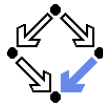


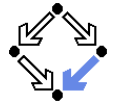
# Templates

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# Templates



In C++, types can also serve as parameters.

- **Parametric polymorphism:** genericity based on types as parameters.
  - An extension to the object-oriented paradigm of **type polymorphism** (genericity based on inheritance).
- **Templates:** functions or classes parameterized over types.
  - By **instantiating** the template parameters with concrete types, concrete functions and classes are constructed.
  - Instantiation is resolved at compile time (no runtime overhead).
- **Template metaprogramming:** let compiler execute programs.
  - Templates allow recursion, selection, and computation.
    - Template programs are executed at compile-time.
  - Selection of different variants of code, modification of the behavior of generated code, set policies for runtime code execution.

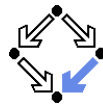
The C++ standard library makes heavy use of templates.

## 1. Function Templates

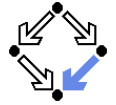
## 2. Class Templates

## 3. Advanced Use of Templates

## 4. Example: Generic Lists



# Function Templates



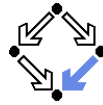
```
template<typename T> T min(T a, T b) {  
    T c = a;  
    if (b < a) c = b;  
    return c;  
}
```

```
int x = min<int>(10, 20);           // explicit instantiation of min<int>  
float y = min<float>(10.4, 20.3); // explicit instantiation of min<float>  
int z = min(10, 20);              // automatic instantiation of min<int>
```

- **template<typename T>:** a template with type parameter  $T$ .
  - Also **class  $T$**  denotes type parameters.  
Typically used, if  $T$  shall denote a class.
- **fun<A>(…):** instantiation of parameter  $T$  by concrete type  $A$ .
  - Instantiated function declaration is generated and compiled.
  - Type checking occurs for each instantiation separately.
- **fun(…):** automatically deduced instantiation.
  - In most cases, the compiler is able to automatically deduce the appropriate instantiation.

Each instantiation of a function template denotes a separate function.

## Operator Templates



Like functions, also operators may be defined as templates.

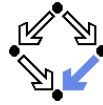
```
template<typename T> int operator+(T x, int y)
{
    return x.getIntValue() + y;
}

class Int {
    int x;
public:
    Int(int x) { this->x = x; }
    int getIntValue() { return x; }
};

Int i(5);
int j = i+1; // automatic: operator+<Int>
int k = operator+<Int>(i, 1); // explicit instantiation
```

Also for operators, argument types may be automatically derived.

## Template Source



Where to put the source of a template?

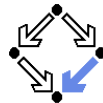
```
// min.h
template<typename T> T min(T a, T b) { ... }

// file1.cpp // file2.cpp
#include "min.h" #include "min.h"
... min<int>(...) ... min<int>(...) ...
```

- **Short answer:** place it in a header file.
  - Each source file using the template includes the file.
  - Each object file contains set of generated template instantiations.
  - Linker merges duplicate instantiations in finally produced executable.
- **Disadvantage:** compilation overhead.
  - Same instantiation repeatedly generated, type-checked, and compiled.
  - Long compilation times, large object files.

A more comprehensive answer will be given later.

## Example: A Generic Sorting Function (V1)



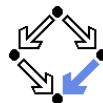
```
template<typename T> void sort(T a[], int n) {
    for (int i=0; i<n-1; i++) {
        for (int j=n-1; i<j; j--) {
            if (a[j] < a[j-1]) {
                T b = a[j];
                a[j] = a[j-1];
                a[j-1] = b;
            }
        }
    }
}

int a[100];
sort(a, 100); // automatic: sort<int>
```

- Function sorts arrays of **any base type**.
  - Type must provide comparison operator <.
- **What if operator < is not appropriate?**
  - We might wish another sorting criterium.

We have "hard-wired" the comparison operation in the sorter.

## Example: A Generic Sorting Function (V2)



```
class IntComparator { public:
    static bool isSorted(int a, int b) { return a <= b; }
};

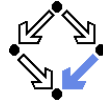
class StringComparison { public:
    static bool isSorted(char *a, char *b) { return strcmp(a, b) <= 0; }
};

template<typename T, typename C> void sort(T a[], int n) {
    for (int i=0; i<n-1; i++) {
        for (int j=n-1; i<j; j--) {
            if (!C::isSorted(a[j-1], a[j])) {
                T b = a[j]; a[j] = a[j-1]; a[j-1] = b;
            }
        }
    }
}

int a[100]; sort<int, IntComparator>(a, 100);
char* b[100]; sort<char*, StringComparison>(b, 100);
```

The sorter is instantiated with a class holding the comparison operation.

## Value Parameters



Template parameters may be also values.

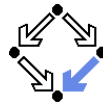
```
template<int N, typename T> void fill(T a[N], T x)
{
    for (int i=0; i<N; i++) a[i] = x;
}

int a[3];
fill<3,int>(a, 7); // explicit instantiation
fill<3>(a,7);     // automatic: fill<3,int>
```

- **template<T v>**: a template with value parameter  $v$  of type  $T$ .
  - $T$  must be an integral, enumeration, or pointer/reference type.
- **fun<a>(...)**:
  - Argument  $a$  must be a **compile-time constant** (a constant expression or the address of an object with external linkage).
  - Must be given by **explicit instantiation** (subsequent type parameters may be automatically instantiated).

Value parameters in templates may be also used in type declarations.

## Example: A Generic Sorting Function (V3)

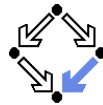


```
template<int N, typename T> void sort(T a[N]) {
    for (int i=0; i<N-1; i++) {
        for (int j=N-1; i<j; j--) {
            if (a[j] < a[j-1]) {
                T b = a[j];
                a[j] = a[j-1];
                a[j-1] = b;
            }
        }
    }
}
```

```
int a[100];
sort<100>(a); // automatic: sort<100, int>
```

The sorter is instantiated with the array length.

## Example: A Generic Sorting Function (V4)



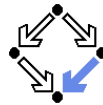
```
template<typename T, bool isSorted(T, T)> void sort(T a[], int n) {
    for (int i=0; i<n-1; i++) {
        for (int j=n-1; i<j; j--) {
            if (!isSorted(a[j-1], a[j])){
                T b = a[j];
                a[j] = a[j-1];
                a[j-1] = b;
            }
        }
    }
}

inline bool lessEqual(int x, int y) { return x <= y; }
int a[100];
sort<int, lessEqual>(a, 100);
```

- Comparison function becomes **value parameter** of template.
  - Function has generic signature `bool isSorted(T, T)`.
  - Type parameter  $T$  must appear in template signature before.
  - If defined in current file, **comparison function may be inlined**.

The sorter is instantiated with the comparison operation.

## Specializing Function Templates



For special instantiations, alternative function definitions may be given.

```
double pow(double x, double y); // exponentiation
int isqrt(int x);                // integer square root
```

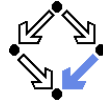
```
template<typename T> T root(T x, T y) {
    return T(pow(x, 1.0/y)); // conversion to T
}
```

```
template<> int root<int>(int x, int y) {
    if (y == 2)
        return isqrt(x); // special implementation
    else
        return int(pow(x, 1.0/y));
}
```

```
int r1 = root(4, 2); // root<int> -> isqrt(4)
double r2 = root(4.5, 2.0); // root<double> -> pow(4.5, 0.5)
```

For achieving higher performance, a generic function implementation may be augmented by special implementations.

## Example: A Generic Sorting Function (V5)



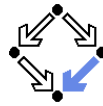
```
// a generic sorting function (V1)
template<typename T> void sort(T a[], int n) { ... }

// provide sorting function applicable to strings
template<> void sort<char*>(char* a[], int n) {
    for (int i=0; i<n-1; i++) {
        for (int j=n-1; i<j; j--) {
            if (strcmp(a[j], a[j-1]) < 0) {
                T b = a[j];
                a[j] = a[j-1];
                a[j-1] = b;
            }
        }
    }
}

char* a[100];
sort(a, 100); // automatic: sort<char*>
```

By specialization, a sorting function with another comparison operation (or another specialized sorting algorithm) may be used.

## Overloading Function Templates



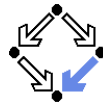
```
template<typename T> void func(T x, T y) { ... }
template<typename T> T func(T x) { ... }
template<typename T, typename U> U func(T x) { ... }

func(y, y); // automatic: func<float>(y, y)
int x = func<int>(1); // explicit instantiation needed
float y = func<int, float>(x); // explicit instantiation needed
```

- Function templates may be overloaded.
  - Same function name but different template/function parameters.
  - If appropriate instantiation can be derived from the types of the function arguments, no explicit instantiation is needed.
  - If different function templates have same names and function parameters, explicit instantiation is needed.

Explicit instantiation may be required in case of disambiguities.

## Changing Parameter Types



To change some parameter types, overload the function template.

```
double pow(double x, double y); // exponentiation
double iroot(double x, int y); // root computation

template<typename T> T root(T x, T y) {
    return T(pow(x, 1.0/y)); // conversion to T
}

template<typename T, typename U> T root(T x, U y) {
    return T(iroot(x, y)); // conversion to T
}

double r2 = root(4.5, 2.0); // root<double> -> pow(4.5, 0.5)
double r2 = root(4.5, 2); // root<double,int> -> iroot(4.5, 2)
```

Specialization and overloading gives large flexibility in selecting the most efficient implementations for arbitrary combinations of types.

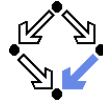
### 1. Function Templates

### 2. Class Templates

### 3. Advanced Use of Templates

### 4. Example: Generic Lists

## Class Templates



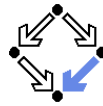
```
template<typename T> class Point {
    T x; T y;
public:
    Point(T a, T b): x(a), y(b) { }
    T getX() { return x; }
    Point flip() { return Point(-x,-y); }
    static Point copy(Point p) { return Point(p.x, p.y); }
};
```

```
Point<int> p(5, 3);
int x = p.getX();
Point<int> q = p.flip();
Point<int> r = Point<int>::copy(q);
```

- `template<typename T>`: also possible for declaration of class `C`.
  - Within the declaration, `C` is a synonym for instantiation `C<T>`.
  - Instantiation by any other type `A` must be explicitly stated as `C<A>`.
- `C<A>`: instantiation of parameter `T` by concrete type `A`.
  - Outside declaration, class template must be explicitly instantiated.

Each instantiation `C<A>` represents a separate class.

## Class Templates



```
// Point.h
template<typename T> class Point { ... } // no member definitions inside

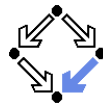
// member definitions outside of class declaration
template<typename T> Point<T>::Point(T a, T b): x(a), y(b) { }
template<typename T> T Point<T>::getX() { return x; }
template<typename T> Point<T> Point<T>::flip() { return Point(-x,-y); }
template<typename T> Point<T> Point<T>::copy(Point p)
{ return Point(p.x, p.y); }
```

- Member definition `C<T>::member` outside class declaration.
  - Inside definition, `C` is a synonym for `C<T>`.

Unfortunately not for types of data members and return types of member functions.

Member functions of class templates are defined in the template header.

## Default Arguments



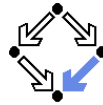
A class template may provide default arguments for its parameters.

```
template<typename T=int, typename U=int>
class Tuple {
    T x; U y;
public:
    Tuple(T a, U b): x(a), y(b) { }
    Tuple() { }
    Tuple(Tuple t): x(t.x), y(t.y) { }
};

Tuple<double, double> t(3.14, 2.71);
Tuple<double> u(3.14, 2);           // Tuple<double, int>
Tuple<> v(3, 2);                  // Tuple<int, int>
```

If the instantiation of a class template provides too few arguments, the default arguments are used instead.

## Value Parameters

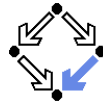


```
template<int N=100, typename T=int>
class Array {
protected:
    T a[N];
public:
    Array(T x = 0) { for (int i=0; i<N; i++) a[i] = x; }
    virtual ~Array() { } // support subclasses with virtual functions
    int length() { return N; }
    T& operator[](int i) {
        if (i < 0 || i >= N) exit(-1);
        return a[i];
    }
};

Array<50> a(-1); // Array<50,int>
a[1] = a[1] + 1;
Array<> b(-1); // Array<100,int>
b[1] = b[1]+a[1];
```

A class template may also have value parameters which may also receive default values; concrete arguments must be compile-time constants.

## Specializing Class Templates



For special instantiations, alternative class definitions may be given.

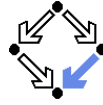
```
template<typename T> class Container {
    T* value;
public:
    Container(T x) { value = new T; *value = x; }
};

template<> class Container<int> {
    int value;
public:
    Container(int x) { value = x; }
};

Tuple<int, int> t(3, 0);
Container<Tuple<int, int> > c(t);
Container<int> d(5);
```

A generic class may be augmented by special representations.

## Partial Specialization



Only some the template parameters may be specialized.

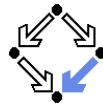
```
template<int N, typename T> class Array { ... }

template<typename T> class Array<1, T> {
protected:
    T a; // no array but scalar variable
public:
    Array(T x = 0): a(x) { }
    virtual ~Array() { }
    int length() { return 1; }
    T& operator[](int i) {
        if (i != 0) exit(-1);
        return a;
    }
};

Array<1, int> a(1);
a[0] = a[0]+1;
```

From a template, more special templates may be derived.

## Example: A Generic Sorting Function (V6)



```
template<typename T> class Comparator { public:
    static bool isSorted(T a, T b) { return a <= b; }
};

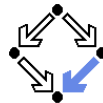
template<> class Comparator<char*> { public:
    static bool isSorted(char *a, char *b) { return strcmp(a, b) <= 0; }
};

template<int N, typename T> void sort(Array<N, T>& a) {
    for (int i=0; i<N-1; i++) {
        for (int j=N-1; i<j; j--) {
            if (!Comparator<T>::isSorted(a[j-1],a[j])) {
                T b = a[j]; a[j] = a[j-1]; a[j-1] = b;
            }
        }
    }
}

Array<100, int> a; sort(a);
Array<100, char*> b; sort(b);
```

Generic sorting with the comparison operation attached to the base type.

## Example: A Generic Sorting Function (V7)



```
template<int N, typename T> class SortableArray: public Array<N, T> { public:
    static bool isSorted(T a, T b) { return a <= b; }
};

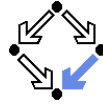
template<int N> class SortableArray<N, char *>: public Array<N, char*> { public:
    static bool isSorted(char *a, char *b) { return strcmp(a, b) <= 0; }
};

template<int N, typename T> void sort(SortableArray<N, T>& a) {
    for (int i=0; i<N-1; i++) {
        for (int j=N-1; i<j; j--) {
            if (!SortableArray<N, T>::isSorted(a[j-1],a[j])) {
                T b = a[j]; a[j] = a[j-1]; a[j-1] = b;
            }
        }
    }
}

Array<100, int> a; sort(a);
Array<100, char*> b; sort(b);
```

Generic sorting with the comparison operation attached to the array type.

## Example: A Generic Sorting Function (V8)



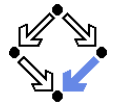
```
template<int N, typename T> class SortableArray2: public Array<N, T> { public:
    virtual bool isSorted(int i, int j) { return this->a[i] <= this->a[j]; }
};
template<int N> class SortableArray2<N, char *>: public Array<N, char*> { public:
    virtual bool isSorted(int i, int j) {return strcmp(this->a[i],this->a[j])<=0;}
};
```

```
template<int N, typename T> void sort(SortableArray2<N, T>& a) {
    for (int i=0; i<N-1; i++) {
        for (int j=N-1; i<j; j--) {
            if (!a.isSorted(j-1,j)) {
                T b = a[j]; a[j] = a[j-1]; a[j-1] = b;
            }
        }
    }
}
```

```
SortableArray2<100, int> a; sort(a);
SortableArray2<100, char*> b; sort(b);
```

Generic sorting with the comparison operation attached to the array object (i.e. operation is looked up at runtime, no inlining is possible).

## Example: A Generic Sorting Function (V8)



```
template<int N, typename T> class SortableArray2: public Array<N, T> { ... }
template<int N, typename T> void sort(SortableArray2<N, T> a) { ... }
```

```
template<int N, typename T>
class ReverseSortedArray: public SortableArray2<N, T> {
public:
    virtual bool isSorted(int i, int j)
    { return !SortableArray2::isSorted(i, j); }
};
```

```
ReverseSortedArray<100, int> a; sort(a);
ReverseSortedArray<100, char*> b; sort(b);
```

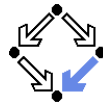
By inheritance and overriding, arrays may be constructed with different comparison operations attached to them.

### 1. Function Templates

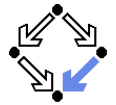
### 2. Class Templates

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## Member Templates



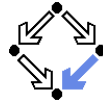
A template may be a member of a class.

```
template<typename T> class Variable {
    T value;
public:
    Variable(T x): value(x) { }
    void set(T x) { value = x; }
    template<typename U> void set(U x) { value = static_cast<T>(x); }
};
```

```
Variable<int> var(0);
var.set(1);           // non-template function set
var.set<double>(1.5); // explicit: template function set<double>
var.set(2.5);        // automatic: template function set<double>
```

By overloading, functions and function templates may have same names; compiler gives precedence to non-template functions.

## Templates as Parameters



A template may receive class templates as parameters.

```
template<template<int, typename> class C, int N, typename T>
void fill(C<N, T> a, int start, int end, T x) {
    for (int i=start; i<end; i++) a[i] = x;
}
```

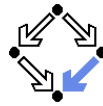
```
Array<100, int> a;
fill(a, 0, 50, 1); // automatic: fill<Array, 100, int>
fill(a, 50, 100, 2); // automatic: fill<Array, 100, int>
```

```
Array<100, double> b;
fill(b, 0, 100, 1.5); // automatic: fill<Array, 100, double>
```

- **template<template<...> class C>**
  - A template with a class template *C* as parameter.
  - *C* must be instantiated as specified by its parameter list *<...>*.

For function templates, the appropriate instantiations of the template parameters can be typically determined automatically.

## Templates and Friends

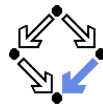


```
class C { };
template<typename T> class U { friend class C; };
class D { friend class U<int>; };
class E { template<typename T> friend class U; };
template<typename T> class V { friend class U<T>; };
template<typename T> class W { template<typename T2> friend class U<T2>; };
```

- **Template instances can grant friendship/be granted friendship.**
  - Class *C* is friend of every instance of template class *U*.
  - Class *U<int>* is friend of class *D* (but no other instance of *U* is).
  - Every instance of template class *U* is friend of class *E*.
  - For every type *T*, class *U<T>* is friend of class *V<T>*.
  - Every instance of template class *U* is friend of every instance of template class *W*.

It is the individual instances that grant/receive friendship status.

## Templates and Type Names



Classes may also hold type definitions.

```
template<int N, typename T> class Array {
    ...
    typedef T value_type;
}
```

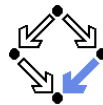
```
template<typename C>
typename C::value_type get(C a, int i) {
    return a[i];
}
```

```
Array<100,int> arr0;
int val = get(arr0, 0); // automatic: get<Array<100,int> >
```

- **typename *C::member***
  - Indicates that *C::member* denotes a type (not a value).
  - Compiler needs to know this for correctly parsing the template.

Type names as class members are frequently used for “traits” (see later).

## Templates and Name Lookup



```
template<int N, typename T> class Array { ... protected: T a[N]; ... }
```

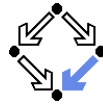
```
template<int N, typename T> class SortableArray2: public Array<N, T> {
public:
    virtual bool isSorted(int i, int j)
    { return this->a[i] <= this->a[j]; } // wrong: "return a[i] < a[j]"
}
```

- **Nondependent names:** looked up in context of template declaration.
  - *i* and *j* are non-dependent (do not depend on template parameters).
  - `return a[i] <= a[j]`: variable *a* is looked up in template context (i.e. typically reported as “undeclared” by compiler).
- **Dependent names:** looked up in context of instantiated template.
  - Name *this* is always dependent.
  - `return this->a[i] <= this->a[j]`: variable *a* is looked up in the context of the instantiated class.

In templates, better refer to class members as `this->member` (this is mandatory when referring to members of base classes).



# Template Metaprogramming



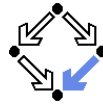
With templates, programs can be written that are executed by compiler.

```
template<int x, unsigned y>
struct ipower {
    static const int value = x*ipower<x,y-1>::value;
};
template<int x>
struct ipower<x, 0> {
    static const int value = 1;
};

int x = ipower<2,5>::value; // 2^5=32, computed by compiler
```

Attention: template metaprograms may take a long time and need not even terminate (compiler might loop forever).

# Template Metaprogramming



```
struct empty {};
template<typename H, typename T> struct node {
    typedef H head; typedef T tail; };

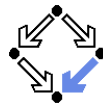
template<typename T, typename U> struct same {
    static const bool result = false; };
template<typename T> struct same<T, T> {
    static const bool result = true; };

template<typename T, typename L> struct member {
    static const bool result =
        same<T, typename L::head>::result ||
        member<T, typename L::tail>::result; };
template<typename T> struct member<T, empty> {
    static const bool result = false; };

typedef node<int, node<bool, node<char, empty> > > typelist;
bool haschar = member<char, typelist>::result; // true, computed by compiler
```

Lists of types that are processed at compile time.

# Compiling Templates

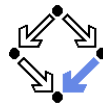


How do compilers handle the compilation of a template t?

- **Approach 1:** Both declaration and definition in header file *t.h*.
  - Some compilers create separate instances for each compiled source; linker ensures that final executable does not contain duplicates.
  - Some compilers maintain a repository of generated instances; this repository is looked up before generating a new instance.
- **Approach 2:** Only declaration in *t.h*, definition in source file *t.cpp*.
  - Some compilers locate the definition automatically from the name of the template and create new instances from there (if required).
- **C++ standard:** keyword `export`.
  - If template declarations and definitions are prefixed by `export`, approach 2 is chosen (approach 1, otherwise).
  - Only few compilers support `export`.

How to organize source code such that it works for all approaches?

# Compiling Templates: Configurations



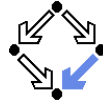
```
// config.h
#ifndef CONFIG_H
#define CONFIG_H

...
// settings for gcc
#ifdef __GNUC__
    #undef HAS_EXPORT
    #define NEED_TEMPLATE_DEFINITIONS
#endif
...

#ifdef HAS_EXPORT
    #define EXPORT export
#else
    #define EXPORT
#endif

#endif CONFIG_H
```

## Compiling Templates: Declarations



```
// point.h
#ifndef POINT_H
#define POINT_H

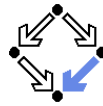
#include "config.h"

// template declaration, definitions only for inlining
EXPORT template<typename T> class Point {
    T x; T y;
public:
    Point(T a, T b): x(a), y(b) { }
    T getX() { return x; }
    Point flip();
    static Point copy(Point p);
};

#ifdef NEED_TEMPLATE_DEFINITIONS
#include "point.cpp";
#endif

#endif POINT_H
```

## Compiling Templates: Definitions



```
// point.cpp
#include "point.h"

// template definitions
EXPORT template<typename T> Point<T> Point<T>::flip() {
    return Point(-x,-y);
}
EXPORT template<typename T> Point<T> Point<T>::copy(Point p) {
    return Point(p.x, p.y);
}

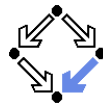
// main.h
#include "point.h"
int main()
{
    Point<int> p(10, 20);
    ...
}
```

### 1. Function Templates

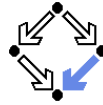
### 2. Class Templates

### 3. Advanced Use of Templates

### 4. Example: Generic Lists



## Example: Generic Lists



```
// empty list is created: ()
List<int> l; cout << l;

// 3 elements are inserted at positions 0,1,1: (1, 3, 2)
l.insert(0, 1).insert(1, 2).insert(1, 3); cout << l;

// element is removed and new one is inserted: (1, 4, 2)
l.remove(1).insert(1, 4); cout << l;

// element at position 1 is updated: (1, 2, 2)
l[1] = 2; cout << l;

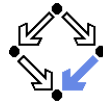
// a copy of the list is created: (1, 2, 2)
List<int> r = l; cout << r;

// copy is updated, original is unchanged: (1, 3, 2) (1, 2, 2)
r[1] = r[1]+1; cout << r; cout << l;

// list is replaced: (1, 3, 2)
l = r; cout << l;
```

A list of values with flexible access and modification operations.

## Example: Generic Lists

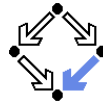


```
// forward declarations
template<typename T> class List;
template<typename T> ostream& operator<<(ostream& out, List<T>& l);

// Node gives friend status to List and operator<<
template<typename T> class Node
{
    T value;
    Node* next;
public:
    Node(T& v, Node* n): value(v), next(n) { }
    friend class List<T>;
    friend ostream& operator<< <T>(ostream& out, List <T> &l);
};
```

Class for representation of list nodes.

## Example: Generic Lists

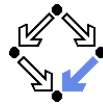


```
template<typename T> class List
{
    Node<T> *head;      // NULL or pointer to first node
    int len;           // number of nodes
    void reset();      // set list to empty
    void copy(List &l); // copy content of l to this list
public:
    List();            // empty list
    ~List();           // discard all values of list
    List(List& l);     // copy values of l to this list
    List& operator=(List& l); // assign values of l to this list
    int length();      // number of values in list
    T& operator[](int i); // reference to value at position i
    List<T>& insert(int i, T value); // insert value at position i
    List<T>& remove(int i); // remove value from position i

    // give friend status to operator <<
    friend ostream& operator<< <T>(ostream& out, List <T>& l);
};
```

The nodes of a list are never exposed and not shared with any other list.

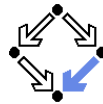
## Example: Generic Lists



```
template<typename T> ostream& operator<<(ostream& out, List<T>& l)
{
    Node<T> *node = l.head;
    out << "(";
    while (node != NULL)
    {
        out << node->value;
        node = node->next;
        if (node != NULL) out << ", ";
    }
    out << ")";
    return out;
}
```

Printing requires access to list head and node fields.

## Example: Generic Lists



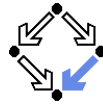
```
template<typename T> List<T>::List(): head(NULL), len(0) { }
template<typename T> List<T>::~List() { reset(); }
template<typename T> List<T>::List(List& l) { copy(l); }
template<typename T> List<T>& List<T>::operator=(List& l) {
    reset(); copy(l); return l;
}

template<typename T> int List<T>::length() { return len; }

template<typename T> T& List<T>::operator[](int i) {
    Node<T> *node = head;
    for (int j=0; j<i; j++)
        node = node->next;
    return node->value;
}
```

The most fundamental list operations.

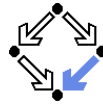
## Example: Generic Lists



```
template<typename T> List<T>& List<T>::insert(int i, T value)
{
    Node<T> *prev = NULL;
    Node<T> *next = head;
    for (int j=0; j<i; j++)
    {
        prev = next;
        next = next->next;
    }
    Node<T> *node = new Node<T>(value, next);
    if (prev == NULL)
        head = node;
    else
        prev->next = node;
    len = len+1;
    return *this;
}
```

Creating a new node and inserting it at the denoted position.

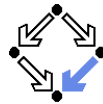
## Example: Generic Lists



```
template<typename T> List<T>& List<T>::remove(int i)
{
    Node<T> *prev = NULL;
    Node<T> *next = head;
    for (int j=0; j<i; j++)
    {
        prev = next;
        next = next->next;
    }
    if (prev == NULL)
        head = next->next;
    else
        prev->next = next->next;
    len = len-1;
    delete next;
    return *this;
}
```

Removing a node from the denoted position (deleting it from memory).

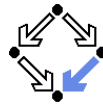
## Example: Generic Lists



```
template<typename T> void List<T>::reset()
{
    Node<T> *node = head;
    while (node != NULL)
    {
        Node<T> *prev = node;
        node = node->next;
        delete prev;
    }
    head = NULL;
    len = 0;
}
```

Resetting a list to the original status (deleting all nodes).

## Example: Generic Lists



```
template<typename T> void List<T>::copy(List& l)
{
    Node<T> *prev = NULL;
    int n = l.length();
    Node<T> *node = l.head;
    for (int i=0; i<n; i++)
    {
        Node<T> *node0 = new Node<T>(node->value, NULL);
        if (prev == NULL)
            head = node0;
        else
            prev->next = node0;
        prev = node0;
        node = node->next;
    }
    len = n;
}
```

Copying the nodes from another list (assuming this list is empty).