Add_A(e, r) \cdot_A []_A$
 $\stackrel{(2)}{=} Add_A(e, r \cdot_A []_A)$
 $\stackrel{(H)}{=} Add_A(e, r) = l$.

Loose Specifications with Constructors

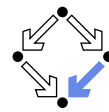


Take logic L .

- **Loose specification with constructors** $sp = (\Sigma, \Phi, S_c, \Omega_c)$ in L :
 - Signature $\Sigma = (S, \Omega)$, set of formulas $\Phi \subseteq L(\Sigma)$, **generated sorts** $S_c \subseteq S$, **constructors** $\Omega_c \subseteq \Omega$ with target sorts in S_c .
- **Semantics** $\mathcal{M}(sp) = Mod_{\mathcal{U}, \Sigma}(\Phi)$ where
 $\mathcal{U} = \{A \in Alg(\Sigma) \mid A \text{ is generated in } S_c \text{ by } \Omega_c\}$.
 - Only generated Σ -algebras are candidates for the specified ADT.

A loose specification with constructors specifies as the ADT the class of all models of its formula set that are generated by the constructors.

Concrete Syntax



loose spec

sorts [**generated**] sort ...

opns [**constr**] operation ...

vars variable: sort ...

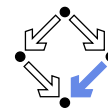
axioms formula ...

endspec

- Signature $\Sigma = (\{sort, \dots\}, \{operation, \dots\})$.
- Set of formulas $\Phi = \{(\forall variable : sort, \dots . formula), \dots\}$.
- Generated sorts $S_c = \{\mathbf{generated\ sort}, \dots\}$.
- Constructors $\Omega_c = \{\mathbf{constr\ operation}, \dots\}$.

We will only use the concrete syntax to define specifications.

Example



loose spec

sorts el

generated bool

generated list

opns

constr True \rightarrow bool

constr False \rightarrow bool

constr [] \rightarrow list

constr Add : $el \times list \rightarrow list$

$.._ :$ list \times list \rightarrow list

vars $l, m : list, e, e_1, e_2 : el$

axioms

$\neg(True = False)$

$\neg([] = Add(e, l))$

$Add(e_1, l_1) = Add(e_2, l_2) \Rightarrow e_1 = e_2$

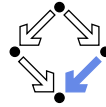
$[].l = l$

$Add(e, l).m = Add(e, l.m)$

endspec

Strictly adequate specification of the "classical" list algebra in PL.

Example



loose spec
sorts

generated *bool*
generated *nat*

opns

constr *True* :→ *bool*
constr *False* :→ *bool*
constr *0* :→ *nat*
constr *Succ* : *nat* → *nat*
_ + _ : *nat* × *nat* → *nat*
_ * _ : *nat* × *nat* → *nat*
_ ≤ _ : *nat* × *nat* → *bool*

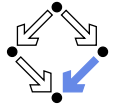
vars *m, n* : *nat*
axioms

$\neg(\text{True} = \text{False})$
 $\neg(0 = \text{Succ}(n))$
 $\text{Succ}(n) = \text{Succ}(m) \Rightarrow n = m$
 $(0 \leq n) = \text{True}$
 $(\text{Succ}(n) \leq 0) = \text{False}$
 $(\text{Succ}(n) \leq \text{Succ}(m)) = (n \leq m)$
 $n + 0 = n$
 $n + \text{Succ}(m) = \text{Succ}(n + m)$
 $n * 0 = 0$
 $n * \text{Succ}(m) = n + (n * m)$

endspec

Strictly adequate specification of Peano arithmetic in PL.

Specified ADT is Strictly Adequate

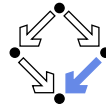


Proof requires two parts.

- Peano arithmetic satisfies the specified axioms.
 - Can be easily checked.
- Specified ADT is monomorphic: $\forall B, C \in \mathcal{M}(sp) : B \simeq C$.
 - There is an isomorphism $h : B \rightarrow C$.
 - A bijective homomorphism.
 - Definition of unique term representation for every carrier.
 - Simplifies the remainder of the proof.
 - Definition of bijective mapping h :
 - By pattern matching on term representation.
 - Proof that h is a homomorphism:
 - By using properties expressed with the help of the term representation.

Term representation essential for this kind of proofs.

Carriers have Unique Term Representations

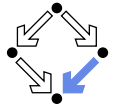


Take arbitrary $A \in \mathcal{M}(sp)$.

- $bool_A = \{\text{True}_A, \text{False}_A\}$ and $\text{True}_A \neq \text{False}_A$.
 - A is generated by $\{\text{True}, \text{False}\}$ in *bool*.
 - **axiom** $\neg(\text{True} = \text{False})$.
- $nat_A = \{\text{Succ}^k(0)_A : k \in \mathbb{N}\}$ and $\forall k \neq l : \text{Succ}^k(0)_A \neq \text{Succ}^l(0)_A$.
 - A is generated by $\{0, \text{Succ}\}$ in *nat*.
 - Proof by induction on k : $\forall l \neq k : \text{Succ}^k(0)_A \neq \text{Succ}^l(0)_A$.
 - $k = 0, l \neq 0$: $0_A \neq \text{Succ}^l(0)_A$ (by **axiom** $\neg(0 = \text{Succ}(n))$).
 - $k \neq 0, l \neq k$: assume $\text{Succ}^k(0)_A = \text{Succ}^l(0)_A$, show $k = l$.
 Know $l \neq 0$ (by **axiom** $\neg(0 = \text{Succ}(n))$).
 Thus $k = k' + 1, l = l' + 1$, it suffices to show $k' = l'$.
 By assumption, $\text{Succ}(\text{Succ}^{k'}(0))_A = \text{Succ}(\text{Succ}^{l'}(0))_A$.
 Thus $\text{Succ}^{k'}(0)_A = \text{Succ}^{l'}(0)_A$ (**axiom** $\text{Succ}(n) = \text{Succ}(m) \Rightarrow n = m$).
 By induction hypothesis, $k' = l'$.

Carriers are uniquely described by constructor applications.

Definition of Bijective Mapping

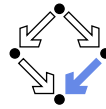


Take arbitrary $B, C \in \mathcal{M}(sp)$.

- h is defined by **pattern matching** on constructor terms:
 - $h_{bool}(\text{True}_B) := \text{True}_C$.
 - $h_{bool}(\text{False}_B) := \text{False}_C$.
 - $h_{nat}(\text{Succ}^k(0)_B) = \text{Succ}^k(0)_C$, for all $k \geq 0$.
- h is consistently defined:
 - True_B and False_B denote different values.
 - $\text{Succ}^k(0)_B$ denote different values for different k .
- h is bijective:
 - True_C and False_C denote different values.
 - $\text{Succ}^k(0)_C$ denote different values for different k .

One-to-one correspondence between the carrier sets of B and C .

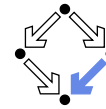
Homomorphism Proof



- Clear for constructors $True, False, 0, Succ$:
 - Definition of h already expresses homomorphism condition.
- **Goal:** $\forall m, n \in nat_B . h(op_B(m, n)) = op_C(h(m), h(n))$.
 $op \dots +, *, \leq$.
 - $\forall k, l \geq 0 . h(op_B(Succ^k(0)_B, Succ^l(0)_B)) = op_C(h(Succ^k(0)_B), h(Succ^l(0)_B))$.
 - B and C are generated by $\{0, Succ\}$ in nat .
 - $\forall k, l \geq 0 . h(op_B(Succ^k(0)_B, Succ^l(0)_B)) = op_C(Succ^k(0)_C, Succ^l(0)_C)$.
 - By definition of h .
 - $\forall k, l \geq 0 . h(op(Succ^k(0), Succ^l(0))_B) = op(Succ^k(0), Succ^l(0))_C$.
 - By definition of term semantics.

Proof goal is expressed with the help of constructor terms.

Homomorphism Proof



The core of the homomorphism proof.

- **Goal:** $h((Succ^k(0) + Succ^l(0))_B) = (Succ^k(0) + Succ^l(0))_C$.
 - First simplify left and right hand side of the equation.
- **Lemma:** $\forall A \in \mathcal{M}(sp) : (Succ^k(0) + Succ^l(0))_A = Succ^{k+l}(0)_A$.
 - Induction base $l = 0$: by **axiom** $n + 0 = n$.
 - Induction step $l = l' + 1$:
$$\begin{aligned} & (Succ^k(0) + Succ^{l'+1}(0))_A \\ &= Succ(Succ^k(0) + Succ^{l'}(0))_A \\ &= Succ(Succ^{k+l'}(0))_A \\ &= Succ^{k+l'+1}(0)_A. \end{aligned}$$
- **Simplified goal:** $h(Succ^{k+l}(0)_B) = Succ^{k+l}(0)_C$.
 - By definition of h .

Similar for the homomorphism proofs of the other operations.

1. General Remarks

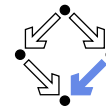
2. Loose Specifications

3. Loose Specifications with Constructors

4. Loose Specifications with Free Constructors

5. Summary

Freely Generated Algebras

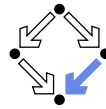


Take signature $\Sigma = (S, \Omega)$, Σ -algebra A .

- Define set of operations $\Omega_c \subseteq \Omega$ (the **constructors**).
 - Restricted signature $\Sigma_c = (S, \Omega_c)$.
- A is **freely generated by** Ω_c :
 - For each sort $s \in S$ and carrier $a \in A(s)$, there exists **exactly one** ground term $t \in T_{\Sigma_c, s}$ with $a = A(t)$.
 - Carrier a can be described by a **unique** term t that involves only constructors.
 - A is **freely generated** if it is generated by Ω .
- A is **freely generated by** Ω_c **in** S_c :
 - Analogous definition as for **generated by ... in ...**.

Algebras have unique constructor term representations for the carrier sets of the freely generated sorts.

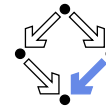
Example



- The “classical” BOOL-algebra $(\{true, false\}, \dots)$:
 - Freely generated by $\{True, False\}$.
 - Not freely generated by $\{True, False, \neg\}$.
- The “one-element” BOOL-algebra $(\{\#\}, \dots)$.
 - Freely generated by $\{True\}$ and by $\{False\}$.
 - Not freely generated by $\{True, False\}$.
- The “classical” NAT-algebra (\mathbb{N}, \dots) :
 - Freely generated by $\{0, Succ\}$.
 - Not freely generated by $\{0, Succ, +\}$.
- The “classical” INT-algebra (\mathbb{Z}, \dots) :
 - $INT = (int, \{0 : \rightarrow int, Succ : int \rightarrow int, Pred : int \rightarrow int\})$.
 - Not freely generated by (any subset of) operations.

A set of free constructors cannot be extended.

Inductive Function Definitions

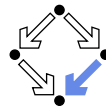


Freely generated algebras allow inductive function definitions.

- Signature $LIST = (S, \Omega)$:
 - $S = \{el, list\}$.
 - $\Omega = \{[\] : \rightarrow list, Add : el \times list \rightarrow list, _ _ : list \times list \rightarrow list\}$.
- Classical LIST-algebra A as in the previous example.
 - A is freely generated by $\Omega_c = \{[\], Add\}$ in $S_c = \{list\}$:
- Inductive definition of function $g : A(list) \rightarrow \mathbb{N}$.
 - $g([\]_A) = 0$.
 - $g(Add(x, t)_A) = g(t_A) + 1$ for all $x \in X, t \in T_{\Sigma_c(x), list}$.

Inductive definition by “pattern matching” on constructor terms (independent of the nature of the carrier set).

Loose Specifications with Free Constructors

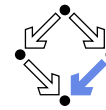


Take logic L .

- Loose specification with free constructors $sp = (\Sigma, \Phi, S_c, \Omega_c)$ in L :
 - Signature $\Sigma = (S, \Omega)$, set of formulas $\Phi \subseteq L(\Sigma)$, freely generated sorts $S_c \subseteq S$, constructors $\Omega_c \subseteq \Omega$ with target sorts in S_c .
- Semantics $\mathcal{M}(sp) = Mod_{\mathcal{U}, \Sigma}(\Phi)$ where
 - $\mathcal{U} = \{A \in Alg(\Sigma) \mid A \text{ is freely generated in } S_c \text{ by } \Omega_c\}$.
 - Only freely generated Σ -algebras are candidates for the specified ADT.

A loose specification with free constructors specifies the class of all models of its formula set that are freely generated by the constructors.

Concrete Syntax

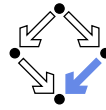


```
loose spec
  sorts [ freely generated ] sort ...
  opns [ constr ] operation ...
  vars variable: sort ...
  axioms formula ...
endspec
```

- Signature $\Sigma = (\{sort, \dots\}, \{operation, \dots\})$.
- Set of formulas $\Phi = \{(\forall variable : sort, \dots . formula), \dots\}$.
- Generated sorts $S_c = \{\text{freely generated sort}, \dots\}$.
- Constructors $\Omega_c = \{\text{constr operation}, \dots\}$.

Also mixing of generated sorts with freely generated sorts possible.

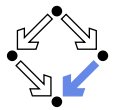
Example



```
loose spec
  sorts el
    freely generated bool
    freely generated list
  opns
    constr True :→ bool
    constr False :→ bool
    constr [] :→ list
    constr Add : el × list → list
    - . - : list × list → list
  vars l, m : list, e, e1, e2 : el
  axioms
    [ ]. l = l
    Add(e, l).m = Add(e, l.m)
endspec
```

Strictly adequate specification of the “classical” list algebra in EL; the non-constructor operation is inductively defined.

Example

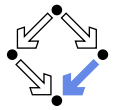


```
loose spec
  sorts
    freely generated bool
    freely generated nat
  opns
    constr True :→ bool
    constr False :→ bool
    constr 0 :→ nat
    constr Succ : nat → nat
    - + - : nat × nat → nat
    - * - : nat × nat → nat
    - ≤ - : nat × nat → bool
  vars m, n : nat
  axioms
    (0 ≤ n) = True
    (Succ(n) ≤ 0) = False
    (Succ(n) ≤ Succ(m)) = (n ≤ m)
    n + 0 = n
    n + Succ(m) = Succ(n + m)
    n * 0 = 0
    n * Succ(m) = n + (n * m)
endspec
```

Strictly adequate specification of the “classical” list algebra in EL; the non-constructor operations are inductively defined.

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Summary

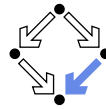


A couple of core messages. . .

- A loose specification describes a class of models as an ADT.
 - To check whether a given algebra implements the specification (i.e., whether it is an element of the specified ADT):
 - Check whether the algebra satisfies the specification axioms.
 - Carrier sets may collapse to singletons (or be too “small”).
 - In *PL*, additional axioms can prevent this.
 - Non-equalities of operation results (injectiveness of operations).
 - Carrier sets may contain junk.
 - In *PL*, an additional axiom can prevent this for a finite carrier set.
 - Axiom enumerates constants that denote all carriers of the sort.

Without constructors, loose specifications are generally clumsy because many “boring” axioms are needed.

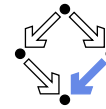
Summary (Contd)



- Loose specifications with **constructors**.
 - Every carrier is denoted by **some** constructor term.
 - Thus junk is removed from (also infinite) carrier sets.
 - Induction proofs on term representation of carriers become possible.
 - Problem: not all carrier sets have term representations.
 - ADT "real" (carrier set is not countable).
- Loose specifications with **free constructors**.
 - Every carrier is denoted by **exactly one** constructor term.
 - Thus the collapse of carrier sets is prevented.
 - Inductive function definitions by pattern matching on term representations of carriers become possible.
 - Problem: not all carrier sets have unique term representations.
 - ADT "set" (no unique representation at all).
 - ADT "integer" (unique representation is unconvient).

With constructors, loose specifications become easy to use.

Summary (Contd)



So what is the role of loose specifications. . .

- Loose specifications are **good** for specifying **requirements**.
 - May specify zero, one, many datatypes (polymorphic ADTs).
 - Thus allow arbitrarily many implementations.
 - A loose specification may not have any model (implementation) at all!
 - Specification axioms can (should) be abstract.
 - Later verification that concrete implementation satisfies the axioms.
- Loose specifications are **not good** for specifying **designs**.
 - Not descriptions of concrete algorithms/implementations.
- Loose specifications are generally **not executable**.
 - No engines to execute loose specifications for rapid prototyping.

Loose specifications are for *reasoning*, not for *executing*; they are the basis of program specification languages such as Larch/C++.