# Formal Specification of Abstract Datatypes

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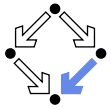
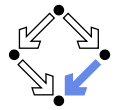




## Datatypes



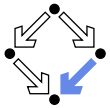
What is a datatype?

- Traditional view: collection of data with same structure.
  - Mathematics:
    set $S := int \times char = \{(a, b) \mid a \in int \wedge b \in char\}$.
  - Programming:
    **struct** $S$ $\{int\ a; char\ b\}$
- Modern view: collection of data with same services.
  - Mathematics
    algebra $T = (S,\ getA : S \to int,\ getB : S \to char)$
    $= (int \times char, \lambda(a, b).a, \lambda(a, b).b)$.
  - Programming:
    **class** $T$ { $S\ x$;
    $int\ getA()$ {**return** $x.a$}; $char\ getB()$ {**return** $x.b$} }.

In this course, we will take the modern view of datatypes.



## Abstract Datatypes



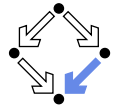
What is an abstract datatype (ADT)?

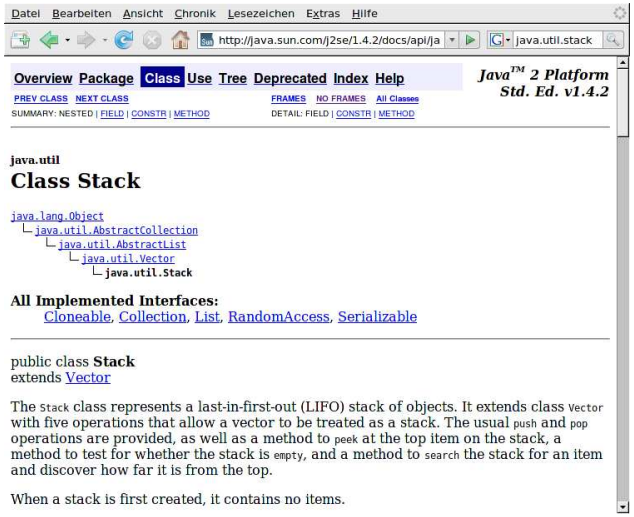
- The set of services to be provided by an implementing datatype.
  - The description of the services is the specification of the ADT.
    - The specification does not enforce a particular data representation.
  - A datatype providing such services is an implementation of the ADT.
    - Provides concrete data representations for the values of the ADT.
    - Provides concrete program methods for the services of the ADT.
- There may be zero, one, many implementations of an ADT possible.
  - The specification of the ADT should be as general as possible in order not to constrain the implementation more than necessary.
- The specification is the contract between user and implementer.
  - "Design by contract" (Bertrand Meyer).

Thus we need specification languages to describe ADTs.

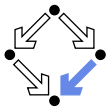


## Java API Documentation





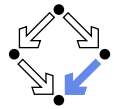
## Java API Documentation



```
public Object push(Object item)
    Pushes an item onto the top of this stack.

    Parameters:
        item - the item to be pushed onto this stack.
    Returns:
        the item argument.

public Object pop()
    Removes the object at the top of this stack and returns that object
    as the value of this function.

    Returns:
        The object at the top of this stack.
    Throws:
        EmptyStackException - if this stack is empty.
```



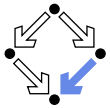
## Java Interfaces



```
interface StackADT
{
  // Pushes an item onto the top of this stack.
  // Returns the item pushed on the stack.
  Object push(Object item);

  // Removes the object at the top of this stack and
  // returns that object as the value of this function.
  // Throws EmptyStackException, if this stack is empty.
  Object pop();

  // Returns the object at the top of this stack
  // without removing it from the stack.
  // Throws EmptyStackException, if this stack is empty.
  Object peek();

  // Returns true if and only if this stack contains no items.
  boolean empty();
}
```



## Specification Languages



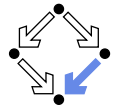
Programming languages only describe the syntax (interface) of an ADT.

- Specification languages also describe the semantics (behavior).
  - Based on concepts from universal algebra and logic.
  - Notions "datatype" and "ADT" have a precise meaning.
    - An algebra $T$ and a (particular) class $\mathcal{A}$ of algebras, respectively.
  - Statement "datatype $T$ implements ADT $\mathcal{A}$" has a precise meaning.
    - $T \in \mathcal{A}$.
    - Formal calculus to prove the statement.
- Constructive specifications may be even executed.
  - Describe not only requirements but also suggest an implementation.
  - Term rewriting engines for executing constructive specifications.
  - Rapid prototyping of specifications in the design phase.

Formal specifications can overcome the ambiguity of natural language when describing program requirements.



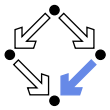
## Larch



```
Stack (E, C): trait
  introduces
    empty: -> C
    push: E, C -> C
    top: C -> E
    pop: C -> C
    isEmpty: C -> Bool
  asserts
    C generated by empty, push
    forall e: E, stk: C
      top(push(e, stk)) == e;
      pop(push(e, stk)) == stk;
      isEmpty(stk) == stk = empty
```

Formal description of ADT "Stack" in the Larch Shared Language (LSL).

## Larch/C++

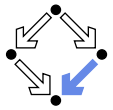


```
template <class Elem                          virtual Stack<Elem>& pop() throw();
/*@ expects contained_objects(Elem) @*/ >     //@ behavior {
class Stack {                                 //@ requires ~isEmpty(self^);
public:                                       //@ modifies self;
                                              //@ ensures self' =
//@ uses Stack(Elem for E,                    //@   pop(self^) /\ result = self; }
               Stack<Elem> for C);
                                              virtual Elem top() const throw();
Stack() throw();                              //@ behavior {
//@ behavior {                                //@ requires ~isEmpty(self\any);
//@ modifies self;                            //@ ensures result = top(self\any); }
//@ ensures liberally self' = empty; }
                                              virtual bool isEmpty() const throw();
virtual Stack<Elem>& push(Elem e) throw();    //@ behavior {
//@ behavior {                                //@ ensures result =
//@ modifies self;                            //@   (isEmpty(self\any)); }
//@ ensures liberally self' =
//@   push(self^,e) /\ result = self; }       };
```

Formal specification of a C++ "Stack" in Larch/C++.



## CafeOBJ

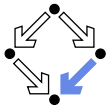


```
dragonfly!1> /zvol/formal/bin/cafeobj
-- loading standard prelude
; Loading /usr3/cafeobj-1.4/prelude/std.bin

          -- CafeOBJ system Version 1.4.6(PigNose0.99,p3) --
                    built: 2004 Nov 17 Wed 6:37:33 GMT
                         prelude file: std.bin
                                  ***
                      2005 Sep 10 Sat 12:39:32 GMT
                            Type ? for help
                                  ***
                    -- Containing PigNose Extensions --
                                  ---
          built on International Allegro CL Enterprise Edition
                6.2 [Linux (x86)] (Nov 17, 2004 15:37)
CafeOBJ>
```

System for executing constructive specifications.



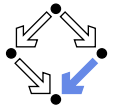
## CafeOBJ



```
CafeOBJ> module! STACK
{
  protecting (NAT)
  signature
  {
    [ Stack ]
    op empty : -> Stack
    op push : Nat Stack -> Stack
    op top : Stack -> Nat
    op pop : Stack -> Stack
  }
  axioms
  {
    var N : Nat
    var S : Stack

    eq top(push(N, S)) = N .
    eq pop(push(N, S)) = S .
  }
}
```

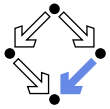


## CafeOBJ



```
CafeOBJ> open STACK
-- opening module STACK.. done.
%STACK> parse top(push(1, empty)) .
top(push(1,empty)) : Nat
%STACK> reduce top(push(1, empty)) .
-- reduce in %STACK : top(push(1,empty))
1 : NzNat
(0.000 sec for parse, 1 rewrites(0.000 sec), 1 matches)
%STACK> parse top(pop(push(2, push(1, empty)))) .
top(pop(push(2,push(1,empty)))) : Nat
%STACK> reduce top(pop(push(2, push(1, empty)))) .
-- reduce in %STACK : top(pop(push(2,push(1,empty))))
1 : NzNat
(0.000 sec for parse, 2 rewrites(0.000 sec), 2 matches)
%STACK> parse top(pop(push(1, empty))) .
top(pop(push(1,empty))) : Nat
%STACK> reduce  top(pop(push(1, empty))) .
-- reduce in %STACK : top(pop(push(1,empty)))
top(empty) : Nat
(0.000 sec for parse, 1 rewrites(0.000 sec), 2 matches)
%STACK> close
```

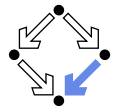
## Algebraic/Axiomatic Specifications



- Approach rooted in universal algebra.
  - Logical axioms relate different operations of ADT to each other.
  - Similar as in the description of algebras in mathematics.
- Original focus (1970s/1980s): initial semantics.
  - Specifications in (conditional) equational logic.
    - Main interest in executable design specifications.
    - Strong connections to term rewriting.
  - Languages: Clear, ACT ONE/TWO, OBJ family, ...
- Alternative focus (1990s): loose semantics.
  - Specifications in full first-order predicate logic.
    - Main interest in precise requirement specifications.
    - Strong connections to object-oriented program specification.
  - Languages: Larch/C++, Java Modeling Language (JML), ...
- Common Algebraic Specification Language (CASL)
  - Result of Common Framework Initiative (CoFI), since 1995.
  - Unifying framework for algebraic specifications in different logics.



## Course Outline



- Abstract Datatypes.
- *CafeOBJ*.
- Logic.
- Loose Specifications.
- *Larch/C++*, *JML*.
- Term Algebras.
- Initial Specifications.
- Specifications in the Large.
- *CASL*.

Interspersed with presentations of various case studies; exercises both theoretical (paper and pencil) and practical (CafeOBJ).