Introduction
Why C++?

Why not Matlab?

- Matlab is a high level language, e.g. provides many functions/algorithms allowing rapid development.
- But Matlab is limited to dense and (to some degree) sparse matrices, therefore not flexible enough, especially for large problems.

Why not Fortran?

- Fortran is one of the main programming language in many areas including numerics.
- Many excellent software libraries are written in Fortran, e.g. LAPACK.
- Fortran 77 quite dated in terms of language features.
- Recent updates of Fortran (90, 95, 2000) modernised the language, but still somewhat dated.
Why C++?

So, Why C++ (and not C) ?

- C is a subset of C++.
- C++ provides many features which make programming easier.
- C++ can be as fast as C (and sometimes faster).
- C++ (like C) can use all software libraries written in Fortran or C.
- Many new software libraries are written in C++.

Why not C++?

- C++ can be complicated as opposed to C.
- If you do not follow strict programming rules, you can make many errors (unlike Matlab, or Fortran).
Like every programming course, we start with something simple:

```cpp
#include <iostream>

using namespace std;

int main ( int argc, char ** argv )
{
    // print welcome message
    cout << "Hello World" << endl;
    return 0;
}
```

Even this small example contains:

- modules and namespaces,
- functions and blocks and
- variables and datatypes

**Remark**

*Comments in C++ begin with a “//” and span the rest of the line.*
Hello World

C++ is a compiler based language, i.e. one has to translate the source code of the program into a machine executable format using another program, called the compiler. Source code files, or just source files, typically have a filename suffix like “.cc”, “.C” or “.cpp”. There are many different C++ compilers available even for one operating system. On Linux, the GNU Compiler Collection provides the g++ compiler. Alternatively, Intel offers another compiler named icpc.

As an example, to compile the source file hello.cc for “Hello World” into an executable binary using the GCC compiler, you’ll have to enter

```
g++ -o hello hello.cc
```

and afterwards run the program via “./hello”.

Variables and Datatypes
Variables and Datatypes

In C++, all variables have to be of some specific datatype, which is, once defined, fixed and can not be changed, e.g. unlike in Matlab.

**Integer Datatypes**

characters :

- **char**: 'c', '/' , '\n', '\\', π (with Unicode)
- also numbers: from $-2^7 \ldots 2^7 - 1$, e.g. 0, −128, 127

signed integers :

- **short**: from $-2^{15} \ldots 2^{15} - 1$, e.g. 0, −32768, 1000
- **int**: from $-2^{31} \ldots 2^{31} - 1$, e.g. 0, −100, 2147483647
- **long**: from $-2^{31} \ldots 2^{31} - 1$, or $-2^{63} \ldots 2^{63} - 1$

unsigned integers :

- **unsigned short**: from 0...$2^{16} - 1$
- **unsigned int** or **unsigned**: from 0...$2^{32} - 1$
- **unsigned long**: from 0...$2^{32} - 1$, or 0...$2^{64} - 1$
**Integer Datatypes: Overflow and Underflow**

When doing arithmetic with integer types, the range of the types has to be considered. If the result is bigger than the maximum value, the result becomes negative, e.g. using `short`:

\[32760 + 100 = -32676\]

Here, an *overflow* occurred.

Similar behaviour can be observed if the result is less than the minimum (underflow):

\[-32760 - 100 = 32676\]
Floating Point Datatypes

Floating point numbers $x$ are represented as

$$x = s \cdot m \cdot 2^e$$

with the sign $s$, the mantissa $m$ and the exponent $e$.

In C++, like in many other languages, we have two floating point types

- **float**: single precision, 23 bits for mantissa, 8 bits for exponent, $x \in [-3 \cdot 10^{38} \ldots -10^{-38}, 0, 10^{-38} \ldots, 3 \cdot 10^{38}]$.
- **double**: double precision, 52 bits for mantissa, 11 bits for exponent, $x \in [-2 \cdot 10^{308} \ldots -10^{-308}, 0, 10^{-308} \ldots, 2 \cdot 10^{308}]$.

Floating point numbers are entered with a *dot*:

- **4.0** (double) or **4.0f** (float) instead of just **4** (int)

Exponent is defined using scientific notation via 'E' or 'e':

- $4.25 \cdot 10^{-4}$ is "**4.25E-4**" or "**4.25e-4**"
Floating Point Datatypes: Rounding

Since number of bits for representing numbers is limited, real numbers are rounded, e.g. \( \pi \):

- **float**: \( \tilde{\pi} = 3.141592741 \),
- **double**: \( \tilde{\pi} = 3.141592653589793116 \)

This might also lead to wrong results:

\[
\pi - 3.1415926 \approx 5.36 \cdot 10^{-8}
\]

but in single precision one obtains

\[
\pi - 3.1415926 = 1.41 \cdot 10^{-7}.
\]

This effect is also known as cancellation.
Floating Point Datatypes: Absorption

When adding two numbers with a large difference in the exponent, the result might be equal to the larger of the two addend, e.g. in single precision for $x \in \mathbb{R}$:

$$x + 1 \cdot 10^{-8} = x$$

For any floating point type, the smallest number $\varepsilon$, such that $1 + \varepsilon \neq 1$ is known as the machine precision:

- for float: $\varepsilon \approx 1.2 \cdot 10^{-7}$,
- for double: $\varepsilon \approx 2.2 \cdot 10^{-16}$.

Coding Principle No. 1

Always check if the range and the precision of the floating point type is enough for your application. If in doubt: use double precision.
Boolean Datatype

Integer and floating point types are also available in C. In C++ one also has a boolean type `bool`, which can be either `true` or `false`.

Missing Types

C++ does not have datatypes for `strings` or `complex numbers`. Those have to be implemented by special ways.
Variables

Variables can be declared at (almost) any position in the source file. The declaration follows the scheme:

\[
\langle \text{typename} \rangle \langle \text{variablename} \rangle ;
\]

or

\[
\langle \text{typename} \rangle \langle \text{variablename1} \rangle , \langle \text{variablename2} \rangle , \ldots ;
\]

Remark

Every statement in C++ is finished with a semicolon.

A name for a variable can contain any alphanumerical character plus ‘_' and must not begin with a number. Also, they can not be identical to a reserved name used by C++. Variable names are case sensitive.
Variables and Datatypes

Variables

Examples:

```c
int n;
int i, j, k;
float pi, Pi, PI;
double 1_over_pi; // ERROR
double _1_over_pi; // Ok
```

Coding Principle No. 2

*Give your variables a reasonable name.*

Variables: Initial Values

When declaring a variable, one can provide an initial value:

```c
int n = 10;
int i, j, k;
float pi = 3.1415926;
double _1_minus_pi = 1.0 - pi;
double max = 1.8e308;
```
Variables: Initial Values

Coding Principle No. 3

*Resource allocation is initialisation (RAII):*  
Whenever a resource, e.g. variable, is allocated/declared, it should be initialised with some reasonable value.

Otherwise, strange things might happen, e.g. what is wrong with:

```c++
int n = 10;
int i, j, k;
float pi;
double _1_minus_pi = 1.0 - pi;
double max = 1.8e308;
```

The value of `_1_minus_pi` is not defined, but only some compilers will give you a warning about that.
Variables and Datatypes

Variables: Usage

Variables can only be used after they have been declared:

```cpp
const double _1_minus_pi = 1.0 - pi;  // ERROR: "pi" is unknown
const float pi = 3.1415926;
const double _2_plus_pi = 2.0 + pi;  // Ok: "pi" is defined
```

Type Modifiers

Each type can be modified with one of the following modifiers:

- `const`: the value of the variable is fixed,
- `static`: the variable is declared only once in the whole program (we’ll come back to that later),

The modifiers can be combined:

```cpp
const int n = 10;
int i, j, k;
const float pi = 3.1415926;
const double _1_minus_pi = 1.0 - pi;
static const double max = 1.8e308;
```
**Type Modifiers**

**Coding Principle No. 4**

*Use `const` as much as possible.*

You avoid errors, e.g. by mistakenly changing the value and the compiler can optimise more, e.g. replace every occurrence by the actual value.
Pointers and References

A pointer is a special datatype derived from a base type, where the variable contains the memory position of another variable. The syntax is:

\[ \langle \text{base type} \rangle \ast \langle \text{pointer name} \rangle; \]

The memory position, i.e. the address, of a standard variable is obtained by the address operator “&”, e.g.

\& \langle \text{variable} \rangle

To obtain the value of the memory position, the pointer directs to, the (unary) dereference operator “*”, e.g.

\* \langle \text{variable} \rangle

is available (not to be mistaken with the binary multiplication operator!).
Points and References

Example for the usage of pointers:

```c
int n = 5;
int * p = & n;
int m1, m2;

m1 = n + 3;
m2 = *p + 3;    // m2 equal to m1
*p = 6;        // this changes the value of n to 6!
m2 = n + 4;    // evaluates to 10!
```

The value of a pointer, e.g. the address, can be assigned to another pointer:

```c
int * q = p;    // q now points to the same position
                // as p, hence, to n

n = 2;
m1 = *p + *q   // is equivalent to n+n
```
Pointers and References

A special pointer value, **NULL**, exists, for the case, that no standard variable is available to point to:

```c
int * p = NULL;
```

Dereferencing a **NULL** pointer is illegal and leads to a program abort.

**Coding Principle No. 5**

*Always initialise a pointer with the address of an existing variable or with **NULL**.*

**Remark**

*RAII is even more important when working with pointers than with standard variables, since undefined pointers almost always lead to hard to find errors.*
Pointers and References

A reference is a special form of a pointer, which can only be initialised with the address of an existing variable. The syntax is:

\[ \langle \text{base type} \rangle \& \langle \text{pointer name} \rangle; \]

One does not need to dereference references:

```cpp
int n = 5;
int & r = n;
int m;

m = r + 3;  // m == n + 3
r = m;      // r still points to n and n == m
m = 0;      // r and n are unchanged
```

And you can not change the address where a reference points to:

```cpp
int & s = m;

r = s;      // r still points to n and n == m (== 0)
```
Pointers and References

Pointers and references can also be combined with \texttt{const} in various forms:

\begin{verbatim}
int *          pn1;  // non-const pointer to non-const var.
const int *    pn2;  // non-const pointer to const var.
int * const    pn3;  // const pointer to non-const var.
const int * const pn4; // const pointer to const var.
\end{verbatim}

If the pointer is constant, the address it is directing to can not be changed. If the variable is constant, the value of it can not be modified:

\begin{verbatim}
int n = 0;
const int m = 1;

int * pn1 = & n;  // Ok
const int * pn2 = & n; // ERROR
int * const pn3 = & n; // Ok
\end{verbatim}
Arithmetic Operators
Arithmetic and Assignment Operators

**Arithmetic**

For integer and floating point types:

\[
\begin{align*}
x + y; \\
x - y; \\
x \ast y; \\
x / y;
\end{align*}
\]

For integer types, the *modulus* operator:

\[
x \% y;
\]

**Remark**

*No operator for power, like \(^\text{^}\) in Matlab.*
Assignment

Standard assignment (as with initial values)

\[
x = y;
\]

Assignment can be combined with arithmetic, so

\[
x = x + y; \quad x = x - y; \\
x = x * y; \quad x = x / y; \\
x = x \% y; \\
\]

// for integers

is the same as

\[
x += y; \quad x -= y; \\
x *= y; \quad x /= y; \\
x %= y; \\
\]

// for integers
Increment and Decrement

In C++ (like in C) exist special versions for variable increment/decrement:

```c
int n = 0;
++n; // same as n = n + 1 or n += 1
n++; // same as n = n - 1 or n -= 1
--n; // same as n = n - 1 or n -= 1
n--; // same as n = n + 1 or n += 1
```

Difference between preincrement and postincrement, e.g.

```c
int n = 5, m = 5 * n++;
```

results in \( n = 6 \) and \( m = 25 \), whereas

```c
int n = 5, m = 5 * ++n;
```

results in \( n = 6 \) and \( m = 30 \).
Examples

```c
int n1 = 3, n2 = 4;
int n3;

n3  = 2 * n1 - n2 + n1 / 2;
n2 *= 6;
n1 -= 8;

const double approx_pi = 355.0 / 113.0;
double f1       = approx_pi / 2.0;
double f2;

f2 = approx_pi * approx_pi + 10.0 * f1;
f1 /= 5.0;
```
Division by Zero and other undefined Operations

With floating point types:

\[ \frac{x}{0.0} = \text{INF} \]

for \( x \neq 0.0 \). \text{INF} is a special floating point number for infinity.

For \( x = 0.0 \):

\[ \frac{x}{0.0} = \text{NAN} \]

\text{NAN} (not-a-number) is another special floating point number for invalid or not defined results, e.g. square root of negative numbers. Both operations are (usually) performed without notification, i.e. the program continues execution with these numbers. NANs often occur with uninitialised variables, therefore RAII.

In integer arithmetic, \( x/0 \) leads to an exception, i.e. the program (usually) aborts.
Comparison

Standard comparison for integer and floating point types:

```
x >  y;    // bigger than
x <  y;    // less than
x >= y;    // bigger or equal
x <= y;    // less or equal
x == y;    // equal
x != y;    // unequal
```

Logic

Logical operators and, or and not for boolean values:

```
b1 && b2;    // and
b1 || b2;    // or
! b1;        // not
```
Minimal Evaluation

Logical expressions are only evaluated until the result is known. This is important if the expression contains function calls (see later), or a sub expression is only allowed if a previous sub expression is true.

```cpp
int x = 2;
int y = 4;
int z = 4;
bool b;

// z == 4 is not tested
b = ( x == 2 && y == 3 && z == 4 );

// only x == 2 is tested
b = ( x == 2 || y == 3 || z == 4 );

// correct, since x != 0 in "y/x"
// however, y/x > 1 will be computed
b = ( x != 0 && y/x > 1 );
```
Relational and Logical Operators

Floating Point Comparison

Coding Principle No. 6

For floating point types, avoid equality/inequality checks due to inexact arithmetic.

Better is interval test:

```c
double f1 = sqrt( 2.0 );
double f2 = f1 * f1;
bool b;

b = ( f2 == 2.0 ); // unsafe

const double eps = 1e-14;

b = ( f2 > 2.0 - eps && f2 < 2.0 + eps ); // safe
b = ( abs( f2 - 2.0 ) < eps ); // even better
```
Precedence and Associativity of Operators

Precedence

When evaluating complex expressions, what is evaluated first, and in which order? Example:

```
int n1 = 2 + 3 * 4 % 2 - 5;
int n2 = 4;
bool b = n1 >= 4 && n2 != 3 || n1 < n2;
```

Precedence of arithmetics follows algebraic/logical precedence, e.g. \* before +, \&\& before \|\|. Increment (\++\) and decrement (\--\) have higher, assignment (=, +=, ...) has lower priority. Parentheses have highest priority.

```
int n1 = (2 + ((3 * 4) % 2) - 5);
int n2 = 4;
bool b = (((n1 >= 4) && (n2 != 3)) || (n1 < n2));
```
**Associativity**

Arithmetic and logical operators are left associative, whereas assignment operators are right associative:

```c
int n1 = 1 + 2 + 3 + 4;
int n2 = 1 * 2 * 3 * 4;
int n3, n4, n5;

n3 = n4 = n5 = 0;
```

is the same as

```c
int n1 = (((1 + 2) + 3) + 4);
int n2 = (((1 * 2) * 3) * 4);
int n3, n4, n5;

(n3 = (n4 = (n5 = 0)));
```
## Summary

<table>
<thead>
<tr>
<th>Priority</th>
<th>Associativity</th>
<th>Operators</th>
</tr>
</thead>
<tbody>
<tr>
<td>highest</td>
<td>left</td>
<td>()</td>
</tr>
<tr>
<td>right</td>
<td></td>
<td>++, --, - (unary), !, &amp; (address), * (dereference)</td>
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<tr>
<td>left</td>
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<td>* (multiplication), /, %</td>
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<tr>
<td>left</td>
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<td>+, -</td>
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<td>&gt;, &lt;, &gt;=, &lt;=</td>
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<tr>
<td>lowest</td>
<td>right</td>
<td>=, +=, -=, *=, /=, %=</td>
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</tbody>
</table>
Precedence of Operators

Usage of Parentheses

Example:

```c
int n1 = 4;
int n2 = 2 + 5 * n1 / 3 - 5;
bool b = n2 >= 4 && n1 != 3 || n2 < n1;
```

vs.

```c
int n1 = 4;
int n2 = 2 + (5 * n1) / 3 - 5;
bool b = ( n2 >= 4 ) && (( n1 != 3 ) || ( n2 < n1 ));
```

Coding Principle No. 7

*When in doubt or to clarify the expression: use parentheses.*
Type Casting
Implicit Type Conversion

Up to now, we have only had expressions with either integer or floating point types. Often, these types are mixed:

```cpp
const double pi = 3.14159265358979323846;
double f = 1 / ( 2 * pi );
```

Here, implicit type conversion occurs: the int numbers 1 and 2 are automatically converted to the double numbers 1.0 and 2.0, respectively.

```cpp
const double pi = 3.14159265358979323846;
int n = 2 * pi;
```

is also allowed. Here, 2 is first converted to double and the result is finally converted back to int.
Type Casting

Explicit Type Conversion

Explicit conversion between data types is performed via

\[
\text{typename}(\text{value})
\]

Examples:

```
const float pi = float(3.14159265358979323846);
int n = 2 * int(pi);
bool b = bool(n);
```

Remark

A non-zero value is interpreted as \textbf{true}, a zero value as \textbf{false}.

The old C syntax (typename) value, e.g.

```
int n = 2 * (int) pi;
```

is also allowed, but \textbf{not} recommended.
Type Casting

Problems while Casting

Problem 1: Different ranges:

```c
int n1 = 5 - 6;
unsigned int n2 = n1;  // underflow
```

Problem 2: Different precision:

```c
const double pi = 3.14159265358979323846;
float f1 = 2.1;
float f2 = 4 * f1 / pi;
```

The last expression is computed in double precision. Using `float(pi)` instead, would result in pure single precision arithmetic, which is (usually) faster.

Coding Principle No. 8

Avoid implicit type conversion.
C++ defines four cast operators for various purposes:

- `const_cast<T>(v)` : remove `const` qualifier of a variable `v`,
- `static_cast<T>(v)` : classic, compile time type conversion with type checking
- `reinterpret_cast<T>(v)` : type conversion with correct handling of variable value and
- `dynamic_cast<T>(v)` : runtime type conversion with type checking

Since these operators are usually used in connection with *classes*, we will come back to them later.
Blocks and Scope
Blocks

Statements in a C++ program are part of a block, which is enclosed by '{' and '}':

```cpp
{ // ... 
}
```

Remark

The trivial block is defined by a single statement.

Blocks can be arbitrarily nested or otherwise put together:

```cpp
{ // block 1
    { // subblock 1.1
    }
    { // subblock 1.2
        { // sub subblock 1.2.1
        }
    }
}
```
Blocks and Scope

Variable Scope

Variables can be declared in each block individually, even with the same name:

```cpp
{ // block 1
    int n1 = 1;
    double f1 = 0.0;
}
{ // block 2
    int n1 = 2;  // n1 has value 2 in this block
}

but not twice in the same block:

```cpp
{
    int n1 = 1;
    // ...
    int n1 = 2;  // ERROR
}
```
Variable Scope

A variable is declared in the **local** block and all **enclosed** blocks:

```cpp
{  // block 1: n1 declared
    int n1 = 1;

    { // block 1.1: n1, n2 declared
        int n2 = 2;

        { // block 1.1.1: n1, n2 declared
        }
    }

    int n4 = 4;

    { // block 1.2: n1, n4, n3 declared
        int n3 = 3;
    }
}
```
**Variable Scope**

Variables with the same name can also be declared in nested blocks.

```cpp
{  // block 1
    int n1 = 1;   // n1 == 1

    { // block 1.1
        int n1 = 2;   // n1 == 2
    }
    // n1 == 1

    { // block 1.2
        int n1 = 3;   // n1 == 3
    }
    { // block 1.3
        n1 = 4;
    }   // n1 == 4 !!!

}  // block 1
```
Variable Scope

A reference to a variable will always be made to the first declaration found when going up the hierarchy of enclosing blocks.

```cpp
{ // block 1
    int m, n1 = 1;

    { // block 1.1
        int n2 = 2;

        { // block 1.1.1
            m = n1 + n2; // evaluates to m = 3
        }
    }

    { // block 1.2
        int n2 = 3;

        m = n1 + n2; // evaluates to m = 4
    }
}
```
Variable Scope

Remark

Using variables with same name in nested blocks is not recommended, since that often leads to erroneous programs.
Variable Lifetime

The scope of a variable also defines their lifetime, e.g. the time where resources are needed for the variable. For non-static variables, memory is allocated if a declaration is encountered and released, when the leaving the block holding the declaration:

```c
{
    int n = 0;  // memory for an integer is allocated

    {
        double f = 1.2;  // memory for a double is allocated
        ...
    }  // memory for "f" is released
    // memory for "n" is released
}
```

For static variables, the memory will never be released and only allocated once per program run:

```c
{
    static int m = 10;  // allocate memory once
    // memory for "m" is not released
}
```
Control Structures
Control Structures

Conditional Structure
A condition is defined by

\[
\text{if} \ ( \langle \text{condition} \rangle \ ) \ \langle \text{block} \rangle
\]

where \langle \text{block} \rangle is executed if \langle \text{condition} \rangle is \textbf{true} or

\[
\text{if} \ ( \langle \text{condition} \rangle \ ) \ \langle \text{if\_block} \rangle
\]
\[
\textbf{else} \ \langle \text{else\_block} \rangle
\]

where additionally \langle \text{else\_block} \rangle is executed if \langle \text{condition} \rangle is \textbf{false},
e.g.

```
int n = 1;

if ( n > 0 )
{
    n = n / n;
}

if ( n < 0 ) n += 5;  // NOTE: trivial block!
else            n -= 6;
```
C++ supports three different loops: *for loops*, *while loops* and *do-while loops*.

**For Loops**

```c++
for (⟨start stmt.⟩ ; ⟨loop condition⟩ ; ⟨loop stmt.⟩ )
⟨block⟩
```

The *start statement* is executed before the loop is entered. Before each iteration, the *loop condition* is evaluated. If it is *false*, the loop is finished. After each iteration, the *loop statement* is executed.

Example for factorial:

```c++
int n = 1;
for (int i = 1; i < 10; ++i )
{
    n = n * i;
}
```
### While Loops

**while (⟨loop condition⟩) ⟨block⟩**

The loop iterates until the loop condition is no longer `true`, i.e. evaluates to `false`. The condition is checked before each iteration. Example for factorial:

```cpp
int n = 1;
int i = 1;

while (i < 10)
{
    n *= i;
    ++i;
}
```
Control Structures

Do-While Loops

do

⟨block⟩

while (⟨loop condition⟩);

The loop condition is tested after each iteration. Hence, the block is at least executed once.

Example for factorial:

```cpp
int n = 1;
int i = 1;

do
{
    n *= i;
    ++i;
}
while (i < 10);
```
Breaking out of Loops

To finish the current loop immediately, e.g. without first testing the loop condition, the keyword \texttt{break} can be used:

```cpp
int n = 1;
for ( int i = 1; i < 20; ++i )
{
    // avoid overflow
    if ( n > 21474836 )
        break;
    n = n * i;
}
```
Breaking out of Loops

Only the current loop is finished, not all enclosing loops:

```cpp
for ( int j = 1; j < 20; ++j )
{
    int n = 1;
    for ( int i = 1; i < j; ++i )
    {
        if ( n > 21474836 ) // break here
            break;
        n = n * i;
    }
    cout << n << endl; // and continue here
}
```
**Finish current Iteration**

To *immediately* finish the current iteration of a loop use the keyword *continue*:

```cpp
int n2 = 0;
for ( int i = 0; i < 1000; i++ )
{
    // skip odd numbers
    if ( i % 2 == 1 )
        continue;

    n2 += i;
}
```

After *continue*, the loop condition of a loop is tested. In for-loops, the loop statement is first evaluated.

**Remark**

*Again, continue effects only the current loop.*
Selective Statement

To directly switch between several cases, the switch structure can be used:

```cpp
switch (⟨value⟩) {
  case ⟨CASE 1⟩: ⟨statements⟩; break;
  case ⟨CASE 2⟩: ⟨statements⟩; break;
  :  
  case ⟨CASE n⟩: ⟨statements⟩; break;
  default: ⟨statements⟩
}
```

The type of ⟨value⟩ must be some integral typ, i.e. it can be mapped to an integer type. Hence, floating point or more advanced types (later) are not possible.
Selective Statement

Example for a `switch` statement:

```c
unsigned int i = 3;
unsigned int n;

switch (i) {
    case 0 : n = 1; break;
    case 1 : n = 1; break;
    case 2 : n = 2; break;
    case 3 : n = 6; break;
    case 4 : n = 24; break;
    default : n = 0; break;
}
```

Coding Principle No. 9

*Always implement the default case to avoid unhandled cases.*
Selective Statement

If \texttt{break} is missing after the statements for a specific case, the statements of the next case are also executed:

\begin{verbatim}
unsigned int i = 3;
unsigned int n;

switch (i)
{
    case 0 :
    case 1 : n = 1;  break;  // executed for i == 0 and i == 1
    case 2 : n = 2;  break;
    case 3 : n = 6;  break;
    case 4 : n = 24; break;
    default : n = 0;  break;
}
\end{verbatim}
Selective Statement

A switch statement can be implemented via if and else:

```c
unsigned int i = 3;
unsigned int n;

if (i == 0) { n = 1; }
else if (i == 1) { n = 1; }
else if (i == 2) { n = 2; }
else if (i == 3) { n = 6; }
else if (i == 4) { n = 24; }
else { n = 0; } // default statement
```

Remark

Using switch is faster than if-else, among other things since less comparisons are performed!
Functions
Function Definition

The definition of a function in C++ follows

\[
\langle \text{return type} \rangle \\
\langle \text{function name} \rangle \ ( \langle \text{argument list} \rangle ) \\
\langle \text{block} \rangle
\]

When a function does not return a result, e.g. a procedure, then the return type is \text{void}.

To return a value from a function, C++ provides the keyword \text{return}.

```cpp
double square ( const double x )
{
    \text{return} \ x*\ x;
}
```
**Function Call**

A function is called by

\[
\langle \text{function name} \rangle \ ( \langle \text{argument1} \rangle, \langle \text{argument2} \rangle, \ldots );
\]

Example:

```cpp
double y = square( 4.3 );
```

One can not define a function in the body of another function:

```cpp
double cube ( const double x )
{
    // ERROR
    double square ( const double y ) { return y*y; }
    return square( x ) * x;
}
```
Functions

Function Examples

Previous computation of factorial in functional form:

```c
int factorial ( const int n )
{
    int f = 1;

    for ( int i = 1; i <= n; i++ )
        f *= i;

    return f;
}
```

Coding Principle No. 10

Make all function arguments `const`, except when changing value (see later).
Function Examples (Cont.)

Power function with positive integer exponents:

double power ( const double x, const unsigned int n )
{
    switch ( n )
    {
        case 0 : return 1;
        case 1 : return x;
        case 2 : return square( x );
        default:
        {
            double f = x;
            for ( int i = 0; i < n; i++ ) f *= x;
            return f;
        }
    }

Coding Principle No. 11

Make sure, that a function has a call to return in every execution path.
Main Function

The main function is the first function called by the operating system in your program. Every program must have exactly one main function.

In principle, only code in main and functions called directly or indirectly from main will be executed.

The main function may be implemented without arguments and has a return type of int:

```cpp
int main ()
{
    // actual program code
    return 0;
}
```

The value returned from main is supplied to the operating system. As a standard, a value of 0 signals no error during program execution.
Call by Value

In previous examples, only the value of a variable (or constant) is used as the argument of a function, e.g. changing the value of the argument does not change the value of the original variable:

```cpp
int f ( int m ) // non const argument!
{
    m = 4; // explicitly changing the value of argument m
    return m;
}

int m = 5;
int n = f( m ); // m is unchanged by f
```

This is known as call-by-value.

Remark

*It is nevertheless advised to use *const arguments.*
Call by Reference

If the original variable should be changed in a function, a pointer or reference to this variable has to be supplied:

```cpp
int f ( int & m )  // reference argument
{
    m = 4;  // changing m, changes the variable pointed to
    return m;
}

int m = 5;
int n = f( m );  // m is changed by f to 4
```

This is known as call-by-reference.
Call by Reference

The same function with pointers:

```c
int f ( int * m )  // reference argument
{
    *m = 4;  // changing m, changes the variable pointed to
    return *m;
}

int m = 5;
int n = f( & m );  // m is changed by f to 4
```
Call by Reference

When using references to *constant* variables, the value can not be changed:

```cpp
int f ( const int & m )
{
    m = 4;         // ERROR: m is constant
    return m;
}
```

Therefore, this is (almost) equivalent to call-by-value and needed for advanced datatypes (see later).

For basic datatypes, using call-by-reference, even with `const`, is usually not advisable, except when changing the original variable.
Call by Reference

Example for multiple return values

```c++
void min_max ( const int n1, const int n2, const int n3,
               int & min, int & max )
{
    if ( n1 < n2 )
        if ( n1 < n3 )
        {
            min = n1;
            if ( n2 < n3 ) max = n3;
            else max = n2;
        }
    else
    {
        min = n3;
        max = n2;
    }
    else
        ...
}
```
Recursion

Calling the same function from inside the function body, e.g. a recursive function call, is allowed in C++:

```cpp
unsigned int factorial ( const unsigned int n )
{
    if ( n <= 1 )
        return 1;
    else
        return n * factorial( n-1 );
}
```

Remark

The recursion depth, i.e. the number of recursive calls, is limited by the size of the stack, a special part of the memory. In practise however, this should be of no concern.
Recursion

It is also possible to perform recursive calls multiple times in a function:

```cpp
unsigned int fibonacci ( const unsigned int n )
{
    unsigned int retval;

    if ( n <= 1 ) retval = n;
    else         retval = fibonacci( n-1 ) +
                              fibonacci( n-2 );

    return retval;
}
```

Remark

*Remember, that variables belong to a specific block and each function call has its own block. Therefore, variables, e.g. *retval*, are specific to a specific function call.*
Function Naming

A function in C++ is identified by it’s name and the number and type of it’s arguments. Hence, the same name can be used for different argument types:

```cpp
int square ( const int x ) { return x*x; }
float square ( const float x ) { return x*x; }
double square ( const double x ) { return x*x; }
```

Coding Principle No. 12

*Functions implementing the same algorithm on different types should be named equal.*

This can significantly reduce the number of different functions you’ll have to remember and simplifies programming.
Function Naming

If only the return type is different between functions, they are identified as equal:

```c
float f ( int x ) { ... }
double f ( int x ) { ... }  // ERROR: "f" already defined
```
Default Arguments

Arguments for a function can have default arguments, which then can be omitted at calling the function:

```cpp
void f ( int n, int m = 10 )
{
    // ...
}
{
    f( 5 ); // equivalent to f( 5, 10 )
    f( 5, 8 );
}
```

Only limitation: after the first default value, all arguments must have default values:

```cpp
void g1 ( int n, int m = 10, int k ); // ERROR
void g2 ( int n, int m = 10, int k = 20 ); // Ok
```
Default Arguments and Function Names

Two functions with the same name must differ by their arguments without default values:

```cpp
void f ( int n1, int n2, int n3 = 1 ) { ... }
void f ( int n1, int n2 ) { ... }
...
{
    f ( 1, 2, 3 ); // Ok: call to f(int, int, int)
    f ( 1, 2 ); // Error: call of "f(int, int)" is ambiguous
}
```
**Function Name Scope**

A function can only be called, if it was previously implemented:

```c
void f ( int x )
{
    g( x );        // ERROR: function "g" unknown
}

void g ( int y )
{
    f( y );        // Ok: function "f" already defined
}
```

or *declared*, i.e. definition of function without function body:

```c
void g ( int y ); // forward declaration

void f ( int x )
{
    g();           // Ok: "g" is declared
}
```

This is known as *forward declaration*. 
Function Name Scope

Of course, every function with a forward declaration has to be implemented eventually:

```c++
void g ( int y );  // forward declaration

void f ( int x )
{
    g();
}
...

void g ( int y )  // implementation
{
    f( y );
}
```
Inline Functions

Calling a function involves some overhead. For small functions, this overhead might exceed the actual computation:

```cpp
double square ( const double x ) { return x*x; }
{
    double f = 0;
    for ( int i = 0; i < 100; i++ )
        f += square( double(x) );
}
```

Here, simply calling `square` takes a significant part of the runtime. Some compilers automatically replace the function call by the function body:

```cpp`
... for ( int i = 0; i < 100; i++ )
    f += double(x) * double(x);
...
```
Inline Functions

Replacing the function call by the function body is called **inlining**. To help the compiler with such decisions, functions can be marked to be inlined by the keyword **inline**:

```cpp
inline double square ( const double x )
{
    return x*x;
}
```

Especially for small functions, this often dramatically increases program performance.

**Remark**

*If the function body is too large, inlining can blow up the program since too much code is compiled, e.g. every occurrence of the function, and therefore decreases performance!*
Function Pointers

A function, like a variable, is stored somewhere in the memory and therefore, also has an address. Hence, a pointer can be acquired for it. For a function

\[
\text{\textlangle return type\textrangle \textlangle function name\textrangle (\textlangle argument list\textrangle )};
\]

a pointer is defined by

\[
\text{\textlangle return type\textrangle ( \ast \textlangle variable name\textrangle ) (\textlangle argument list\textrangle )};
\]

Example:

```cpp
int f ( \textbf{const} int n, \textbf{int} & r );
{
    \textbf{int} ( \ast \textbf{pf} ) ( \textbf{const} \textbf{int} n, \textbf{int} & r ); \// function ptr named "pf"
    \textbf{pf} = \textbf{f};
}
```
Function Pointers

A variable holding the address of a function can be used as a function by itself:

```c
int n = 0;

pf = f;  // pf holds address to f
pf( 2, n );  // call to f
```

Since function pointers are normal variables, they can be supplied as function arguments:

```c
double f1 ( const double x ) { return x*x; }

double f2 ( double ( * func ) ( const double x ),
           const double x ) { return func( x ); }

int main ()
{
    f2( f1, 2.0 );  // returns f1( 2.0 )
}
```
Function Pointers

Example: apply Simpson rule to various functions

double simpson_quad ( const double a, const double b, double ( * func ) ( const double ) )
{
    return (b-a) / 6.0 * ( func(a) +
        4 * func( (a+b) / 2.0 ) +
        func(b) );
}

double f1 ( const double x ) { return x*x; }
double f2 ( const double x ) { return x*x*x; }

int main ()
{
    cout << simpson_quad( -1, 2, f1 ) << endl;
    cout << simpson_quad( -1, 2, f2 ) << endl;
}
Functions and Minimal Evaluation

As discussed, C++ uses minimal evaluation when looking at logical expressions, e.g. only evaluates until results is known. If functions are used in the expressions, it can imply, that they are not called at all:

```cpp
double f ( const double x ) { ... }
...
// f is not called if x >= 0.0
if ( ( x < 0.0 ) && ( f( x ) > 0.0 ) )
{
    ...  
}
```

For the programmer this means:

**Coding Principle No. 13**

*Never rely on a function call in a logical expression.*
Functions and static Variables

In contrast to standard variables in a function, which are specific to a specific function call, for `static` variables in all function calls the same instance, e.g., memory position, is referenced:

```cpp
double f ( const double x, long & cnt )
{
    static long counter = 0; // allocated and initialised // once per program
    cnt = ++counter;

    return 2.0*x*x - x;
}

int main ()
{
    long cnt = 0;

    for ( double x = -10; x <= 10.0; x += 0.1 )
        f( x, cnt );

    cout << cnt << endl; // print number of func. calls
}
```
Arrays and Dynamic Memory
Array Definition

So far, we had only datatypes with one entry per variable. Arrays with a fixed number of entries are defined as:

\[
\langle \text{datatype} \rangle \langle \text{variblename} \rangle [\langle \text{number of entries} \rangle];
\]

where the number of entries is a constant, e.g.

\begin{verbatim}
int n[ 5 ];
double f[ 10 ];
const int len = 32;
char str[ len ];
\end{verbatim}

Arrays can also be preinitialised. In that case, the array size can be omitted:

\begin{verbatim}
int n1[5] = { 0, 1, 2, 3, 4, 5 };
int n2[] = { 3, 2, 1, 0 }; // automatically size of 4
\end{verbatim}
**Array Access**

A single entry in an array is accessed by the index operator `[·]`:

```c
double f[5];
int i;

f[0] = -1.0;
f[1] = 3.0;
f[4] = f[1] * 42.0;

i = 3;
f[i] = f[0] + 8.0;
```

In C++, indices are counted from zero. The valid index range is therefore:

\[ [0, \ldots, \text{array size} - 1] \]

```c
for ( int i = 0; i < 5; i++ )
    f[i] = 2*i;
```
Array Access

There are normally no array boundary checks in C++, i.e. you can specify arbitrary, even negative indices, resulting in an undefined program behaviour.

Typical error:

```c
double f[5];
for ( int i = 0; i < 5; i++ ) // Ok
    f[i] = 2*i;
for ( int i = 0; i <= 5; i++ ) // Bug
    f[i] = 2*i;
```

Coding Principle No. 14

*Always make sure, that you access arrays within the valid index range.*
Array Operations

Unfortunately, there are no operators for arrays, e.g. no assignment, elementwise addition or multiplication like in other languages. All of these have to be programmed by yourself:

```cpp
void copy ( const double x[3], double y[3] )
{
    for ( int i = 0; i < 3; i++ )
        y[i] = x[i];
}

void add ( const double x[3], double y[3] )
{
    for ( int i = 0; i < 3; i++ )
        y[i] += x[i];
}
```

Remark

*Arrays can be used as function arguments like all basic datatypes. But not as function return types!*
Arrays and Dynamic Memory

Multidimensional Arrays

So far, all arrays have been onedimensional. Multidimensional arrays are defined analogously by appending the corresponding size per dimension:

```c
int M[3][3];
double T3[10][10][10];
long T4[100][20][50];
```

The access to array elements in multidimensional arrays follows the same pattern:

```c
M[0][0] = 1.0; M[0][1] = 0.0; M[0][2] = -2.0;
M[1][0] = 0.0; M[1][1] = 4.0; M[1][2] = 1.0;
M[2][0] = -2.0; M[2][1] = 1.0; M[2][2] = -1.5;

for ( int i = 0; i < 100; i++ )
    for ( int j = 0; j < 20; j++ )
        for ( int k = 0; k < 50; k++ )
            T3[i][j][k] = double(i+j+k);
```
Multidimensional Arrays

Example: Matrix-Vector multiplication

```c
void mulvec ( const double M[3][3],
              const double x[3],
              double       y[3] )
{
    for ( int i = 0; i < 3; i++ )
    {
        y[i] = 0.0;

        for ( int j = 0; j < 3; j++ )
            y[i] += M[i][j] * x[j];
    }
}
```
Arrays and Pointers

C++ does **not** support variable sized arrays as an intrinsic datatype. Hence, arrays with an unknown size at compile time are not possible with previous array types in C++. But, in C++, there is **no** distinction between a pointer and an array. A pointer not only directs to some memory address, it is also the base point, e.g. index 0, of an array.

```cpp
int * p = n;

cout << p[0] << endl; // yields n[0]
cout << p[1] << endl; // yields n[1]
```

The index operator `[i]` of a pointer `p` gives access to the `i`'th element of the array starting at address `p`. 
Arrays and Dynamic Memory

Dynamic Memory

Since pointers and arrays are equivalent, one needs to initialise a pointer with the address of a memory block large enough to hold the wanted array. This is accomplished by dynamic memory management:

*Memory of arbitrary size can be allocated and deallocated at runtime.*

In C++ this is done with the operators `new` and `new[]` to allocate memory and `delete` and `delete[]` to deallocate memory.

For a single element:

```cpp
⟨datatype⟩ * p = new ⟨datatype⟩;
delete p;
```

For more than one element:

```cpp
⟨datatype⟩ * p = new ⟨datatype⟩[⟨size⟩];
delete[] p;
```
Dynamic Memory

Examples:

```cpp
char * s = new char[ 100 ];
int n = 1024;
double * v = new double[ n ];
float * f = new float;

for ( int i = 0; i < n; i++ )
    v[i] = double( square( i ) );

*f = 1.41421356237; // dereference f
...

delete[] v; // new[] => delete[]
delete[] s;
delete f; // new => delete
```

Remark

The size parameter to `new` does not need to be a constant.
Arrays and Dynamic Memory

Problems with Pointers

The corresponding array to a pointer has no information about the array size. Remember, that C++ performs no boundary checks. That opens the door to many errors (see Coding Principle No. 14).

```cpp
double * v = new double[1000];
...

v[2000] = 1.0;
```

With the last instruction, you overwrite a memory position corresponding to completely other data. The program will only terminate, if the memory does not belong to the program (segmentation fault).
Arrays and Dynamic Memory

Problems with Pointers

The programmer does not know if the memory was allocated or deallocated, except if the pointer contains NULL (see Coding Principle No. 5).

```cpp
double * v = new double[ 1000 ];
...
delete[] v;
...
v[100] = 2.0; // Bug: memory for v is deallocated
```

Again, the last instruction will be executed and will only result in an immediate error, if the memory is no longer part of the program.

**Coding Principle No. 15**

*After calling delete, reset the pointer value to NULL.*
**Problems with Pointers**

Memory addressed by forgotten pointers is lost for the program. C++ does not automatically delete memory with no references to it (garbage collection).

```cpp
void f ()
{
    double * v = new double[ 1000 ];
    ... // no delete[] v
}
// v is no longer accessible, memory is lost
```

This bug is not directly a problem, since no other data is overwritten. But if a lot of memory is not deleted after use, the program will have no available memory left.

**Coding Principle No. 16**

*Always make sure, that allocated memory is deallocated after using.*
Arrays and Dynamic Memory

Problems with Pointers

Remark
The aftermath of a pointer related bug, e.g. array boundary violation or accessing deleted memory, may show up much later than the actual position of the error.

Summary: pointers are dangerous and require careful programming. But we have no choice 😞.
Arrays and Dynamic Memory

Problems with Pointers

Remark

The aftermath of a pointer related bug, e.g. array boundary violation or accessing deleted memory, may show up much later than the actual position of the error.

Summary: pointers are dangerous and require careful programming. But we have no choice 😞. Well, almost 😊 (see later).
Multidimensional Arrays with Pointers

The analog of multidimensional arrays are **pointers of pointers**, i.e. pointers which direct to a memory address containing a pointer to another memory address:

```c++
int * p1 = & n[2];
int ** p2 = & p1;
```

This can be generalised to multiple dimensions:

```c++
int n1[4], n2[4], n3[4], n4[4];
int * p1 = n1;
int * p2 = n2;
int * p3 = n3;
int * p4 = n4;
```

```c++
cout << p[1][3] << endl; // yields 8
```

```
Memory (array)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>11</td>
</tr>
</tbody>
</table>
```

```
p2 ----------> p1
```

```
1 2 3 4
5 6 7 8
9 8 7 6
5 4 3 2
```
Multidimensional Arrays with Pointers

The same example with dynamic memory:

```cpp
int * p1 = new int[4];
int * p2 = new int[4];
int * p3 = new int[4];
int * p4 = new int[4];

int ** p = new int*[4];

p[0] = p1;
p[1] = p2;
p[2] = p3;
p[3] = p4;

p[0][0] = 1;
p[0][1] = 2;
...
p[2][2] = 7;
p[2][3] = 6;
p[3][0] = 5;
...
```
Multidimensional Arrays with Mappings

Working with pointers to pointers is only one way to implement multidimensional arrays. You can also map the multiple dimensions to just one:

```c
int * p = new int[4*4];
```

```c
p[ 2 * 4 + 1 ] = 8; // p[2][1]
p[ 0 * 4 + 2 ] = 3; // p[0][2]
```
Multidimensional Arrays with Mappings

In theory, one could use any mapping. In practise, two different mappings are standard:

- **row-wise**: standard in C, C++
- **column-wise**: standard in Fortran, Matlab

For a two-dimensional array, e.g. a matrix, with dimensions \( n \times m \), the mappings are for index \((i,j)\):

- **row-wise**: \( i \cdot m + j \),
- **column-wise**: \( j \cdot n + i \).

It is up to you, which mapping you prefer.
Arrays and Dynamic Memory

**Example: $n \times m$ Matrix (row-wise)**

```c++
void set_entry ( const double * M, const int i, const int j, const int m, const double f ) {
    M[ i*m + j ] = f;
}

int main ()
{
    int n = 10;
    int m = 20;
    double * M = new double[ n * m ];

    set_entry( M, 3, 1, m, 3.1415 );
    set_entry( M, 2, 7, m, 2.7182 );
}
```
Comparison: Pointers vs. Mapping

Two approaches have been introduced for multidimensional arrays: pointers of pointers and user defined mapping. Which is to be preferred?

A user defined mapping is faster since only simple arithmetic is performed for a memory access. The pointer based approach needs to follow each pointer individually, resulting in many memory accesses.

Pointers are more flexible, e.g. for triangular matrices, whereas a special mapping has to be defined for each shape.

My recommendation: use mappings, especially if you want fast computations.
Arrays and Dynamic Memory

Application: BLAS

Properties and requirements:

- vectors are onedimensional arrays, matrices implemented via mapping (row-wise),
- should provide functions for all standard operations, e.g. creation, access, linear algebra

Initialisation:

```cpp
inline double * vector_init ( const unsigned i )
{
    return new double[i];
}

inline double * matrix_init ( const unsigned n, const unsigned m )
{
    return new double[ n * m ];
}
```
Application: BLAS

Vector Arithmetic:

```c
void fill ( const unsigned n, const double f, double * y );
void scale ( const unsigned n, const double f, double * y );
void add ( const unsigned n, const double f, const double * x, double * y );
{
    for ( unsigned i = 0; i < n; i++ ) y[i] += f * x[i];
}

double dot ( const unsigned n, const double * x, const double * y )
{
    double d = 0.0;
    for ( unsigned i = 0; i < n; i++ ) d += x[i] * y[i];
    return d;
}
inline double norm2 ( const unsigned n, const double * x )
{
    return sqrt( dot( n, x, x ) );
}
```
Arrays and Dynamic Memory

**Application: BLAS**

Matrix Arithmetic:

```c
void
fill ( const unsigned n, const unsigned m,
       const double f, double * M )
{ fill( n*m, f, M ); }   // use vector based fill

void
scale ( const unsigned n, const unsigned m,
       const double f, double * M );

void
add ( const unsigned n, const unsigned m,
      const double f, const double * A, double * M );

inline double
normF ( const unsigned n, const unsigned m,
        double * M )
{ return norm2( n*m, M ); }   // use vector based norm2
```
Arrays and Dynamic Memory

Application: BLAS

Matrix-Vector Multiplication $y := y + \alpha A \cdot x$:

```c
void mul_vec ( const unsigned n, const unsigned m,
               const double alpha, const double * M,
               const double * x,
               double * y )
{
  for ( unsigned i = 0; i < n; i++ )
  {
    double f = 0.0;

    for ( unsigned j = 0; j < m; j++ )
      f += get_entry( n, m, i, j, M ) * x[j];
    // alternative: f = dot( m, & M[ i * m ], x );

    y[i] += alpha * f;
  }
}
```

Remark

*Compute dot product in local variable to minimize memory accesses.*
Application: BLAS

Matrix-Matrix Multiplication $C := C + \alpha A \cdot B$:

```c
void mul_mat ( const unsigned n, const unsigned m, const unsigned k, const double alpha, const double * A, const double * B, double * C )
{
    for ( unsigned i = 0; i < n; i++ )
        for ( unsigned j = 0; j < m; j++ )
        {
            double f = 0.0;
            for ( unsigned l = 0; l < k; l++ )
                f += get_entry( n, k, i, l, A ) * get_entry( k, m, l, j, B );
            add_entry( n, m, i, j, f, M );
        }
}
```
Application: BLAS

```c
double * M = matrix_init( 10, 10 );
double * x = vector_init( 10 );
double * y = vector_init( 10 );

fill( 10, 1.0, x );
fill( 10, 0.0, y );

...  // fill matrix M

cout << normF( 10, 10, M ) << endl;

mul_vec( 10, 10, -1.0, M, x, y );
```
Arrays and Dynamic Memory

Strings

One important datatype was not mentioned up to now: strings. Strings are implemented in C++ as arrays of characters, e.g.

\[
\text{char str[]} \quad \text{or} \quad \text{char * str}
\]

As arrays have no size information, there is no information about the length of a string stored. To signal the end of a string, by convention the character '0' is used (as an integer, not the digit), entered as '\0':

```c
char str[] = { 'S', 't', 'r', 'i', 'n', 'g', '\0' };
```

Constant strings can also be defined and used directly with ‘“...”’:

```c
char str[] = "String"; // array initialisation
```

Here, '\0' is automatically appended.
Strings

If a string is too long for one input line, it can be wrapped by a backslash '\':

```c
const char * str = "This is a very long \n string";
```

C++ does not provide operators for string handling, e.g. concatenation or searching for substrings. All of that has to be implemented via functions:

```c
char * concat ( const char * str1, const char * str2 )
{
    const unsigned len1 = strlen( str1 );
    const unsigned len2 = strlen( str2 );
    char * res = new char[ len1 + len2 + 1 ];
    int pos = 0, pos2 = 0;

    while ( str1[pos] != '\0' ) { res[pos] = str1[pos]; pos++;
    while ( str2[pos2] != '\0' ) { res[pos++] = str2[pos2++]; }
    res[pos] = '\0';

    return res;
}
```
Strings

Usage:

```cpp
const char * str1 = "Hallo ";
char * str2 = concat( str1, "World" );

cout << str2 << endl;

delete[] str2; // don’t forget to deallocate!
```

It can not be emphasised too much:

**Coding Principle No. 17**

Always ensure, that strings are terminated by `\0`.

Otherwise, operations on strings will fail due to array boundary violations.
Strings

'\0' is one example of a special character in C++ strings. Others are

<table>
<thead>
<tr>
<th>Character</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>'\n'</td>
<td>a new line</td>
</tr>
<tr>
<td>'\t'</td>
<td>a tab</td>
</tr>
<tr>
<td>'\r'</td>
<td>a carriage return</td>
</tr>
<tr>
<td>'\b'</td>
<td>a backspace</td>
</tr>
<tr>
<td>'''</td>
<td>single quote ''</td>
</tr>
<tr>
<td>'&quot;'</td>
<td>double quote &quot;&quot;</td>
</tr>
<tr>
<td>'\'</td>
<td>backslash ''</td>
</tr>
</tbody>
</table>

Examples:

```cpp
cout << "First \t Second" << endl;
cout << "line1 \n line2" << endl;
cout << "special \"word\"" << endl;
cout << "set1 \ \ set2" << endl;
```
Advanced Datatypes
**Type Definition**

Often you do not always want to care about the actual datatype used in your program, e.g. if it is `float` or `double` or if strings are `char *`, but instead give the types more reasonable names, e.g. `real` or `string`. In C++ you can do this via `typedef`:

```cpp
typedef ⟨data type⟩ ⟨name⟩;
```

Afterwards, ⟨name⟩ can be used like any other datatype:

```cpp
typedef double real_t;
typedef char * string_t;
typedef real_t ** matrix_t; // pointers of pointers

const string_t str = "String";
matrix_t A = new real_t*[ 10 ];
real_t f = real_t( 3.1415926 );
```
Type Definition

Remark

A `real_t` datatype allows you to easily change between `float` and `double` in your program.

To simplify the distinction between variables and datatypes, the following is strongly advised:

**Coding Principle No. 18**

*Follow a strict convention in naming new types, e.g. with special prefix or suffix.*
Predefined Types

The C++ library and the operating system usually define some abbreviations for often used types, e.g.

- `uint`: unsigned integer, sometimes special versions `uint8`, `uint16` and `uint32` for 8, 16 and 32 bit respectively,
- `int8`, `int16` and `int32` are defined for signed integers,
- `size_t`: unsigned integer type for holding size informations best suited for the local hardware
- `ssize_t`: analog to `size_t` but signed integer (not always available)
Records

Working with vectors and matrices always involved several variables, e.g. the size and the arrays. That results in many arguments to functions and hence, to possible errors. It would be much better to store all associated data together. That is done with records:

```c++
struct ⟨record name⟩ {
    ⟨datatype 1⟩ ⟨name 1⟩;
    ...
    ⟨datatype n⟩ ⟨name n⟩;

};
```

By defining a `struct`, also a new type named ⟨record name⟩ is defined.
**Records**

Example:

```c
struct vector_t {
    size_t size;
    real_t * coeffs;
};

struct matrix_t {
    size_t nrows, ncolumns;
    real_t * coeffs;
};

void mul_vec ( const real_t alpha,
               const matrix_t & A,
               const vector_t & x,
               vector_t & y );

struct triangle_t {
    int vtx_idx[3];  // indices to a vertex array
    real_t normal[3];
    real_t area;
};
```
Access Records

The individual variables in a record are accessed via "\.", e.g.:

```cpp
vector_t x;

x.size = 10;
x.coeffs = new real_t[ x.size ];
```

If a pointer to a record is given, the access can be simplified. Instead of "\*" (dereference) and "\.", the operator "\->" is provided:

```cpp
vector_t * x = new vector_t;

x->size = 10;
x->data = new real_t[ x->size ];

cout << (*x).size << endl; // alternative
```
Access Records

In case of a reference, e.g. `vector_t &`, the standard access has to be used, e.g. via ".":

```c++
vector_t x;

x.size = 10;
x.coefs = new real_t[ x.size ];

vector_t & y = x;

cout << y.size << endl;
cout << y.coefs[5] << endl;
```
Records and Functions

Records can be supplied as normal function arguments, either as call-by-value or call-by-reference:

```c
double dot ( const vector_t x, const vector_t y );
void fill ( const real_t f, vector_t & y );
void add ( const real_t f, const vector_t & x, vector_t & y );
```

When using call-by-value, a copy of the complete record is actually created. For large records, this can be a significant overhead:

```c
struct quadrule_t {
    real_t points[ 100 ];
    real_t weights[ 100 ];
};

double quadrature ( const quadrule_t rule,
    double ( * func ) ( const double x ) );
```
Records and Functions

In such cases, call-by-reference with a `const` argument is necessary to avoid this overhead:

```cpp
double quadrature ( const quadrule_t & rule,
        double ( * func ) ( const double x ) );
```

Here, only a single pointer is supplied to the function instead of 200 `real_t` values.
Application: BLAS (Version 2)
Modified BLAS function set using the previous record types for vectors and matrices:

```cpp
inline vector_t *
vector_init ( const unsigned i )
{
    vector_t * v = new vector_t;
    v->size = i;
    v->coeffs = new real_t[ i ];

    for ( unsigned i = 0; i < n; i++ ) // RAII
        v->coeffs[i] = 0.0;

    return v;
}

inline matrix_t *
matrix_init ( const unsigned n, const unsigned m )
{
    ... }
```
Application: BLAS (Version 2)

// vector functions
void fill ( const double f, vector_t & x );
void scale ( const double f, vector_t & x );

void add ( const double f, const vector_t & x, vector_t & y )
{
    for ( unsigned i = 0; i < n; i++ )
    {
        y.coeffs[i] += f * x.coeffs[i];
    }
}

double dot ( const vector_t & x, const vector_t & y );
inline double norm2 ( const vector_t & x )
{ return sqrt( dot( x, x ) ); }

// matrix functions
void fill ( const double f, matrix_t & M );
void scale ( const double f, matrix_t & M );
void add ( const double f, const matrix_t & A, matrix_t & M );

inline double
normF ( double & M )
{ ... } // can not use vector based norm2!
void mul_vec ( const double alpha,
             const matrix_t & M,
             const vector_t & x, 
             vector_t & y )
{
    for ( unsigned i = 0; i < M.nrows; i++ )
    {
        double f = 0.0;

        for ( unsigned j = 0; j < M.ncolumns; j++ )
            f += get_entry( M, i, j ) * x.coeffs[j];

        y.coeffs[i] += alpha * f;
    }
}

void mul_mat ( const double alpha,
              const matrix_t & A,
              const matrix_t & B,
              matrix_t & C );
Application: BLAS (Version 2)

```c
matrix_t * M = matrix_init( 10, 10 );
vector_t * x = vector_init( 10 );
vector_t * y = vector_init( 10 );

fill( 1.0, x );
fill( 0.0, y );

... // fill matrix M

cout << normF( M ) << endl;

mul_vec( -1.0, M, x, y );
```
Recursive Records

Records can have variables of its own type in the form of a pointer. That way, recursive structures can be defined, e.g. a binary tree:

```c
struct node_t {
    int val;
    node_t * son1, * son2;
};

node_t root;
node_t son1, son2;
node_t son11, son12, son21, son22;

root.son1 = & son1; root.son2 = & son2;
son1.son1 = & son11; son1.son2 = & son12;
son2.son1 = & son21; son2.son2 = & son22;
```

The above code yields:
Recursive Records

Insert new value in binary tree:

```c++
void insert ( const node_t & root, const int val )
{
  if ( val < root.val )
  {
    if ( root.son1 != NULL )
      insert( * root.son1, val );
    else
    {
      root.son1 = new node_t;
      root.son1->val = val;
      root.son1->son1 = NULL;
      root.son1->son2 = NULL;
    }
  }
  else
  {
    if ( root.son2 != NULL )
      insert( * root.son2, val );
    else
      ...
  }
}
```
Recursive Records

Example for insertion:

```c
int values[7] = { 5, 3, 1, 4, 8, 6, 9 };
node_t root;

root.son1 = root.son2 = NULL;
root.val = values[0];

for ( int i = 1; i < 7; i++ )
    insert( root, values[i] );
```

yields:
Recursive Records

Looking for value in binary tree:

```cpp
bool is_in ( const node_t & root, const int val )
{
    if ( root.val == val )
        return true;

    return is_in( * root.son1, val ) ||
            is_in( * root.son2, val );
}

...  

cout << is_in( root, 6 ) endl;  // yields true  
cout << is_in( root, 7 ) endl;  // yields false
```
Arrays of Records

Like any other datatype, records can also be allocated in the form of an array:

```c
struct coord_t {
    real_t x, y, z;
};
coord_t coordinates[10];
```

for fixed sized array or

```c
coord_t * coordinates = new coord_t[10];
```

using dynamic memory management.
Arrays of Records

The access to record variables then comes after addressing the array entry:

```c++
for ( unsigned i = 0; i < 10; i++ )
{
    coordinates[i].x = cos( real_t(i) * 36.0 * pi / 180.0 );
    coordinates[i].y = sin( real_t(i) * 36.0 * pi / 180.0 );
    coordinates[i].z = real_t(i) / 10.0;
}
```

If instead, an array of pointers to a record is allocated:

```c++
coord_t ** coordinates = new coord_t*[ 10 ];

for ( int i = 0; i < 10; i++ )
    coordinates[i] = new coord_t;
```

the access if performed with the arrow operator `->`:

```c++
coordinates[i]->x = cos( real_t(i) * 36.0 * pi / 180.0 );
```
Record Application: Sparse Matrices

We only want to store nonzero entries in a sparse matrix. For this, each entry is stored in a record type, containing the column index and the coefficient:

```c
struct entry_t {
    unsigned column; // column of the entry
    real_t coeff; // actual coefficient
    entry_t * next; // next entry in row
};
```

All entries in a row are stored in a list, provided by the `next` pointer in an entry type. A **NULL** value of `next` signals the end of the list.
Record Application: Sparse Matrices

A sparse matrix is then allocated as an array of entry lists per row:

```c
struct sparsematrix_t {
    unsigned nrows, ncolumns;
    entry_t * entries;
};
```
Record Application: Sparse Matrices

As an example, consider the matrix

\[
\begin{pmatrix}
1 & 3 \\
2 & -1 \\
-4 & 1 & 1 \\
1 & 3 \\
\end{pmatrix}
\]

```c
sparsematrix_t S;
entry_t * entry;

S.nrows = 4; S.ncolumns = 4;
S.entries = new entry_t[4];

// first row
entry = & S.entry[0];
entry->column = 0; entry->coeff = 1.0; entry->next = new entry_t;
entry = entry->next;
entry->column = 2; entry->coeff = 3.0; entry->next = NULL;
...
```
Record Application: Sparse Matrices

As an example, consider the matrix

\[
\begin{pmatrix}
1 & 3 & \cdot & \cdot \\
\cdot & 2 & -1 & \cdot \\
\cdot & -1 & 1 & 3 \\
1 & \cdot & \cdot & \cdot
\end{pmatrix}
\]

sparsematrix_t S;
entry_t * entry;

S.nrows = 4; S.ncolumns = 4;
S.entries = new entry_t[4];

// first row
entry = & S.entry[0];
entry->column = 0; entry->coeff = 1.0; entry->next = new entry_t;

entry = entry->next;
entry->column = 2; entry->coeff = 3.0; entry->next = NULL;
...
Advanced Datatypes

Record Application: Sparse Matrices

As an example, consider the matrix

\[
\begin{pmatrix}
1 & 3 \\
2 & -1 \\
-4 & -1 & 1 \\
1 & 3
\end{pmatrix}
\]

```c
sparsematrix_t S;
entry_t * entry;

S.nrows = 4; S.ncolumns = 4;
S.entries = new entry_t[4];

// first row
entry = & S.entry[0];
entry->column = 0; entry->coeff = 1.0; entry->next = new entry_t;

entry = entry->next;
entry->column = 2; entry->coeff = 3.0; entry->next = NULL;
...```

C++ for Scientific Computing
Record Application: Sparse Matrices

As an example, consider the matrix

\[
\begin{pmatrix}
1 & 3 \\
2 & -1 \\
-4 & 1 \\
1 & 3
\end{pmatrix}
\]

sparsematrix_t S;
entry_t * entry;

S.nrows = 4; S.ncolumns = 4;
S.entries = new entry_t[4];

// first row
entry = & S.entry[0];
entry->column = 0; entry->coeff = 1.0; entry->next = new entry_t;

entry = entry->next;
entry->column = 2; entry->coeff = 3.0; entry->next = NULL;
...

C++ for Scientific Computing
Record Application: Sparse Matrices

Matrix-Vector multiplication:

```c++
void mul_vec ( const real_t alpha, const sparsematrix_t & S,
               const vector_t x, vector_t & y )
{
    for ( unsigned i = 0; i < S.nrows; i++ )
    {
        real_t f = 0.0;
        entry_t * entry = & S.entries[i];

        while ( entry != NULL )
        {
            f += entry->coeff * x[ entry->column ];
            entry = entry->next;
        }

        y[ i ] += alpha * f;
    }
}
```
Record Application: Sparse Matrices (Version 2)

We can store sparse matrices even more memory efficient, without pointers. For this, we’ll use three arrays:

- **colind**: stores column indices for all entries, sorted by row,
- **coeffs**: stores all coefficients in same order as in colind and
- **rowptr**: stores at rowind[i] the position of the first values corresponding to row i in the arrays colind and coeffs. The last field, contains the number of nonzero entries.

This format is known as the *compressed row storage* format.

```c
struct crsmatrix_t {
    unsigned nrows, ncolumns;
    unsigned * rowptr;
    unsigned * colind;
    real_t * coeffs;
};
```
Record Application: Sparse Matrices (Version 2)

For the matrix

\[
\begin{pmatrix}
1 & 3 \\
\ & 2 & -1 \\
\ & -4 & -1 & 1 \\
1 & & & 3
\end{pmatrix}
\]

the corresponding source code is:

```c
#include <stdio.h>

typedef struct crsmatrix_t {
    int nrows, ncolumns;
    unsigned *rowptr;
    unsigned *colind;
    real_t *coeffs;
} crsmatrix_t;

int main() {
    crsmatrix_t S;
    unsigned rowptr[] = { 0, 2, 4, 7, 9 };
    unsigned colind[] = { 0, 2, 1, 3, 0, 1, 2, 0, 3 };
    real_t coeffs[] = { 1, 3, 2, -1, -4, -1, 1, 1, 3 };

    S.nrows = 4; S.ncolumns = 4;
    S.rowptr = rowptr;
    S.colind = colind;
    S.coeffs = coeffs;
    
    return 0;
}
```

C++ for Scientific Computing
Record Application: Sparse Matrices (Version 2)

Matrix-Vector multiplication:

```cpp
void mul_vec ( const real_t alpha, const crsmatrix_t & S,
               const vector_t x, vector_t & y )
{
    for ( unsigned row = 0; row < S.nrows; row++ )
    {
        real_t f = 0.0;
        const unsigned lb = S.rowptr[ row ];
        const unsigned ub = S.rowptr[ row+1 ];

        for ( unsigned j = lb; j < ub; j++ )
            f += S.coeffs[ j ] * x[ S.colind[ j ] ];

        y[ i ] += alpha * f;
    }
}
```
Enumerations

A special datatype is available to define enumerations:

```cpp
enum ⟨enum name⟩ { 
    ⟨name 1⟩, ⟨name 2⟩, ..., ⟨name n⟩
};
```

Example:

```cpp
enum matrix_type_t { unsymmetric, symmetric, hermitian }; 

matrix_type_t t; 

if ( t == symmetric ) { ... }
```

Enumerations are handled as integer datatypes by C++. By default, the members of an enumeration are numbered from 0 to \( n - 1 \), e.g. \( ⟨\text{name 1}⟩ = 0, ⟨\text{name 2}⟩ = 1 \), etc..
Enumerations

One can also define the value of the enumeration members explicitly:

```cpp
enum matrix_size_t { small = 10, middle = 1000, large = 1000000 };

if ( nrows < small ) { ... }
else if ( nrows < middle ) { ... }
else if ( nrows < large ) { ... }
else { ... }
```

Since enumerations are equivalent to integer types, they can also be used in `switch` statements:

```cpp
switch ( type )
{
    case symmetric: ...; break;
    case hermitian: ...; break;

    case unsymmetric: default: ...;
}
Advanced Datatypes

Unions

A union is a special record datatype where all variables share the same memory, i.e. changing one variable changes all other variables.

```
union ⟨union name⟩ {
    ⟨datatype 1⟩ ⟨name 1⟩;
    ...
    ⟨datatype n⟩ ⟨name n⟩;
};
```

Example:

```c
union utype_t {
    int n1;
    int n2;
    float f;
};

utype_t u;

u.n1 = 2;
cout << u.n2 << endl;  // yields 2
cout << u.f << endl;  // ???
```
Unions can also be used inside records:

```c
enum smat_type_t { ptr_based, crs_based };

struct general_sparse_matrix_t {
    smat_type_t type;

    union {
        sparsematrix_t ptrmat;
        crsmatrix_t crsmat;
    } matrix;
};

general_sparse_matrix_t S;

S.type = ptr_based;
S.matrix.ptrmat.nrows = 10;
```

**Remark**

Typical usage for unions: save memory for different representations.
**Unions**

The name `matrix` of the `union` can be omitted. The access is then as if it were a direct member of the `struct`.

```cpp
enum smat_type_t { ptr_based, crs_based };

struct general_sparse_matrix_t {
    smat_type_t type;

    union {
        sparsematrix_t ptrmat;
        crsmatrix_t crsmat;
    }
};

general_sparse_matrix_t S;

S.type = ptr_based;
S.ptrmat.nrows = 10;
```
Modules and Namespaces
Header Files

Up to now, all source code was placed into one file. For reasonable programs, this is not desirable, especially if functions are reused by different programs.

Unfortunately, C++ has no real module system like, e.g. Pascal or Java, to group similar functions or types. Instead, header files are used to make C++ objects known to different source files. As you remember, functions can be used if they were previously declared or implemented. By separating declaration and implementation into header and source file:

```cpp
// header file: f.hh
void f ( int n, double f );

// source file: f.cc
void f ( int n, double f )
{ ... }
```

the function can be reused by just including the header file.
Header Files

Including another file into the current source code is performed by the `include` directive:

```cpp
#include "filename" or
#include <filename>
```

The first version is usually used for files in the same project, whereas the second version is for files from other projects, e.g. the operating system or the C++ compiler.

```cpp
#include "f.hh"  // contains decl. of "f"

test main ()
{
  f( 42, 3.1415926 );
}
```
Header Files

Remark

By convention, the filename suffix of the header file should be either “h” (like in C), “H”, “hh” or “hpp”.
C++ Library

The C++ compiler comes with a set of standard include files containing declarations of many functions:

**cstdlib**: standard C functions, e.g.
- **exit**: stop program,
- **atoi** and **atof**: string to **int** and **double** conversion,
- **qsort**: sort arrays,
- **malloc** and **free**: C-style dynamic memory management,

**cmath**: mathematical functions, e.g.
- **sqrt**: square root,
- **abs**: absolute value,
- **sin** and **cos**, 
- **log**: natural logarithm
C++ Library

cstdio: C-style IO functions, e.g.
  - printf: print variables to standard output,
  - fopen, fclose, fread and fwrite: file IO

cstring: string functions, e.g.
  - strlen: string length,
  - strcat: string concatenation,
  - strcmp: string comparison,
  - strcpy: string copy

cctype: character tests, e.g.
  - isdigit: test for digit,
  - islower: test for lower case,
  - isspace: test for white-space

etc.: cassert, cerrno, cinttypes, climits, ctime.
Specific C++ functionality usually comes in the form of the **standard template library**. It is implemented via classes (see later) and provided by the following header files:

- **iostream**: file input/output functions and classes,
- **vector**: dynamic containers similar to arrays,
- **valarray**: similar to **vector** but better suited for numerics,
- **limits**: functions for determining type limits, e.g. minimal or maximal values,
- **map**: associative array, e.g. indices are arbitrary types,
- **list**: provides standard list and iterators,
- **complex**: provides complex datatype,
- etc.

The specific classes and their usage will be discussed later.
Libraries without Headers (LAPACK)

LAPACK is written in Fortran and no header files exist for C++. Therefore, we will have to write them ourselves. Consider

```
SUBROUTINE DGESVD( JOBU, JOBVT, M, N, A, LDA, S, U, LDU, VT, LDVT,
                    WORK, LWORK, INFO )
CHARACTER JOBU, JOBVT
INTEGER INFO, LDA, LDU, LDVT, LWORK, M, N
DOUBLE PRECISION A( LDA, * ), S( * ), U( LDU, * ),
                    VT( LDVT, * ), WORK( * )
```

To define a C++ function corresponding to the above Fortran function the datatypes have to be mapped to C++ types. In Fortran, every variable is provided as a pointer, hence:

- `CHARACTER` → `char *`
- `INTEGER` → `int *`
- `DOUBLE PRECISION` → `double *`
Libraries without Headers (LAPACK)

Fortran function names are in lower case and end with and underscore '_' when seen from C or C++. Hence, the name of the above Fortran function is `dgesvd_`:

```c
void dgesvd_ ( char * jobu, char * jobv, int * n, int * m,
              double * A, int * lda, double * S, double * U,
              int * ldu, double * V, int * ldv, double * work,
              int * lwork, int * info );
```

Furthermore, there is a difference between C and C++ functions. Fortran only provides C-style functions, whereas the above is a C++ function. To tell the compiler that a C-style function should be declared, the `extern "C"` instruction is provided:

```c
extern "C" {
void dgesvd_ ( char * jobu, char * jobv, int * n, int * m,
              double * A, int * lda, double * S, double * U,
              int * ldu, double * V, int * ldv, double * work,
              int * lwork, int * info );
}
```
Libraries without Headers (LAPACK)

Afterwards, the function `dgesvd_` can be used like any other C++ function. To compute the SVD $M = U \cdot S \cdot V^T$ of a matrix $M$, the code looks like:

```c++
int n = 10;
double * M = new double[ n*n ];
char jobu = 'O';        // overwrite M with U
char jobv = 'S';        // store V^T in VT
int info = 0;
int lwork = 10*n*n;
double * work = new double[ work ];  // workspace for dgesvd
double * S = new double[ n ];
double * VT = new double[ n*n ];
...
// fill M

dgesvd_( &jobu, &jobv, &n, &n, M, &n, S, M, &n, V, &ldv,
        work, &lwork, &info );
```
Header File Recursion

The `include` directive can be seen as simple text replacement: the directive is replaced by the content of the corresponding file.

```cpp
#include "f.hh"

int main ()
{
    f( 42, 3.1415926 );
}
```

This might lead to infinite loops, if you have recursive `include` directives in different files, e.g. “file1.hh” includes “file2.hh”, which by itself includes “file1.hh”.

```
// FILE: file1.hh
#include "file2.hh"
...
```

```
// FILE: file2.hh
#include "file1.hh"
...
```
Header File Encapsulation

To prevent infinite loops, two other directives are provided:

```c
#ifndef ⟨NAME⟩
   :
   #endif
```

tests, if the symbol ⟨NAME⟩ was previously defined by the directive

```c
#define ⟨NAME⟩
```

If it was not defined, all source code between the `ifndef` directive and the corresponding `endif` will be included by the C++ compiler. Otherwise, the source code will be omitted.

**Remark**

*It is recommended to name the symbol ⟨NAME⟩ after the name of the header file.*
Header File Encapsulation

Now, for the recursive example:

```c++
// FILE: file1.hh
ifndef __FILE1_HH
define __FILE1_HH
#include "file2.hh"
endif

// FILE: file2.hh
ifndef __FILE2_HH
define __FILE2_HH
#include "file1.hh"
endif
```

If “file1.hh” is included by a source file, the symbol “__FILE1_HH” will be defined and the content of the header file included. Similar, `#include ‘file2.hh’` will be replaced by the content of “file2.hh”. If now again “file1.hh” should be included, “__FILE1_HH” is already defined and the content of “file1.hh” is omitted, stopping the recursion.
Header File Encapsulation

Coding Principle No. 19

Always encapsulate your header files by an `ifndef-define-endif` construct.
Inline Functions

It is also possible to implement a function in a header file. In that case, it has to be declared `inline`, because otherwise, the function is defined in each source file, where the header is included. If you than compile all source files together, you would have multiple instances of the same function, which is not allowed.

```cpp
#ifndef __SQUARE_HH
#define __SQUARE_HH

inline double square ( const double x )
{
    return x*x;
}
#endif
```
Variables

Beside functions, you can also declare variables in header files. For non-const data, the declaration and definition has to be separated to prevent multiple instances. In the header file, the variables have to be declared with the keyword `extern`:

```cpp
// header file: real.hh

#ifndef __REAL_HH
#define __REAL_HH

typedef double real_t;

const real_t PI = 3.1415926; // const: "extern" not needed
extern real_t eps;
extern int stepwidth;
#endif
```
Variables

The definition than has to be made in a source file:

```
// source file: real.cc

#include "real.hh"  // for real_t

real_t   eps   = 1e-8;
int      stepwidth = 1024;
```

Afterwards, every module including the corresponding headerfile has access to the variables \texttt{eps} and \texttt{stepwidth}:

```
#include "real_t.hh"

int
main ()
{
  eps = 1e-4;
  cout << stepwidth << endl;

  \textbf{return} 0;
}
```
Module Scope

If a function or variable is declared in a header file, it is globally visible by all other parts of the program. It is in **global** scope. For variables, that simplifies access, e.g. global variables do not need to be supplied as function parameters. But it has a major **drawback**: every function can change the variable, independent on possible side effects. Better approach: define a function for changing the variable. That way, the access can be controlled:

```c++
// header
void set_eps ( const real_t aeps );
real_t get_eps ();

// source
static real_t eps = 1e-8;
void set_eps ( const real_t aeps )
{
    if ( aeps < 0.0 ) eps = 0.0;
    else if ( aeps > 1.0 ) eps = 1.0;
    else eps = aeps;
}
```
Module Scope

Therefore:

Coding Principle No. 20

Only if absolutely necessary make non-const variables global.

Remark

The `static` declaration of a variable or function in a source file prevents other modules from using that variable or function, respectively.
Namespaces

Following situation: we have written datatypes and functions for dense matrices in a module, e.g.

```c
struct matrix_t {
    size_t    nrows, ncolumns;
    real_t *  coeffs;
};

matrix_t * init ( ... );
void      mul_vec ( ... );
```

and you want to join that with another module for sparse matrices:

```c
struct matrix_t {
    size_t    nrows, ncolumns, nnzero;
    size_t *  rowptr, * colind;
    real_t *  coeffs;
};

matrix_t * init ( ... );
void      mul_vec ( ... );
```
Namespaces

Problem: although functions with the same name are allowed, two datatypes must not have the same name.

Solution 1: rename all occurrences of `matrix_t` for sparse matrices, and change all functions, or

Solution 2: put each type and function set into a different namespace.

A namespace is a mechanism in C++ to group types, variables and functions, thereby defining the scope of these objects, similar to a block. Till now, all objects were in the `global` namespace.

Namespace definition:

```cpp
namespace ⟨namespace name⟩ {
  :
  :
}
```
Namespaces

Applied to the two matrix modules from above:

```cpp
namespace Dense {
    struct matrix_t {
        unsigned nrows, ncolumns;
        real_t * coeffs;
    };
    matrix_t * init ( ... );
    void mul_vec ( ... );
}

namespace Sparse {
    struct matrix_t {
        unsigned nrows, ncolumns, nnzero;
        unsigned * rowptr, * colind;
        real_t * coeffs;
    };
    matrix_t * init ( ... );
    void mul_vec ( ... );
}
```

This defines two namespaces `Dense` and `Sparse`, each with a definition of `matrix_t` and corresponding functions.
Namespace Access

The access to functions or types in a namespace is performed with the namespace operator “::”:

```cpp
Dense::matrix_t * D = Dense::init( 10, 10 );
Sparse::matrix_t * S = Sparse::init( 10, 10, 28 );

Dense::mul_vec( 1.0, D, x, y );
Sparse::mul_vec( 1.0, S, x, y );
```
Namespace Access

To make all objects in a namespace visible to the local namespace, the keyword `using` is provided:

```cpp
using namespace Dense;
using namespace Sparse;

Dense::matrix_t * D = init( 10, 10 );  // call to Dense::init
Sparse::matrix_t * S = init( 10, 10, 28 );  // call to Sparse::init

mul_vec( 1.0, D, x, y );  // call to Dense::mul_vec
mul_vec( 1.0, S, x, y );  // call to Sparse::mul_vec
```

**Remark**

*Remember, that types must have different names.*

*Hence, the types for \( D \) and \( S \) have to be named with their namespaces.*
Namespace Access

Restrict the usage of `using` to source files and avoid `using` directives in header files, because all modules including the header would also include the corresponding `using` instruction:

```cpp
// header file: vector.hh
#include "dense.hh"
using namespace Dense;
...
// source file: module.cc
#include "vector.hh"
#include "sparse.hh"
using namespace Sparse;
void f ( matrix_t & M );
```

Here, `matrix_t` is ambiguous, e.g. either `Dense::matrix_t` or `Sparse::matrix_t`. 
Namespace Aliases

It is also possible to define an alias for a namespace, e.g. to abbreviate it:

```cpp
namespace De = namespace Dense;
namespace Sp = namespace Sparse;

De::matrix_t * D = De::init( 10, 10 );
Sp::matrix_t * S = Sp::init( 10, 10, 28 );
De::mul_vec( 1.0, D, x, y );
Sp::mul_vec( 1.0, S, x, y );
```
Nested Namespaces

Namespaces can also be nested and different parts of a namespace can be defined in different modules:

```cpp
namespace LinAlg {
  namespace Dense {
    ...
  }
}

namespace LinAlg {
  namespace Sparse {
    ...
  }
}
```

```cpp
LinAlg::Dense::matrix_t * D = LinAlg::Dense::init( 10, 10 );
LinAlg::Sparse::matrix_t * S = LinAlg::Sparse::init( 10, 10, 28 );
LinAlg::Dense::mul_vec( 1.0, D, x, y );
LinAlg::Sparse::mul_vec( 1.0, S, x, y );
```
Anonymous Namespaces

Namespaces can also be defined without a name:

```cpp
namespace {
    void f ()
    {
        ...
    }
}
```

The C++ compiler will then automatically assign a unique, hidden name for such a namespace. This name will be different in different modules.

Functions in an anonymous namespace can be used without specifying their namespace name:

```cpp
namespace {
    void f () { ... }
}

void g () { f(); }
```
Anonymous Namespaces

On the other hand, since the automatically assigned name is unique per module, only functions in the same module as the anonymous namespace can access the functions within:

```cpp
// module 1
namespace {
  void f () { ... }
}
void g () {
  f(); // Ok: same module
}

// module 2
void h () {
  f(); // Error: unknown function "f"
}
```

Such functions are therefore hidden for other modules and purely local to the corresponding module.
Anonymous Namespaces

Remark

If an anonymous namespace is defined in a header file, each module including the header would define a new, local namespace!

Coding Principle No. 21

Put module local functions into an anonymous namespace.

This approach is different from the previous C-style version using static functions and variables and should be preferred.
The std Namespace

All functions (and classes) of the C++ standard library, e.g. `sqrt` or `strcpy` are part of the `std` namespace. Previous use always assumed a corresponding `using` command:

```cpp
using namespace std;

const real_t PI = 3.14159265358979323846;
const real_t sqrtPI = sqrt( PI );

cout << sqrtPI << endl;
```

is equivalent to

```cpp
const real_t PI = 3.14159265358979323846;
const real_t sqrtPI = std::sqrt( PI );

std::cout << sqrtPI << std::endl;
```
Classes
Records with Functions

Records were previously introduced only as a way to group data. In C++, records can also be associated with functions.

```cpp
struct vector_t {
    unsigned size;
    real_t * coeffs;

    void init ( const unsigned n );
    void fill ( const real_t f );
    void scale ( const real_t f );
};
```

For the implementation of these functions, the function name is prefixed by the record name:

```cpp
void vector_t::init ( const uint n )
{
    ...
}
```
Records with Functions

A record function is called specifically for an instance of a record, using the same dot operator '.' as for record variables:

```cpp
int main ()
{
    vector_t x;

    x.init( 10 );
    x.fill( 1.0 );
    x.scale( 5.0 );

    return 0;
}
```
Classess

Record Function Implementation

Inside a record function, one has implicit access to all record variables of the specific record object, for which the function was called. Therefore, the following two functions are equivalent:

```cpp
void vector_t::init ( const uint n )
{
    size = n;
    coeffs = new real_t[n];
}

... x.init( 10 );
```

```cpp
void init ( vector_t * x,
            const uint n )
{
    x->size = n;
    x->coeffs = new real_t[n];
}

... init( x, 10 );
```
Record Function Implementation

A pointer to the corresponding record object is actually available in C++. It is called `this`. Hence, one can also write:

```cpp
void vector_t::init ( const uint n )
{
    this->size = n;
    this->coeffs = new real_t[n];
}
```

Record member functions can also be implemented in the definition of the `struct`. They are then automatically declared as `inline` functions:

```cpp
struct vector_t {
    ...
    void init ( const unsigned n )          // inline function
    {
        size = n;
        coeffs = new real_t[n];
    }
    ...
};
```
**Records: const functions**

Member functions not changing the record data should be defined as *const* functions:

```cpp
class vector_t {
    ...
    void scale ( const real_t f );
    real_t norm2 () const;
    ...
};
```

When calling record functions for *const* objects, e.g.

```cpp
const vector_t x( 10 );
```

only such *const* functions are allowed to be called, since all non-*const* functions potential change the object:

```cpp
cout << x.norm2() << endl;       // Ok: vector_t::norm2 is const
x.scale( 2 );                  // ERROR: vector_t::scale is non-const
```
Records: Constructors and Destructors

There are special functions for each record:

constructors: functions automatically called when a record type is instantiated, e.g. by \texttt{new}, and

destructor: a function automatically called when a record variable is destroyed, e.g. by \texttt{delete}.

The name of a constructor function is identical to the name of the record, whereas the name of the destructor is the record name prefixed by ‘\~’:

```
struct vector_t {
    unsigned size;
    real_t * coeffs;

    vector_t (); // constructor 1
    vector_t ( \texttt{const} unsigned n ); // constructor 2
    ~vector_t (); // destructor
};
```
Records: Constructors and Destructors

By definition, constructors should create necessary resources for the object, whereas destructors should free all record object resources:

```cpp
vector_t::vector_t ()
{
    size   = 0;
    coeffs = NULL;
}

vector_t::vector_t ( const uint n )
{
    size   = n;
    coeffs = new real_t[n];
}

vector_t::~vector_t ()
{
    delete [] coeffs;
}
```

Remark

Constructors and the destructor have no return type. Furthermore, destructors must not have function arguments.
Records: Constructors and Destructors

Example 1: instantiated and destroyed explicitly by `new` and `delete`:

```cpp
vector_t * x = new vector_t();       // calling constructor 1
vector_t * y = new vector_t( 10 );   // calling constructor 2
y->fill( 1.0 );
delete x;                           // calling destructor
```

Remark

*If the constructor has no arguments, the corresponding parentheses can be omitted:*

```cpp
vector_t * x = new vector_t;       // calling constructor 1
```
**Records: Constructors and Destructors**

Example 2: instantiated and destroyed implicitly by block scope:

```cpp
{
    vector_t x;  // calling constructor 1
    vector_t y( 10 );  // calling constructor 2
    y.fill( 1.0 );  // destructor called automatically
}
```

Here, the record objects are not pointers. When leaving the block, the destructors of all record objects are called automatically! Thereby, it is ensured, that all resources are released.
Records: Special Constructors

By default, each record type has two constructors already implemented by the C++ compiler: the default constructor and the copy constructor.

The default constructor is a constructor without arguments, e.g. constructor 1 in the previous example. The copy constructor is a constructor with one argument being a constant reference to an object of the same type as the record itself:

```cpp
struct vector_t {
    ... 
    vector_t(const vector_t &x);  // copy constructor
    ...
};
```

This is used for

```cpp
vector_t x(10);
vector_t y(x);  // call copy constructor
vector_t z = y;  // usually converted to z(y)
```
Records: Special Constructors

The default constructor implemented by the C++ compiler does nothing, e.g. it does not initialise the member variables. Hence, without a user implemented default constructor, the values of the member variables are random (ref. Coding Principle No. 3). The C++ generated copy constructor simply copies the data in each member variable of the record:

```cpp
vector_t * x = new vector_t( 10 );
vector_t * y = new vector_t( & x ); // now: x.coeffs == y.coeffs,
// e.g. equal pointers
```

Here, changing `y` also changes `x`:

```cpp
x->coeffs[ 5 ] = 2;  // also changes y.coeffs[ 2 ]
y->coeffs[ 3 ] = 4;  // also changes x.coeffs[ 3 ]
```
Records: Special Constructors

For vectors, instead of the pointers, the content of the array should be copied:

```cpp
vector_t::vector_t ( const vector_t & v )
{
    size = v.size;
    coeffs = new real_t[size];
    for ( uint i = 0; i < size; i++ ) coeffs[i] = v.coeffs[i];
}
```

Now, the instructions

```cpp
vector_t * x = new vector_t( 10 );
vector_t * y = new vector_t( & x );
x->coeffs[ 5 ] = 2;
y->coeffs[ 3 ] = 4;
```

only effect either \( x \) or \( y \), not both.
Records: Special Constructors

To sum this up:

**Coding Principle No. 22**

*Always make sure, that the C++ generated default and copy constructors behave as expected. If in doubt: implement constructors by yourself.*
Records: Visibility

All member variables and functions of a record were visible and accessible from any other function or datatype in C++. This makes illegal changes to the data in a record possible, e.g. change the size variable of `vector_t` without also changing the `coeffs` variable.

To prevent this behaviour, one can change the visibility of variables and functions using one of the following keywords:

- **public**: variables or functions can be accessed without restrictions,
- **protected**: variables or functions can only be accessed by member functions of the record type or by derived records (see later),
- **private**: variables or functions can only be accessed by member functions of the record type.
Records: Visibility

Example 1:

```cpp
struct vector_t {
  private: // all following variables and functions
    size_t size; // are private
    real_t * coeffs;

  public: // all following variables and functions
    // are public
    vector_t ( const size_t n );
    ...
    size_t get_size () const { return size; }
  }
  ...
{
  vector_t x( 10 );

  cout << x.size << endl; // ERROR: <size> is private
  cout << x.get_size() << endl; // OK: <get_size> is public
}
```
Records: Visibility

Example 2:

```cpp
struct vector_t {
    private:
        size_t size;
        real_t * coeffs;

    public:
        ...

    protected:
        void init ( const size_t n )
        {
            size = n; // Ok: <size> is visible to member functions
            coeffs = new real_t[n];
        }
    };

    { vector_t x( 10 );
        x.init( 20 ); // ERROR: <init> is protected
    }
```
Records: Visibility

Illegal states of member variables can be prevented by making them `private` and allowing modifications only via `public` member functions:

```cpp
struct vector_t {
    private:
        size_t size;
        real_t * coeffs;

    public:
        ...
        size_t get_size () const { return size; }
        void set_size ( const size_t n ) { init( n ); }
        ...
};
```

Coding Principle No. 23

Make all member variables of a record `private` and allow read-/write-access only via member functions.
Records: Operator Overloading

In C++, operators, e.g. `+`, `*`, `=` or `[]`, can be defined for record datatypes to simplify access or to ensure correct behaviour. Depending on the operator, it can be defined inside or outside the record definition, e.g. operators changing the object like `=` or `+=` in the record definition and binary operators working on two objects typically outside the record.

In terms of syntax, operator functions are treated like any other function. The name of the operator is defined by

```
operator ⟨operator name⟩
```

e.g.
```
operator =
operator +
operator *
operator []
```
struct vector_t {
    ... 
    // provide index operator for vectors
    real_t operator [] ( const size_t i ) { return coeffs[i]; } 

    // arithmetics
    vector_t & operator += ( const vector_t & v ) {
        for ( size_t i = 0; i < size; i++ ) coeffs[i] += v.coeffs[i];
        return *this;
    }
    vector_t & operator -= ( const vector_t & v ) { ... }
    vector_t & operator *= ( const real_t f ) {
        for ( size_t i = 0; i < size; i++ ) coeffs[i] *= f;
        return *this;
    }
    ... 
};

{ ... 
    x += y;
    y *= 2.0;
}
Records: Operator Overloading

Be very careful when overloading the standard arithmetic operators, e.g. `+` or `*`, since that can lead to very inefficient code:

```cpp
// vector addition
vector_t operator + ( const vector_t & v1, const vector_t & v2 )
{
    vector_t t( v1 );
    return ( t += v2 );
}
```

Here, a temporary object `t` has to be created. Furthermore, usually another temporary object is created by the compiler since the lifetime of `t` ends when returning from the function. Each of these temporary objects needs memory and performs a copy operation. Hence, the addition is very inefficient.

**Coding Principle No. 24**

*Only overload operators if necessary and reasonable.*
Records: Special Operators

The analog to the copy constructor is the copy operator ‘==’, e.g. used in

\[ x = y; \]

It is also generated by the C++ compiler by default, simply copying the individual member variables of the record. Thereby, the same problems occur, e.g. copying pointers instead of arrays.

Coding principle for copy operators (see Coding Principle No. 22):

**Coding Principle No. 25**

*Always make sure, that the C++ generated copy operator behaves as expected. If in doubt: implement operator by yourself.*
Records: Special Operators

Copy operator for vectors:

```cpp
struct vector_t {
    ... 
    vector_t & operator = ( const vector_t & v )
    {
        init( v.size );

        for ( uint i = 0; i < size; i++ ) coeffs[i] = v.coeffs[i];

        return *this;
    }
    ... 
};
```

Now, when assigning record objects to each other, e.g.

```cpp
x = y;
```

the user implemented copy operator is used, ensuring correctness.
Records: Special Operators

The copy operator also allows a simplified copy constructor:

```cpp
vector_t::vector_t ( const vector_t & v )
{
    *this = v;
}
```
Classes

Records provide all mechanisms for object-oriented programming. What about classes? C++ also provides a class type, e.g.

```cpp
class ⟨class name⟩ {
    :
};
```

Classes in C++ are identical to records, except for one little difference: if the visibility specifiers, e.g. public, protected and private, are missing, by default all member variables and functions are private in a class and public in a record. Therefore, it is up to you, which form you prefer: classes or records. One possible rule: for simple records without functions use a struct, otherwise use a class. But remember Coding Principle No. 22, Coding Principle No. 25 and Coding Principle No. 3 (RAII).
Classes

Application: BLAS (Version 3)

Vector type:

```cpp
class vector_t {
private:
    size_t size;
    real_t * coeffs;

public:
    vector_t ( const size_t n = 0 );
    vector_t ( const vector_t & x );
    ~vector_t ();

    size_t get_size () const;

    real_t operator [] ( const size_t i ) const;
    real_t & operator [] ( const size_t i );

    void fill ( const real_t f );
    void scale ( const real_t f );
    void add ( const real_t f, const vector_t & x );

    vector_t & operator = ( const vector_t & x );
};
```
Application: BLAS (Version 3)

Remarks to the vector class:

• The constructor

```cpp
template <size_t n = 0>
vector_t ( const size_t n = 0 );
```

also serves as a default constructor since it can be called without an argument.

• The index operator

```cpp
real_t & operator [] ( const size_t i )
{
    return coeffs[i];
}
```

provides write access to the coefficients since a reference to the corresponding entry is returned. Therefore, it is defined non-`const`.
Application: BLAS (Version 3)

Matrix type:

class matrix_t {
private:
    size_t nrows, ncolumns;
    real_t * coeffs;

public:
    matrix_t ( const size_t n, const size_t m );
    matrix_t ( const matrix_t & M );
    ~matrix_t ();

    size_t get_nrows () const;
    size_t get_ncolumns () const;

    real_t operator [] ( const size_t i, const size_t j ) const;
    real_t & operator [] ( const size_t i, const size_t j );

    void fill ( const real_t f );
    void scale ( const real_t f );
    void add ( const real_t f, const matrix_t & M );
}
Classes

Application: BLAS (Version 3)

```cpp
void mul_vec ( const real_t alpha, const vector_t & x, vector_t & y ) const;

real_t normF () const;

matrix_t & operator = ( const matrix_t & M );
```

```cpp
private:
    matrix_t ();
};
```

```cpp
void mul_mat ( ... );
```

Remarks:

- The private default constructor prevents accidental matrices of dimension 0, since it can not be called.
- The function `mul_mat` is not part of the matrix class, since the algorithm can not be connected with a specific matrix.
Classes

Application: BLAS (Version 3)

```cpp
matrix_t * M = new matrix_t( 10, 10 );
vector_t * x = new vector_t( 10 );
vector_t * y = new vector_t( 10 );

x.fill( 1.0 );
y.fill( 0.0 );

...
M[3,4] = ... // fill matrix M
...

cout << M.normF() << endl;
M.mul_vec( -1.0, x, y );

delete x;
delete y;
delete M;
```
Generic Programming
Consider

```cpp
int square ( const int x ) { return x*x; }
float square ( const float x ) { return x*x; }
double square ( const double x ) { return x*x; }
```

The same algorithm is implemented for different datatypes. For more complicated algorithms, this potentially leads to a lot of programming overhead. If one aspect of the algorithm should be changed, all other implementations have to be changed as well.

A similar overhead is involved with record datatypes used with multiple base types, e.g. lists or dynamic arrays. The record has to be reprogrammed whenever a new type should be placed in the list or array, respectively.

Alternative: write source code for the record or function once and leave out the specific datatype to operate on. That is called generic programming.
**Templates**

C++ supports generic programming in the form of templates. A template function is defined as

```cpp
template < typename ⟨name⟩ >
⟨return type⟩ ⟨function name⟩ ( ⟨argument list⟩ )
⟨function body⟩
```

e.g.

```cpp
template <typename T>
T square ( const T f ) { return f*f; }
```

If the C++ compiler detects the usage of a template function, e.g.

```cpp
double sq2 = square( 2.0 );
```

it will automatically generate the corresponding function:

```cpp
double square ( const double f ) { return f*f; }
```
**Templates**

Similar defined are template record (or class) types:

```cpp
template < typename name >
struct record name {
    ...;
};
```

Example for a simple list:

```cpp
template <typename T>
struct list {
    T element;
    list * next;
};
```
Templates

Template datatypes are used by explicitly defining the corresponding type to be used in the template. The syntax is:

\[ \langle \text{record name} \rangle < \langle \text{type} \rangle > \]

For the list type, this looks as:

```c++
int main ()
{
    list< int > ilist;
    list< double > * dlist = new list< double >;

    ilist.element = 2;
    ilist.next = NULL;

    dlist->element = 2.0;
    dlist->next = NULL;
}
```
**Templates**

The template type can be a template by itself:

```cpp
int main ()
{
    list< list< float > > fllist;

    fllist.element.element = 2.0f;
    fllist.element.next = NULL;
    fllist.next = NULL;
}
```

Here, the list can be extended in two dimensions, either by the `next` pointer or the `element.next` pointer.
Templates

Template functions can also be explicitly typed using the same syntax:

```cpp
float sq2 = square< float >( 2.0f );
double sq3 = square< double >( 3.0 );
```

This is necessary, if the compiler can not automatically determine the type used for a template function:

```cpp
template <typename T>
T min ( const T a, const T b )
{
    if ( a < b ) return a;
    else return b;
}
```

```cpp
int n1 = 10;
unsigned n2 = 20;
int n3 = min( n1, n2 ); // ambiguous: int or unsigned?
int n4 = min<int>( n1, n2 ); // ok: int explicitly chosen
```
Templates

Since template functions or types are generated at compile time, the full specification, e.g. function header and body, has to be available whenever such a function is used. Therefore, template functions must always be implemented in a header file.

Remark

If many template types and functions are used for many different datatypes, this significantly can bloat the resulting compiled program. Also, the compilation time can be much higher.
Templates: Example (CG iteration for $Ax = b$)

```cpp
template <typename T_MAT> void cg ( const T_MAT & A, vector_t & x, const vector_t & b )
{
    vector_t r( b ), p, a( x.get_size() );

    mul_vec( -1.0, A, x, r ); // $r = b - A x$
    p = r; // $p = r$

    for ( size_t it = 0; it < 1000; it++ )
    {
        real_t lambda;
        a.fill( 0.0 );
        mul_vec( 1.0, A, p, a ); // $a = A p$
        lambda = dot( r, p ) / dot( a, p ); // $\lambda = \frac{\langle r, p \rangle}{\langle a, p \rangle}$
        x.add( lambda, p ); // $x = x + \lambda p$
        r.add( -lambda, a ); // $r = r - \lambda a$
        p.scale( -dot( r, a ) / dot( a, p ) );
        p.add( 1.0, r ); // $p = r - \left( \frac{\langle r, a \rangle}{\langle a, p \rangle} \right) p$

        if ( r.norm2() < 1e-10 ) // stop crit.: $|r|_2 < 1e-10$
            break;
    }
}
```
Templates: Example (CG iteration for $Ax = b$)

Remark

*Works for arbitrary matrix types, e.g. dense and sparse, as long as *mul_vec* is implemented for each type:*

```cpp
Dense::matrix_t M( n, n );
vector_t x( n );
vector_t b( n );
cg( M, x, b );

Sparse::matrix_t S( n, n, nnonzero );
cg( S, x, b );
```
**Templates: Multiple Template Arguments**

Template functions and datatypes are also possible with more than one argument type:

```cpp
template <typename T_MAT, typename T_VEC> void cg(const T_MAT & A, T_VEC & x, const T_VEC & b)
{
    ...
}
```
Templates: Value Templates

Previous templates were used to leave out the type to work on. One can also predefine the type and leave out the specific value:

```cpp
template <int N>
struct smallvector_t {
    real_t coeffs[N];  // constant size array

    smallvector_t ()
    {
        for ( size_t i = 0; i < N; i++ )
            coeffs[i] = 0.0;
    }

    smallvector_t & operator += ( const smallvector_t & v ) { ... }
    smallvector_t & operator -= ( const smallvector_t & v ) { ... }
    smallvector_t & operator *= ( const real_t f ) { ... }
};

template <int N>
smallvector<N> operator + ( const smallvector_t<N> & v1,
                          const smallvector_t<N> & v2 ) { ... }
```
Templates: Value Templates

smallvector_t<3> x, y, z;

x += y;
y *= 2.0;

z = x -= z + y;

Remark

As long as $N$ is small, e.g. $\leq 5$, the arithmetic operators are still very efficient.
Templates: Conclusion

Templates are a very powerful tool to simplify programming. Furthermore, they are Turing complete, i.e. you can program every computable program by only using templates. Unfortunately, templates are also quite complex and involve a significant overhead in terms of programming, compilation time and (possibly) program size. Therefore, it is suggested to use them sparsely.
Error Handling
### General Thoughts

Consider

```cpp
vector_t x( 10 );
vector_t y( 20 );

y = x;
```

The copy operator of `vector_t` simply copies all elements up to the size of the vector:

```cpp
for ( size_t i = 0; i < size; i++ )
    (*this)[i] = x[i];
```

but the argument `x` only has 10 elements. Hence, memory is overwritten, which is not part of the vector.
General Thoughts

Another typical error involves NULL pointers:

```cpp
bool is_in ( const node_t & root, const int val )
{
    if ( root.val == val ) return true;
    else return is_in( * root.son1, val ) ||
             is_in( * root.son2, val );
}
```

Here, the recursive call to `is_in` for the sons is only possible, if the sons are not `NULL`, which is not tested.
General Thoughts

The following example for a LU factorisation of a dense matrix shows another problem:

```c
for ( uint j = 0; j <= min(nrows,ncolumns); ++j )
{
    if ( j < n-1 )
        scale( nrows-1-j, 1.0 / A[j, j], & A[j + 1, j] );

    if ( j < mrc )
        // rank-1 update
        geru( nrows-1-j, ncolumns-1-j, -1.0,
               & A[j + 1, j], 1,
               & A[j, j + 1], n,
               & A[j + 1, j + 1], n );
}
```

The division by the diagonal element is not guarded against division by zero, which would result in \textbf{INF} numbers.
General Thoughts

Obviously, we need some protection against possible errors. Even more important is, that errors are detected and reported. For detecting errors:

Coding Principle No. 26

- Always check function arguments, especially pointers for illegal values (*pre condition* of a function).
- If a critical situation is possible by an instruction, check the operands of the instruction.
- Check, whether the results of a function are as expected (*function post condition*).
General Thoughts

For reporting errors different strategies are possible:

by message: Detect the error and print a (detailed) message that a problem occurred, but otherwise continue the program. This is usable for non-critical errors.

by abort: Detect the error and abort the program, possibly with a detailed description of the error. This behaviour is acceptable for short running programs.

by exception: Detect the error and throw an exception and let the programmer either catch the exception or not, in which case the program is aborted.
**Assertions**

Assertions fall into the category “error handling by abort”. An assertion is defined using the function `assert` defined in the module `cassert`.

**Remark**

Assertions are also possible in C, therefore the filename `cassert`.

The `assert` function expects a logical expression as its function argument. If the expression is `false`, the program is terminated, printing the definition of the failed assertion together with the filename and line number, where the assertion failed.
Assertions

For the copy operator of `vector_t` this looks as:

```cpp
#include <cassert>

struct vector_t {
    ...

    vector_t & operator = ( const vector_t & x )
    {
        assert( get_size() == x.get_size() );

        for ( size_t i = 0; i < size; i++ )
            (*this)[i] = x[i];
    }
}
```

Now, if `x` has a different size than the local vector, the application will immediately abort.
 Assertions and Optimisation

When using optimisation to translate the source code into machine code, assertions are usually omitted. This is an advantage and a disadvantage:

- one can put quite expensive tests into assertions, which are only executed when running the program without optimisation, e.g. in test mode,
- but the optimised program will not detect those errors.

Therefore, it should be used only if one can test all cases without optimisation and simply want to have a fast program for such known and tested cases.
Assertion Usage

The size of the logical expression in the assertion is not limited, but large expressions do not give the programmer the information, he seeks:

```c++
void mul_mat ( const real_t alpha, const matrix_t & A, const matrix_t & B, matrix_t & C )
{
    assert( A.get_nrows() == C.get_nrows() &&
            B.get_ncolumns() == C.get_ncolumns() &&
            A.get_ncolumns() == B.get_nrows() );
    ...
}
```

Although the function will only be executed, if the prerequisite for matrix multiplication are fulfilled, in case of an error, the programmer does not know, which matrix was wrong.
Assertion Usage

Alternatively the assertion can be split, resulting in more information if some incompatible matrices are used:

```c++
void mul_mat ( const real_t alpha, const matrix_t & A, const matrix_t & B, matrix_t & C )
{
    assert( A.get_nrows() == C.get_nrows() );
    assert( B.get_ncolumns() == C.get_ncolumns() );
    assert( A.get_ncolumns() == B.get_nrows() );
    ...
}
```
Assertion Conclusion

Assertions are suitable for

- non-critical programs or programs with a short runtime,
- for errors, which can be detected in a previous test mode of the program.

Assertions are not suitable for

- programs which shall not terminate or have a very long runtime,
- programs with many different input data.

Although not suitable for all programs:

Remark

*Assertions are better than nothing!*
By Return Value

In C, the error status of a function was typically reported by the return value, e.g. if non-zero, an error occurred (see `main`). This is not encouraged:

- Since the return code of every function has to be tested, the resulting source code is very complex:

```c
if ( f1( ... ) != 0 ) { ... } // Error
else
  { ... } // Ok

if ( f2( ... ) != 0 ) { ... } // Error
else
  { ... } // Ok

if ( f3( ... ) != 0 ) { ... } // Error
else
  { ... } // Ok
```

- One can simply ignore the return value of called functions, bypassing error handling.

- Local objects, e.g. records, cannot be deleted if an error occurs and a `return` is instructed.
Exceptions

C++ allows to **try** to execute portions of the source code and **catch** detected errors by special handlers. Furthermore, the error information is supplied in the form of an arbitrary datatype, thereby allowing to provide further information about the error. This mechanism is called *exception handling* and the error objects (or the errors) are *exceptions*.

The syntax for exception handling is:

```
try
  ⟨block⟩
catch (⟨error type⟩ ⟨error⟩ )
  ⟨block⟩
```

Here, ⟨error type⟩ can be any datatype and ⟨error⟩ is the corresponding error variable.
Throwing Exceptions

Example:

```cpp
vector_t x( 10 );
vector_t y( 20 );

try {
    y = x;
} catch ( VectorSizeErr & e ) {
    ... // handle error
}
```

Of course, one can not catch an error, if it is not *thrown*. C++ provides the keyword `throw` to generate an error object:

```cpp
vector_t & operator = ( const vector_t & x ) {
    if ( get_size() == x.get_size() )
        throw VectorSizeErr;
    ...
}
```
Exception Types

The type of the exception can be defined according to the needs of the programmer, no limitations are set. Example with a class:

```cpp
class VectorSizeErr
{
public:
    const char * what () const
    {
        return "vector sizes differ";
    }
};
```

Here, only a simple information is provided about the type of the error. The error handler could therefore simply print this information:

```cpp
try { y = x; }
catch ( VectorSizeErr & e )
{
    cout << e.what() << endl;
}
```
Exception Types

Alternatively, the error can be more described:

```cpp
class VectorSizeErr
{
    const char * err_function;

public:
    VectorSizeErr ( const char * err_fn )
    {
        err_function = err_fn;
    }

    const char * what () const { return "vector sizes differ"; }
    const char * where () const { return err_function; }
};
```
**Exception Types**

Now, the function where the error occurred is stored while throwing the exception:

```cpp
vector_t & operator= ( const vector_t & x )
{
    if ( get_size() == x.get_size() )
        throw VectorSizeErr( "vector::operator=" );
    ...
}
```

and the exception handler can use that information:

```cpp
try { y = x; }
catch ( VectorSizeErr & e )
{
    cout << "in function "
    << e.where()
    << " : "
    << e.what() << endl;
}
```
Multiple Exception Handlers

C++ permits to implement multiple exception handlers for a single try block:

```cpp
try {
    y = x;
    x[30] = 1.0;  // throws ArrayBoundErr
}
catch ( VectorSizeErr & e )
{
    ...
}
catch ( ArrayBoundErr & e )
{
    ...
}
```

If no exception handler is implemented for a specific exception type, it will be handled by the default handler implemented by C++. By default, this handler aborts the program.
General Exception Handlers

To catch all exceptions with a single handler, the following construct is allowed:

```cpp
try
{
    y = x;
    x[30] = 1.0;
}
catch (...)
{
    cout << "exception occurred" << endl;
}
```

By specifying `...`, all exceptions are caught. Of course, no further information is then available about the type of error. The general exception handler can be combined with other handlers, thereby providing a fallback in the case of an unexpected exception.
Exceptions and Functions

For a C++ function one can define the exception types the function and all directly or indirectly called functions can throw by using

\[ \langle \text{function header} \rangle \ \textbf{throw}( \langle \text{exception list} \rangle ); \]

e.g.:

```c++
void mul_mat ( ... ) \textbf{throw}( \text{MatrixSizeErr, ArrayBoundErr} );
```

Here, `mul_mat` is expected to throw `MatrixSizeErr` or `ArrayBoundErr`, which can be caught by a handler. All other exceptions will cause the program to abort. The exception list can also be empty:

```c++
void f ( ... ) \textbf{throw}();
```

in which case the function is expected to not throw an exception at all.
Predefined Exceptions

Some exceptions are already defined by the C++ library, e.g.

- **bad_alloc**: thrown by `new` if no memory is left to serve the allocation request
- **bad_exception**: thrown, if no exception handler is found for a previously thrown exception.

These exceptions are defined in the module `exception` of the `std` namespace.
Error Handling

Rethrow an Exception

A caught exception can be thrown again by the exception handler, thereby forwarding the handling of the error to another exception handler:

```c++
try {
   ...
}
catch ( ArrayBoundErr & e ) {
   ...
   throw; // rethrow exception
}
```

Remark

*The instruction `throw;` is only allowed in an exception handler.*
Stack Unwinding

Suppose that an error occurs inside a complicated recursive function, which allocates many variables, e.g.

```cpp
void f ( ... )
{
    record1_t r1;
    ...
    f( ... );
    ...
    record2_t r2;
    ...
    f( ... );
    ...
}
```

If the error is thrown in the form of an exception, all of these record types will be automatically deallocated. This is known as *stack unwinding*. This mechanism ensures, that no memory is left allocated in the case of an error.
Error Handling

Stack Unwinding

**Remark**

*Unfortunately, this does not hold for objects allocated by* `new`. *But that can be fixed (see later).*
Exceptions: Conclusion

Exceptions are superior to all other forms of error handling, e.g.

- they do not interfere with the normal algorithm like the usage of return values,
- the program does not need to terminate as with assertions,
- specific handling can be implemented for specific errors,
- the cleanup of record objects is provided,
- etc.

Hence:

**Coding Principle No. 27**

*Use exceptions for all error handling.*

In the simplest case, implement the `throw` instructions for all errors and wrap your main function in a `try-catch` construct.
Standard Template Library
**C++ and STL**

The standard library of C++, e.g. the standard set of functions and types, is provided by the *Standard Template Library* or *STL* for short.

Most of these functions and types are implemented using generic programming, e.g. with templates.

The set of functionality in the STL includes

- dynamic arrays and associative arrays,
- lists and iterators,
- strings and complex numbers

**Remark**

*Unfortunately, although the individual functions and types are defined by the C++ standard, not all compilers support all features.*
Streams

Input and output in C++ is implemented in the form of streams. A C++ stream can be considered to be a sequential stream of bytes to which one can write or from which one can read data. Writing to a stream is provided by the operator `<<`:

```cpp
cout << 42 << endl;
```

The stream defined by the object `cout`, which is of type `std::ostream` and provides the function:

```cpp
class ostream {
    ...
    std::ostream & operator << ( const int n );
    ...
};
```

`endl` is a constant, which is equivalent to `'
'`, new line.
Output Streams

We also have already made use of the successive calling of the operator `<<`:

```
cout << 42 << 3.1415 << '5' << "Hello World" << endl;
```

For new datatypes, special stream functions have to written, which always follows the same scheme, e.g. for a vector:

```cpp
#include <ostream>

std::ostream &
operator << ( std::ostream & os, const vector_t & v )
{
    for ( size_t i = 0; i < v.get_size(); ++i )
        os << v[i] << endl;

    return os;
}
```
Output Streams

The corresponding stream output function for a matrix is declared as:

```cpp
std::ostream &
operator << ( std::ostream & os, const matrix_t & M);
```

**Remark**

*Remember to split declaration and implementation into header and source file or to use the inline keyword.*
Input Streams

Reading from a stream is provided by the operator `>>`:

```cpp
int n;
 cin >> n;
```

Here, `cin` is the equivalent to `cout` and represents the standard input, e.g. keyboard input, and is of type `std::istream`. Again, the operator `>>` can be used multiple times in a single statement:

```cpp
int n1, n2;
double f1;
float f2;
 cin >> n1 >> f1 >> n2 >> f2;
```

The order in which the elements are read from the stream is defined by the order at which they appear in the statement, e.g. `n1` first and `f2` last.
Input Streams

Input stream functions are provided for all basic datatypes. For user defined types, they have to be implemented similar to stream output:

```cpp
std::istream &
operator >> ( std::istream & is, vector_t & v )
{
    ... // vector input
    return is;
}
```
File Streams

The advantage of streams is, that one can switch between different output media, e.g. standard output or a file, and use the same functions. As an example, the output of a vector to a file looks like:

```cpp
#include <fstream>

... 

vector_t x;
std::ofstream file( "output" );

file << x << endl;
```

Here, `file` is an object of type `std::ofstream` provided by the module `fstream` for file output. The constructor of the stream expects the name of the file to write to.
File Streams

Similar, file input is used:

```cpp
vector_t x;
std::ifstream file( "input" )
file >> x;
```

Now, `file` is of type `std::ifstream` for file input, provided by the same module.

Closing an open file, being either an input or output file, is implemented by the member function `close`:

```cpp
file.close();
```
**File Streams**

Another member function of file streams is `is_eof`, which tests whether the end of the stream (or file) was reached:

```cpp
// read whole file
while ( ! file.is_eof() )
{
    char c;
    file >> c;
}
```

If a file is open or not can be tested with `is_open`:

```cpp
std::ifstream file( "input" );
if ( ! file.is_open() )
    throw "could not open file";
```
Stream Manipulators

The output format of data and, to some degree, also the input format of data can be modified by manipulator objects. These are provided by the file `iomanip`:

- **setw(n)**: set the minimal width of a data field in the stream to $n$, e.g. each output item will at least use $n$ characters (default: $n = 0$).

- **setprecision(n)**: set the precision of the number output to $n$ (default: $n = 6$),

- **setfill(c)**: set the character to be used to fill the remaining characters for an entry (default: whitespace),

```c++
#include <iomanip>
...
cout << setw( 8 ) << 5
    << setprecision( 4 ) << pi << endl;
    << setfill( '#' ) << "pi" << endl;
```
Stream Manipulators

fixed: use fixed point format, e.g. “100.432”,

scientific: use scientific notation, e.g. “1.00432e2”,

flush: immediately write all output to stream if buffers are used,

endl: write new line character.

```cpp
cout << fixed << 2.7182818284590452354 << endl
<< scientific << 2718.2818284590452354 << endl;
```
Containers and Iterators

Several *container* datatypes are implemented in the STL, e.g. lists, vectors and sets. All of these types are template types, hence the type of data that can be stored by container types is not fixed.

All containers in the STL implement the following functions:

- `insert( x )`: insert *x* into the container,
- `clear()`: remove all elements in container,
- `size()`: return number of elements in container.
- `empty()`: return *true*, if the container is empty and *false* otherwise.

**Remark**

*The complexity of *size* is not $O(1)$ for all container classes and depends in the implementation of the STL.*
Containers and Iterators

Furthermore, all of these container types can be accessed in the same way: through iterators.

Suppose that container is such a type from the STL. Then, container provides a subclass container::iterator, e.g.

```cpp
container cont;
container::iterator iter;
```

and functions begin and end to return iterators corresponding to the first and last element in the container, respectively.

```cpp
container::iterator first = cont.begin();
container::iterator last = cont.end();
```
Containers and Iterators

That can be used to iterate through the container in the same way as previously was done with arrays:

```cpp
for ( container::iterator iter = cont.begin();
     iter != cont.end();
     ++iter )
{
    ...
}
```

To access the actual data element to which the current iterator points, the dereference operator is overwritten by the iterator class:

```cpp
for ( container::iterator iter = cont.begin();
     iter != cont.end();
     ++iter )
{
    cout << *iter << endl;
}
```
Container Classes: Lists

Lists in C++ are implemented in list by the std::list template class:

```cpp
template <typename T>
class list
{
    ...
};
```

e.g.:

```cpp
#include <list>

...

std::list< int > list1;
std::list< double * > list2;
std::list< std::list< double > > list3;
```
Container Classes: Lists

In addition to the standard container functions, the following member functions are implemented in the list class:

- `front()`/`back()`: return first/last element in list,
- `push_front( x )`: insert \textit{x} at the front of the list,
- `push_back( x )`: insert \textit{x} at the end of the list,
- `pop_front()`: remove first element in list,
- `pop_back()`: remove last element in list,
Container Classes: Lists

Example:

```cpp
list< int > ilist;

ilist.push_front( 1 );
ilist.push_front( 2 );
ilist.push_back( 3 );
ilist.push_back( 4 );

for ( list<int>::iterator it = ilist.begin();
     it != ilist.end();
     ++it )
    cout << *it << endl;

int sum = 0;

while ( ! ilist.empty() )
{
    sum += ilist.front();
ilist.pop_front();
}
```
Container Classes: Vectors

A vector is a container class providing a dynamic array, which can grow or shrink with respect to the number of elements. Furthermore, a vector provides $O(1)$ access to elements in the array.

Again, vector is a template class:

```cpp
template<typename T>
class vector
{
    ...
};
```

implemented in the module vector.

```cpp
#include <vector>

...

std::vector<int> vector1;
std::vector<double *> vector2;
std::vector<std::vector<double>> vector3;
```
Container Classes: Vectors

To make resizing more efficient, vectors usually allocate more memory than necessary and do not immediately deallocate memory if the number of elements is reduced. The following functions are implemented in vector beside the standard container functions:

- `front() / back()`: return first/last element in vector,
- `resize( n )`: set new size for vector,
- `push_back( x )`: insert $x$ at the end of the vector,
- `pop_back()`: remove last element in vector,
- `operator [] (i)`: return i’th element of vector (read/write).

Remark

*By default, elements in the vector are initialised with 0, or the corresponding equivalent of the stored type, e.g. NULL.*
Container Classes: valarray

Whereas `vector` is a container suitable for changing the size of the container efficiently, in numerical applications the size is usually fixed. For that, the class `valarray` is provided:

```cpp
template <typename T>
class valarray {

...;

}
```

Examples:

```cpp
#include <valarray>

...;

std::valarray<int> array1(10);
std::valarray<double> array1(1000);
```
Container Classes: valarray

`valarray` provides all functions also defined by `vector` but furthermore, overloads all standard arithmetics operators, e.g. `+`, `-`, `*`, `/`, etc., with element wise versions. In addition to that, the class also provides the following methods:

- `min()`: return minimal element in array,
- `max()`: return maximal element in array,
- `sum()`: return sum of elements in array,
Container Classes: valarray

Example for a vector class in linear algebra without pointers:

```cpp
#include <valarray>

class vector_t
{
private:
    std::valarray< real_t > coeffs;

public:
    vector_t ( const size_t n ) { coeffs.resize( n ); }
    vector_t ( const vector_t & v );

    real_t operator [] ( const size_t i ) const
    { return coeffs[i]; }

    vector_t & operator = ( const vector_t & v )
    {
        coeffs = v.coeffs;
        return *this;
    }
};
```
Other Container Classes

Not described here are:

- **map**: class for an associative array, e.g. indexed by arbitrary types,

- **multimap**: similar to **map** but allows different elements with same index,

- **set**: stores unique elements, indexed by the elements themselves,

- **queue**: container for FIFO (first-in first-out) access,

- **stack**: container for LIFO (last-in first-out) access,

- **priority_queue**: a container type, where the first element is always the greatest with respect to some defined order.
Strings

Previous strings were implemented as null terminated character arrays with all their limitations. The STL also provides a string class which provides a much more convenient way of handling strings.

The class is implemented in the module `string` and is not a template class (although implemented with such):

```cpp
#include <string>
...

std::string str1;  // empty string
std::string str2( "Hello World" );  // preinitialised string

cout << str2 << endl;
```
**Strings**

The `std::string` class implements operators for standard string handling, e.g. assignment (`=`), concatenation (`+` and `+=`) and comparison (`==` and `!=`):

```cpp
std::string str1( "Hello" );
std::string str2( "World" );
std::string str3;

str3 = str1 + ' ' + str2;
str3 += " Example";

if ( str1 == str2 )
    str3 = str1;

if ( str1 != str2 )
    str3 = str2;
```
Strings

It also provides functions for string operations:

- `find( substr )`: return position of `substr` in the string or `string::npos` if not contained,
- `rfind( substr )`: similar to `find`, but start search at the end of the string,
- `substr( pos, n )`: return substring starting at position `pos` with length `n`,
- `c_str()`: return traditional character array for the string.

Remark

The pointer returned by `c_str` is actually the internal representation of the string. So do not delete that pointer!
Complex Numbers

As mentioned before, C++ does not support complex numbers as part of the language. Fortunately, there is an implementation of a class for complex numbers in the STL. The complex class is again a template class, thereby enabling single and double precision complex numbers:

```cpp
#include <complex>

std::complex< float > c1;
std::complex< double > c2;
```

Complex objects store the real and the imaginary part in two public member variables: re and im.

```cpp
c1.re = 1.0;
c1.im = -2.0;
```
Complex Numbers

The constructors for complex numbers provide initialisation of both data fields:

```cpp
std::complex< double > I( 0.0, 1.0 );
std::complex< double > r( 5.0 );       // == 5 + 0i
std::complex< double > z;             // == 0 + 0i
std::complex< double > i = I;
```

Furthermore, all standard arithmetical operators are provided and all standard mathematical functions are implemented:

```cpp
std::complex< double > c1, c2, c3;

c1 = c2 * c3;
c2 = 2.0 + c3;
c3 = std::sqrt( -3.0 * c1 + c2 / c3 );
```
Auto Pointers

When a block is left or an exception occurs in a function, all normal record variables are destroyed. Unfortunately, this is not true for record variables allocated by `new`, e.g.

```{lang-c++}
{ 
    vector_t x( 10 );
    vector_t * y = new vector_t( 10 );
}
```

// "x" is deallocated, but not "y"

The STL provides a solution for this problem: the class `auto_ptr`. An auto pointer is a class with a single data element, a pointer of the specified type:

```{lang-c++}
template <typename T>
class auto_ptr
{
private:
    T * ptr;
...
};
```
Auto Pointers

Furthermore, `auto_ptr` provides operators, such that a `auto_ptr` variable behaves like a standard pointer:

```cpp
#include <memory>
...

std::auto_ptr< vector_t > x( new vector_t( 10 ) );

x->fill( 2.0 );
cout << x->norm2() << endl;
```

One can even access the pointer stored in the auto pointer:

```cpp
vector_t * y = x.get();
```
Auto Pointers

But what makes auto pointers so special? Remember, that all normal record variables are automatically deleted at the end of a block. Auto pointers are *normal record variables*:

```cpp
std::auto_ptr< vector_t > x( new vector_t( 10 ) );
```

Hence, upon leaving the block, the destructor of `auto_ptr` is called. But the destructor of `auto_ptr` is implemented as follows:

```cpp
~autoptr () { delete ptr; }
```

Therefore, if the auto pointer is destroyed, so is the stored pointer.

```cpp
{ 
    vector_t x( 10 );
    auto_ptr< vector_t > y( new vector_t( 10 ) );

} // "x" and "y" are deallocated
```
Auto Pointers

The class auto_ptr also provides two other functions for handling the local pointer:

reset(ptr): Exchange the local pointer by ptr. If the previous pointer was not NULL, it will be deleted.

release(): Set the local pointer value to NULL and return the previous pointer, but do not delete it.

Especially release can be used to program exception safe:

```cpp
vector_t * f ( ... )
{
    auto_ptr<vector_t> v( new vector_t( 10 ) );

    ...

    return v.release(); // a previous exception would delete v
}
```
Class Inheritance
Class Inheritance

Inheritance
In an earlier section, generic programming was used to provide a single implementation of an algorithm for multiple types. There is another way to do that in C++: by using object oriented programming or OOP.
In OOP one defines a hierarchy of classes, connected via inheritance, sharing a set of functions, which then can be called for all members of the hierarchy.
As an example, we will consider matrices. Up to now we had:

- matrix_t: a dense matrix,
- sparsematrix_t: a sparse matrix using lists and pointers and
- crsmatrix_t: a sparse matrix using arrays.
Inheritance

All of these matrix types had similar functions:

```cpp
size_t get_nrows () const;
size_t get_ncolumns () const;

void fill ( const real_t f );
void scale ( const real_t f );
void add ( const real_t f, const matrix_t & x );

void mul_vec ( const real_t alpha, const vector_t & x, vector_t & y ) const;

real_t normF () const;
```

but also different functions:

```cpp
// sparse matrices
size_t get_nnonzero () const;

// dense matrices
real_t operator [] ( const size_t i, const size_t j ) const;
```
Class Inheritance

Base Classes

Now, let us define a general matrix type, with only the set of common functions and data to all other matrix types:

```cpp
class matrix_t {
private:
    size_t nrows, ncolumns;
public:
    matrix_t ( const size_t n, const size_t m );
    matrix_t ( const matrix_t & M );

    size_t get_nrows () const { return nrows; }
    size_t get_ncolumns () const { return ncolumns; }

    void fill ( const real_t f );
    void scale ( const real_t f );
    void add ( const real_t f, const matrix_t & x );
    void mul_vec ( const real_t alpha, const vector_t & x, vector_t & y ) const;
    real_t normF () const;
};
```

This class is the start of the inheritance hierarchy, a so called base class.
Base Classes

Although the base class defines all functions that can be used with a general matrix, it can not provide the corresponding implementation since no data is provided. Therefore, most functions, which are called methods in the terminology of OOP, are actually empty, i.e. have no body.

In C++ this can be define by using

\[ \langle \text{function header} \rangle = 0; \]

\[ \text{e.g.} \]

```cpp
void fill ( const real_t f ) = 0;
```

Such methods are called abstract. Classes with abstract methods are also called abstract and can not be instantiated, e.g. one can not define objects of that type.
Class Inheritance

Base Classes

The base class for matrices now looks like:

```cpp
class matrix_t {
private:
  size_t nrows, ncolumns;
public:
  matrix_t ( const size_t n, const size_t m );
  matrix_t ( const matrix_t & M );

  size_t get_nrows () const { return nrows ;}
  size_t get_ncolumns () const { return ncolumns ;}

  void fill ( const real_t f ) = 0;
  void scale ( const real_t f ) = 0;
  void add ( const real_t f, const matrix_t & x ) = 0;
  void mul_vec ( const real_t alpha, const vector_t & x, const vector_t & y ) const = 0;
  real_t normF () const = 0;
};
```
Derived Classes

To really work with matrices, functionality has to be provided. Since that is specific to specific matrix formats, one needs to define new classes for each special matrix type. But, since all matrix types can also be considered to be general matrix, they are matrices in the end, this should also be described in C++. For that, the new classes are derived from the base class:

```cpp
class densematrix_t : matrix_t {
    ...
};

class sparsematrix_t : matrix_t {
    ...
};
```

Here, `matrix_t` is provided as a base class in the definition of the derived classes using `:`.
Derived Classes

A derived class inherits all methods and variables of the base class, e.g. the variables `nrows` and `ncolumns` and the methods `get_nrows` and `get_ncolumns`. Objects of the derived classes can therefore use all methods which were already implemented in the base class without providing an implementation:

```cpp
densematrix_t M;

cout << M.get_nrows() << " x " << M.get_ncolumns() << endl;
```

Abstract methods can not be called.
Derived Classes

The derived classes now need to provide functionality, e.g.

```cpp
class densematrix_t : matrix_t {
private:
    std::valarray< real_t > coeffs;

public:
    ...  
    void scale ( const real_t f );
    ...
};

void densematrix_t::scale ( const real_t f )
{
    coeffs *= f;
}
```

They overload the corresponding methods of the base class.
Derived Classes

The same can be done for sparse matrices:

```cpp
class sparsematrix_t : matrix_t {
private:
    std::valarray< size_t > rowptr;
    std::valarray< size_t > colind;
    std::valarray< real_t > coeffs;

public:
    ...
    void scale ( const real_t f );
    ...
};

void sparsematrix_t::scale ( const real_t f )
{
    coeffs *= f;
}
```
Polymorphism

Now, if objects of each derived class are created:

```cpp
densematrix_t M( 10, 10 );
sparsematrix_t S( 10, 10, 28 );
```

the overloaded methods can be called like for any other class previously presented:

```cpp
M.scale( -1.0 );
S.scale( 10.0 );
```

Here, OOP comes into play:

> Every object of a derived class is also an object of the base class.

```cpp
matrix_t * A;
A = & M;  // A now points to the dense M
A = & S;  // A now points to the sparse S
```
Polymorphism

But what happens when one calls

```cpp
A = & M; A->scale( 1.5 );
A = & S; A->scale( 0.5 );
```

Here, although `A` is a pointer to a base class, the object to which it points is a derived class and OOP ensures, that the overloaded methods are called. This is called **polymorphism**. So, the previous instructions are equivalent to

```cpp
M.scale( 1.5 );
S.scale( 0.5 );
```
Polymorphism

This allows us to define a general algorithm, e.g. CG iteration, to work only with the base class:

```cpp
void cg ( const matrix_t & A, vector_t & x, const vector_t & b )
{
    vector_t r( b ), p, a( x.get_size() );

    A.mul_vec( -1.0, x, r ); p = r;

    for ( size_t it = 0; it < 1000; it++ ) {  
        real_t lambda;

        a.fill( 0.0 );
        A.mul_vec( 1.0, p, a );
        lambda = dot( r, p ) / dot( a, p );
        x.add( lambda, p );
        r.add( -lambda, a );
        p.scale( -dot( r, a ) / dot( a, p ) );
        p.add( 1.0, r );

        if ( r.norm2() < 1e-10 )
            break;
    }
}
```
Polymorphism

But since all objects of derived classes are also objects of the base class, the general algorithm can be used for these derived classes too:

```cpp
densematrix_t D( n, n );
vector_t x( n );
vector_t b( n );

cg( D, x, b );

sparsematrix_t S( n, n, nnonzero );
cg( S, x, b );
```
Virtual Methods

For polymorphism to actually work in C++, one thing has to be added to the definition of methods in classes. Consider

```cpp
class matrix_t {
    ...
    void nullify () { scale( 0.0 ); }
}
```

Here, the method `nullify` in the base class `matrix_t` makes use of the method `scale`, which is only implemented in a derived class. Such functions in a base class would not call the function in the derived class:

```cpp
densematrix_t M( 10, 10 );
M.nullify();  // does not call densematrix_t::scale( 0.0 )
```
Virtual Methods

For polymorphism to work in such situations, these functions have to be virtual:

```cpp
class matrix_t {
private:
    size_t nrows, ncolumns;
public:
    matrix_t ( const size_t n, const size_t m );
    matrix_t ( const matrix_t & M );

    size_t get_nrows () const { return nrows };  // get_nrows is a virtual function
    size_t get_ncolumns () const { return ncolumns };  // get_ncolumns is a virtual function

    virtual void fill ( const real_t f ) = 0;  // fill is a virtual function
    virtual void scale ( const real_t f ) = 0;  // scale is a virtual function
    virtual void add ( const real_t f, const matrix_t & x ) = 0;  // add is a virtual function
    virtual void mul_vec ( const real_t alpha, const vector_t & x, vector_t & y ) const = 0;  // mul_vec is a virtual function

    virtual real_t normF () const = 0;  // normF is a virtual function
};
```
Virtual Methods

The same holds for derived classes:

class densematrix_t : matrix_t {
    ...
    virtual void scale ( const real_t f );
    ...
};

class sparsematrix_t : matrix_t {
    ...
    virtual void scale ( const real_t f );
    ...
};

Remark

The keyword virtual is only necessary in the method declaration, not the implementation.
Virtual Methods

Now, the call to `scale(0.0)` in the function `nullify` of the base class will be handled by the corresponding methods in the derived classes:

```cpp
densematrix_t M(10, 10);
M.nullify();  // call to densematrix_t::scale(0.0)
```

Remark

*If a class has a virtual function, it also must have a virtual destructor. Constructors can not be virtual and polymorphism does not work in constructors.*

Remark

*Abstract methods must also be virtual.*
Extending the Hierarchy

In the beginning we had two different classes for a sparse matrix but have implemented only the CRS version. Instead of that, `sparsematrix_t` should only serve as a base class for sparse matrices. Hence, it should only implement common functions and data:

```cpp
class sparsematrix_t : matrix_t
{
private:
    size_t nnonzero;

public:
    sparsematrix_t ( const size_t n, const size_t m, const size_t nnzero );

    size_t get_nnonzero () const { return nnonzero; }
}
```

Note that it does not overload any method from `matrix_t` and is therefore also an abstract class.
Extending the Hierarchy

The special sparse matrix types are then derived from the base sparse matrix class:

```cpp
class crssparsematrix_t : sparsematrix_t {
private:
    std::valarray< size_t > rowptr, colind;
    std::valarray< real_t > coeffs;
public:
    ...
    virtual void mul_vec ( ... ) const;
    ...
};

class ptrsparsematrix_t : sparsematrix_t {
private:
    std::valarray< entry_t > entries;
public:
    ...
    virtual void mul_vec ( ... ) const;
    ...
};
```
Extending the Hierarchy

The complete class hierarchy now is:

```
  matrix_t
  /  \   
 densematrix_t sparsematrix_t
    \   /
     crssparsematrix_t ptrsparsematrix_t
```

Due to inheritance, each object of the new classes `crssparsematrix_t` and `ptrsparsematrix_t` is not only an object of `sparsematrix_t`, but also of `matrix_t`:

```cpp
crssparsematrix_t S( 10, 10, 28 );
matrix_t * A = & S;
A->scale( 5.0 ); // call to crssparsematrix_t::scale
cg( S, x, b );
```
Visibility

Remember the visibility keywords **public**, **protected** and **private** for variables and functions in a record or class, respectively. The last only differ in the context of inheritance:

*One can access **protected** variables or functions of base class in a derived class but not **private** members.*

```cpp
class densematrix_t
{
    ...
    void print ()
    {
        // Error: nrows and ncolumns are private in matrix_t
        cout << nrows << " x " << ncolumns << endl;
    }
}
```
Visibility

Visibility can also be defined during inheritance. The previous examples always assumed:

```cpp
class densematrix_t : public matrix_t
{
    ...
};

class sparsematrix_t : public matrix_t
{
    ...
};

class crssparsematrix_t : public sparsematrix_t
{
    ...
};

class ptrsparsematrix_t : public sparsematrix_t
{
    ...
};
```
Visibility

One can also define **private** inheritance:

```cpp
class densematrix_t : private matrix_t
{
    ...
};

class sparsematrix_t : private matrix_t
{
    ...
};
```

The difference is, that all methods in the base class are now private in the derived class and can **not** be called from outside.
Class Inheritance

Constructors

A constructor of a base class can also be called in the constructor of a derived class:

```cpp
class densematrix_t : public matrix_t
{
    ...
    densematrix_t ( const size_t n, const size_t m )
        : matrix_t( n, m )
    {
        coeffs.resize( n*m );
    }
    ...
}
```

By default, the default constructor of the base class is called.

Remark

Constructors are not inherited, they have to be implemented in each derived class.
Class Inheritance

**Calling overloaded Functions**

Methods of a base class can also be called in the derived class even though they were overloaded:

```cpp
class densematrix_t : public matrix_t
{
    ...
    virtual void nullify ()
    {
        matrix_t::nullify();   // call nullify of base class
        ...
    }
    ...
}
```

All methods in all base classes are available for that, not only the direct ancestor.
Type Casting

We have discussed type casting operators, e.g. \texttt{const\_cast}, \texttt{static\_cast} and \texttt{dynamic\_cast}. Especially the last one is important for classes, as it uses \textit{runtime type information} and respects class hierarchy:

```cpp
densematrix\_t * M = \texttt{new} densematrix\_t( 10, 10 );
crssparseset\_t * S1 = \texttt{new} crssparseset\_t( 10, 10, 28 );
ptrsparseset\_t * S2 = \texttt{new} ptrsparseset\_t( 10, 10, 28 );

matrix\_t * A = M;

// cast a pointer of a base class to a derived class
densematrix\_t * M2 = \texttt{dynamic\_cast}< densematrix\_t * >( A );
A = S1;

// cast a pointer of a base class to a derived class
crssparseset\_t * S3 = \texttt{dynamic\_cast}< crssparseset\_t * >( A );
A = S2;
S3 = \texttt{dynamic\_cast}< crssparseset\_t * >( A ); // returns NULL
M2 = \texttt{dynamic\_cast}< densematrix\_t * >( A ); // returns NULL
```
Type Casting

A dynamic cast will only return the requested pointer value, i.e. perform the cast, if the object to which the pointer directs is of that type, e.g. explicitly of that type or implicitly due to inheritance. Otherwise a NULL pointer is returned.

Remark

The complexity of a dynamic cast is not \( \mathcal{O}(1) \), because the class hierarchy has to be parsed up to the specific datatype.

Coding Principle No. 28

Use dynamic casts for type casting of derived datatypes as much as possible.
Appendix
Coding Principles

1. choice of floating point type
2. variable names
3. RAII
4. `const` usage
5. pointer init to `NULL`
6. float equality test
7. parentheses
8. implicit casts
9. default case in `switch`
10. `const` function arguments
11. return in function
12. function naming
13. functions and minimal evaluation
14. array boundaries
15. pointer reset to `NULL`
16. deallocate pointer
17. string termination
18. type naming
19. header encapsulation
20. global variables
21. anonymous namespaces
22. default copy constructor
Coding Principles

23 data access in a record
24 operator overloading
25 default copy operator
26 detecting errors
27 use exceptions
28 dynamic casts
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