Materialsammlung - generische Programmierung

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Inhaltsverzeichnis

Vorbemerkungen:

Literatur

- B. Stroustrup: Einführung in die Programmierung mit C++, Pearson 2010, München, Kapitel 19.3 ff.
- R. Grimm: C++11, Der Leitfaden zum neuen Standard, Pearson 2011
- D. Vandervoorde, N. M. Josuttis: C++ Templates — The Complede Guide, Pearson 2003, Boston
- Scott Meyers: Effective STL, Addison-Wesley 2001, Indianapolis,
- D. Abrahams, A. Gurtovoy: C++ Template Metaprogramming, Addison Wesley 2005
- Björn Karlsson: Beyond the C++ Standard Library — An Introduction to Boost, Pearson 2006, Boston
- B. Schäling: The Boost C++ Libraries, XML Press 2011
- A. Alexandrescu: Modern C++ Design — Generic Programming and Design Patterns Applied, Pearson 2001, Indianapolis
- Sumant Tambe: More C++ Idioms, WikiBooks 2009

Einordnung in Programmierparadigmen
imperativ, objektbasiert, objektorientiert, funktional, generisch, ...

Die Entwicklung der Aussagekraft der formalen generischen Parameter

- von einfallslosen Parameternamen wie `class T1, class T2, ...`
  vergleiche http://www.cplusplus.com/doc/tutorial/templates/
- über semantisch inhaltsvolle Parameternamen wie `typename InputIterator1, typename InputIterator2, typename NumericT, ...`
  vergleiche http://www.iue.tuwien.ac.at/phd/heinzl/node32.html#SECTION010223000000000000000
- hin zur Nennung der Requirements an die zur Instantiierung benutzbaren aktuellen Parameter wie `T shall meet the requirements of CopyConstructible and CopyAssignable types`

(Seite 972 von http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2011/n3242.pdf) mit der Erläuterung:

Table 33 — DefaultConstructible requirements [**defaultconstructible**]

Expression	Post-condition
`T t;`	object `t` is default-initialized
`T u{};`	object `u` is value-initialized
`T()` `T{}`	a temporary object of type `T` is value-initialized

Table 34 — MoveConstructible requirements [**moveconstructible**]

Expression	Post-condition
`T u(rv);`	`u` is equivalent to the value of `rv` before the construction
`T(rv)`	`T(rv)` is equivalent to the value of `rv` before the construction
[*Note:* `rv` remains a valid object. Its state is unspecified — *end note*]	

Table 35 — CopyConstructible requirements (in addition to MoveConstructible) [**copyconstructible**]

Expression	Post-condition
`T u(v);`	the value of `v` is unchanged and is equivalent to `u`
`T(v)`	the value of `v` is unchanged and is equivalent to `T(v)`

Table 36 — MoveAssignable requirements [**moveassignable**]

Expression	Return type	Return value	Post-condition
`t = rv`	`T&`	`t`	`t` is equivalent to the value of `rv` before the assigment
[*Note:* `rv` remains a valid object. Its state is unspecified. — *end note*]			

(Seite 431f. des Drafts)

http://www.heise.de/newsticker/meldung/C-11-einstimmig-als-Standard-angenommen-1322726.h

C++11 ohne „Concepts“
http://en.wikipedia.org/wiki/C%2B%2B11

... aber dokumentatorisch z.B. im STL-Manual benutzt:
accumulate

TR1 - ein „Zwischenstandard“ für die C++-Bibliothek
TR1
http://en.wikipedia.org/wiki/Technical_Report_2#Mathematical_special_functions

Was hätten Concepts gebracht?
http://en.wikipedia.org/wiki/Concepts_(C%2B%2B)

Ziele des Draft-Desings
http://www.artima.com/cppsource/cpp0x.html

TR2 call for proposals

http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2005/n1810.html

Welche Eigenschaften von C++11 beherrscht g++ schon?
C++0x/C++11 Support in GCC

Typsicherheit ... bei generischen Konstrukten
http://de.wikipedia.org/wiki/Typsicherheit

http://en.wikipedia.org/wiki/Type_safety

Typsichere generische Typen in C++

Irreführende Monster-Fehlermeldungen bei Instanziierung generischer C++-Konstrukte

Hinweise zur Fehlermeldungsqualität der C++ Template-Programmierung

Generic Programming Glossary
Glossar des generischen Progrmmierens
Verallgemeinerung/Lifting konkreter Implementierungen ähnlicher Algorithmen

neue C++11 Standard Library
C++ standard library changes
C++ Reference
Standard Template Library Manual

Generic Programming: Libraries

Metaprogramming
Metaprogramming
$Factorial < 4 >:: value$

1 Generische Programmierung

1.1 Was ist generische Programmierung?

http://pdfcast.org/pdf/the-java-generic-programming-system
http://www.boost.org/community/generic_programming.html
http://en.wikipedia.org/wiki/Generic_programming

1.2 Beispiel einer generische Funktion mit einem generischen Parameter

```
#include <iostream>
template <typename T>
/*
 * Requirements: T muss einen Kopierkonstruktor haben,
 *               T muss einen Zuweisungsoperator zu T haben.
 */
void swap(T& a, T& b)
{
   T  old_a(a);

   a = b;
   b = old_a;
}
int main(){
   int k(1);
   int l(5);
   std::cout << k << " " << l << std::endl;
   swap(k,l);
   std::cout << k << " " << l << std::endl;
   double d1(3.1415);
   double d2(15.1055);
   std::cout << d1 << " " << d2 << std::endl;
   swap(d1, d2);
   std::cout << d1 << " " << d2 << std::endl;
}
```

1.3 Benutzung von `std::swap()`

```cpp
#include <iostream>
using std::cout;

int main(){

  int i = 5;
  int j = 6;
  cout << "i = " << i << "; j = " << j << std::endl;
  std::swap(i,j);
  cout << "i = " << i << "; j = " << j<< std::endl;

  int a[2] = {2, 3};
  int b[2] = {12, 13};
  cout << a[0] << " " << a[1] << std::endl;
  cout << b[0] << " " << b[1] << std::endl;
  std::swap(a, b);
  cout << a[0] << " " << a[1] << std::endl;
  cout << b[0] << " " << b[1] << std::endl;
}
```

unter Benutzung der „gerneral utilities library“ (Kapitel 20 des C++-Drafts):

20.2.2 swap **[utility.swap]**

`template<class T> void swap(T& a, T& b) noexcept(`*`see below`*`);`

1 *Remark:* The expression inside noexcept is equivalent to:

```
is_nothrow_move_constructible<T>::value &&
is_nothrow_move_assignable<T>::value
```

2 *Requires:* Type `T` shall be `MoveConstructible` (Table 20) and `MoveAssignable` (Table 22).

3 *Effects:* Exchanges values stored in two locations.

Zu den Requirements an den generischen Parameter siehe `[utility.arg.requirements]`:

Table 20 — `MoveConstructible` requirements **[moveconstructible]**

Expression	Post-condition
`T u = rv;`	u is equivalent to the value of `rv` before the construction
`T(rv)`	`T(rv)` is equivalent to the value of `rv` before the construction
`rv`'s state is unspecified [*Note:* `rv` must still meet the requirements of the library component that is using it. The operations listed in those requirements must work as specified whether `rv` has been moved from or not. — *end note*]	

Table 21 — `CopyConstructible` requirements (in addition to MoveConstructible) **[copyconstructible]**

Expression	Post-condition
`T u = v;`	the value of `v` is unchanged and is equivalent to `u`
`T(v)`	the value of `v` is unchanged and is equivalent to `T(v)`

Table 22 — `MoveAssignable` requirements **[moveassignable]**

Expression	Return type	Return value	Post-condition
`t = rv`	`T&`	`t`	`t` is equivalent to the value of `rv` before the assignment
`rv`'s state is unspecified. [*Note:* `rv` must still meet the requirements of the library component that is using it. The operations listed in those requirements must work as specified whether `rv` has been moved from or not. — *end note*]			

Table 23 — `CopyAssignable` requirements(in addition to MoveAssignable) **[copyassignable]**

Expression	Return type	Return value	Post-condition
`t = v`	`T&`	`t`	`t` is equivalent to `v`, the value of `v` is unchanged

Die `swappable.requirements` findet man in Aschnitt 20.2.2 des Drafts. Fassen Sie sie in eigenen Worten zusammen.

SGI-Manual: swap-Parameter Assignable
automatically generated C++98-Class-members

1.4 Einsatzgebiete und Beispielrepositorien für generische Konstrukte: die STL, ...

http://www.sgi.com/tech/stl/
generische Java-Datentypen
Die Boost C++-Bibliotheken

1.5 Instanzen generischer Objekte

1.5.1 Objekt-Dateien: wo sind welche Instanzen meiner generischen Objekte (nm und c++filt)?

What goes into an object file?
http://en.wikipedia.org/wiki/Executable_and_Linkable_Format
http://www.ibm.com/developerworks/aix/library/au-unixtools/index.html

GCC Compilation Process

Template Compilation Models
extern template in C++11

ldd und was es zeigt:

```
> ls
swap1.cpp
> cat swap1.cpp
```

```
#include <iostream>
template <typename T>
/*
 * Requirements: T muss einen Kopierkonstruktor haben,
 *               T muss einen Zuweisungsoperator zu T haben.
 */
void swap(T& a, T& b)
{
   T  old_a(a);

   a = b;
   b = old_a;
}
int main(){
...
   int k(1);
   int l(5);
   swap(k,l);
...
}
```

```
> make swap1
g++  -g -I. -I/home/username/include   swap1.cpp   -o swap1
```

```
> ldd ./swap1
        linux-vdso.so.1 =>  (0x00007fffe1b0d000)
        libstdc++.so.6 => /usr/lib64/libstdc++.so.6 (0x00007fa6005e9000)
        libm.so.6 => /lib64/libm.so.6 (0x00007fa600392000)
        libgcc_s.so.1 => /lib64/libgcc_s.so.1 (0x00007fa60017c000)
        libc.so.6 => /lib64/libc.so.6 (0x00007fa5ffe1c000)
        /lib64/ld-linux-x86-64.so.2 (0x00007fa6008f3000)
```

Beim Programmlauf werden nacheinander die „shared object“-Bibliotheken geöffnet und nötige Teile in das auszuführende Binary eingebunden:

```
> strace ./swap1
execve("./swap1", ["./swap1"], [/* 66 vars */]) = 0
brk(0)                                  = 0x602000
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f17e3146000
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY)      = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=335735, ...}) = 0
mmap(NULL, 335735, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f17e30f4000
close(3)                                = 0
open("/usr/lib64/libstdc++.so.6", O_RDONLY) = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0\260\305\5\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=1003544, ...}) = 0
mmap(NULL, 3182936, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f17e2c1f000
fadvise64(3, 0, 3182936, POSIX_FADV_WILLNEED) = 0
mprotect(0x7f17e2d0b000, 2093056, PROT_NONE) = 0
mmap(0x7f17e2f0a000, 40960, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0xeb000) = 0x7f17e2f0a000
mmap(0x7f17e2f14000, 82264, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7f17e2f14000
close(3)                                = 0
open("/lib64/libm.so.6", O_RDONLY)      = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0‘>\0\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=391908, ...}) = 0
mmap(NULL, 2449592, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f17e29c8000
fadvise64(3, 0, 2449592, POSIX_FADV_WILLNEED) = 0
mprotect(0x7f17e2a1e000, 2093056, PROT_NONE) = 0
mmap(0x7f17e2c1d000, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x55000) = 0x7f17e2c1d000
close(3)                                = 0
open("/lib64/libgcc_s.so.1", O_RDONLY)  = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0‘-\0\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=88544, ...}) = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f17e30f3000
mmap(NULL, 2184184, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f17e27b2000
fadvise64(3, 0, 2184184, POSIX_FADV_WILLNEED) = 0
mprotect(0x7f17e27c7000, 2093056, PROT_NONE) = 0
mmap(0x7f17e29c6000, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x14000) = 0x7f17e29c6000
close(3)                                = 0
open("/lib64/libc.so.6", O_RDONLY)      = 3
read(3, "\177ELF\2\1\1\0\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0\220\354\1\0\0\0\0\0"..., 832) = 832
fstat(3, {st_mode=S_IFREG|0755, st_size=1670469, ...}) = 0
mmap(NULL, 3537800, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7f17e2452000
fadvise64(3, 0, 3537800, POSIX_FADV_WILLNEED) = 0
mprotect(0x7f17e25a8000, 2097152, PROT_NONE) = 0
mmap(0x7f17e27a8000, 20480, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x156000) = 0x7f17e27a8000
mmap(0x7f17e27ad000, 19336, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7f17e27ad000
close(3)                                = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f17e30f2000
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f17e30f0000
arch_prctl(ARCH_SET_FS, 0x7f17e30f0720) = 0
mprotect(0x7f17e27a8000, 16384, PROT_READ) = 0
mprotect(0x7f17e29c6000, 4096, PROT_READ) = 0
```

```
mprotect(0x7f17e2c1d000, 4096, PROT_READ) = 0
mprotect(0x7f17e2f0a000, 32768, PROT_READ) = 0
mprotect(0x600000, 4096, PROT_READ)     = 0
mprotect(0x7f17e3147000, 4096, PROT_READ) = 0
munmap(0x7f17e30f4000, 335735)          = 0
fstat(1, {st_mode=S_IFCHR|0620, st_rdev=makedev(136, 2), ...}) = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7f17e3145000
write(1, "1 5\n", 41 5
)                   = 4
write(1, "5 1\n", 45 1
)                   = 4
write(1, "3.1415 15.1055\n", 153.1415 15.1055
)        = 15
write(1, "15.1055 3.1415\n", 1515.1055 3.1415
)        = 15
exit_group(0)                           = ?
```

Neben gcc, g++, as, ld, gprof und gdb/ddd sind die folgenden Tools von Interesse.

Die GNU-Binutils:

- nm
- objdump
- objcopy
- readelf
- strip
- size
- c++filt
- ar
- ranlib

```
> file ./swap1
./swap1: ELF 64-bit LSB executable, x86-64, version 1 (SYSV),
   dynamically linked (uses shared libs), for GNU/Linux 2.6.15, not stripped
> nm ./swap1
0000000000600e20 d _DYNAMIC
0000000000600fe8 d _GLOBAL_OFFSET_TABLE_
0000000000400a75 t _GLOBAL__I_main
0000000000400bd8 R _IO_stdin_used
                 w _Jv_RegisterClasses
0000000000400a35 t _Z41__static_initialization_and_destruction_0ii
0000000000400ab6 W _Z4swapIdEvRT_S1_
0000000000400a8a W _Z4swapIiEvRT_S1_
                 U _ZNSolsEPFRSoS_E@@GLIBCXX_3.4
```

```
                 U _ZNSolsEd@@GLIBCXX_3.4
                 U _ZNSolsEi@@GLIBCXX_3.4
                 U _ZNSt8ios_base4InitC1Ev@@GLIBCXX_3.4
                 U _ZNSt8ios_base4InitD1Ev@@GLIBCXX_3.4
0000000000601060 B _ZSt4cout@@GLIBCXX_3.4
                 U _ZSt4endlIcSt11char_traitsIcEERSt13basic_ostreamIT_T0_ES6_@@GLIBCXX_3.
0000000000601180 b _ZStL8__ioinit
                 U _ZStlsISt11char_traitsIcEERSt13basic_ostreamIcT_ES5_PKc@@GLIBCXX_3.4
0000000000600e00 d __CTOR_END__
0000000000600df0 d __CTOR_LIST__
0000000000600e10 D __DTOR_END__
0000000000600e08 d __DTOR_LIST__
0000000000400d40 r __FRAME_END__
0000000000600e18 d __JCR_END__
0000000000600e18 d __JCR_LIST__
0000000000601060 A __bss_start
                 U __cxa_atexit@@GLIBC_2.2.5
0000000000601050 D __data_start
0000000000400b90 t __do_global_ctors_aux
0000000000400850 t __do_global_dtors_aux
0000000000601058 D __dso_handle
                 w __gmon_start__
                 U __gxx_personality_v0@@CXXABI_1.3
0000000000600dec d __init_array_end
0000000000600dec d __init_array_start
0000000000400af0 T __libc_csu_fini
0000000000400b00 T __libc_csu_init
                 U __libc_start_main@@GLIBC_2.2.5
0000000000601060 A _edata
0000000000601188 A _end
0000000000400bc8 T _fini
0000000000400730 T _init
0000000000400800 T _start
000000000040082c t call_gmon_start
0000000000601170 b completed.7424
0000000000601050 W data_start
0000000000601178 b dtor_idx.7426
00000000004008c0 t frame_dummy
00000000004008e4 T main
```

... und mit demangled Symbolen:

```
nm ./swap1 | c++filt
0000000000600e20 d _DYNAMIC
```

```
0000000000600fe8 d _GLOBAL_OFFSET_TABLE_
0000000000400a75 t global constructors keyed to main
0000000000400bd8 R _IO_stdin_used
                 w _Jv_RegisterClasses
0000000000400a35 t __static_initialization_and_destruction_0(int, int)
0000000000400ab6 W void swap<double>(double&, double&)
0000000000400a8a W void swap<int>(int&, int&)
                 U std::basic_ostream<char, std::char_traits<char> >::operator<<(
                 U std::basic_ostream<char, std::char_traits<char> >::operator<<(
                 U std::basic_ostream<char, std::char_traits<char> >::operator<<(
                 U std::ios_base::Init::Init()@@GLIBCXX_3.4
                 U std::ios_base::Init::~Init()@@GLIBCXX_3.4
0000000000601060 B std::cout@@GLIBCXX_3.4
                 U std::basic_ostream<char, std::char_traits<char> >& std::endl<c
0000000000601180 b std::__ioinit
                 U std::basic_ostream<char, std::char_traits<char> >& std::operat
0000000000600e00 d __CTOR_END__
0000000000600df0 d __CTOR_LIST__
0000000000600e10 D __DTOR_END__
0000000000600e08 d __DTOR_LIST__
0000000000400d40 r __FRAME_END__
0000000000600e18 d __JCR_END__
0000000000600e18 d __JCR_LIST__
0000000000601060 A __bss_start
                 U __cxa_atexit@@GLIBC_2.2.5
0000000000601050 D __data_start
0000000000400b90 t __do_global_ctors_aux
0000000000400850 t __do_global_dtors_aux
0000000000601058 D __dso_handle
                 w __gmon_start__
                 U __gxx_personality_v0@@CXXABI_1.3
0000000000600dec d __init_array_end
0000000000600dec d __init_array_start
0000000000400af0 T __libc_csu_fini
0000000000400b00 T __libc_csu_init
                 U __libc_start_main@@GLIBC_2.2.5
0000000000601060 A _edata
0000000000601188 A _end
0000000000400bc8 T _fini
0000000000400730 T _init
0000000000400800 T _start
000000000040082c t call_gmon_start
0000000000601170 b completed.7424
0000000000601050 W data_start
```

```
0000000000601178 b dtor_idx.7426
00000000004008c0 t frame_dummy
00000000004008e4 T main
```

```
> c++filt -n _Z4swapIiEvRT_S1_
void swap<int>(int&, int&)
```

Vergleiche:
C++ name mangling
name mangling in Java
Getting the best from g++

```
> objdump -x swap1 | c++filt

swap1:     file format elf64-x86-64
swap1
architecture: i386:x86-64, flags 0x00000112:
EXEC_P, HAS_SYMS, D_PAGED
start address 0x00000000004007e0

Program Header:
    PHDR off    0x0000000000000040 vaddr 0x0000000000400040 paddr 0x0000000000400040 align 2**3
         filesz 0x00000000000001f8 memsz 0x00000000000001f8 flags r-x
  INTERP off    0x0000000000000238 vaddr 0x0000000000400238 paddr 0x0000000000400238 align 2**0
         filesz 0x000000000000001c memsz 0x000000000000001c flags r--
...
Dynamic Section:
  NEEDED               libstdc++.so.6
  NEEDED               libm.so.6
  NEEDED               libgcc_s.so.1
  NEEDED               libc.so.6
  INIT                 0x0000000000400720
  FINI                 0x0000000000400ba8
...
Version References:
  required from libc.so.6:
    0x09691a75 0x00 03 GLIBC_2.2.5
  required from libstdc++.so.6:
    0x08922974 0x00 02 GLIBCXX_3.4
Sections:
Idx Name          Size      VMA               LMA               File off  Algn
  0 .interp       0000001c  0000000000400238  0000000000400238  00000238  2**0
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  1 .note.ABI-tag 00000020  0000000000400254  0000000000400254  00000254  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  2 .note.SuSE    00000018  0000000000400274  0000000000400274  00000274  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  3 .note.gnu.build-id 00000024  000000000040028c  000000000040028c  0000028c  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  4 .hash         00000048  00000000004002b0  00000000004002b0  000002b0  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  5 .gnu.hash     00000030  00000000004002f8  00000000004002f8  000002f8  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  6 .dynsym       00000138  0000000000400328  0000000000400328  00000328  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  7 .dynstr       0000015e  0000000000400460  0000000000400460  00000460  2**0
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  8 .gnu.version  0000001a  00000000004005be  00000000004005be  000005be  2**1
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
  9 .gnu.version_r 00000040  00000000004005d8  00000000004005d8  000005d8  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 10 .rela.dyn     00000030  0000000000400618  0000000000400618  00000618  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 11 .rela.plt     000000d8  0000000000400648  0000000000400648  00000648  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 12 .init         00000018  0000000000400720  0000000000400720  00000720  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
```

```
 13 .plt          000000a0  0000000000400738  0000000000400738  00000738  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
 14 .text         000003c8  00000000004007e0  00000000004007e0  000007e0  2**4
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
 15 .fini         0000000e  0000000000400ba8  0000000000400ba8  00000ba8  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, CODE
 16 .rodata       00000006  0000000000400bb8  0000000000400bb8  00000bb8  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 17 .eh_frame_hdr 00000044  0000000000400bc0  0000000000400bc0  00000bc0  2**2
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 18 .eh_frame     00000104  0000000000400c08  0000000000400c08  00000c08  2**3
                  CONTENTS, ALLOC, LOAD, READONLY, DATA
 19 .ctors        00000018  0000000000600de0  0000000000600de0  00000de0  2**3
                  CONTENTS, ALLOC, LOAD, DATA
 20 .dtors        00000010  0000000000600df8  0000000000600df8  00000df8  2**3
                  CONTENTS, ALLOC, LOAD, DATA
...
25 .data         00000010  0000000000601048  0000000000601048  00001048  2**3
                  CONTENTS, ALLOC, LOAD, DATA
26 .bss          00000128  0000000000601060  0000000000601060  00001058  2**5
                  ALLOC
...
SYMBOL TABLE:
0000000000400238 l    d  .interp        0000000000000000              .interp
0000000000400254 l    d  .note.ABI-tag  0000000000000000              .note.ABI-tag
0000000000400274 l    d  .note.SuSE     0000000000000000              .note.SuSE
000000000040028c l    d  .note.gnu.build-id     0000000000000000              .note.gnu.build-id
00000000004002b0 l    d  .hash  0000000000000000              .hash
00000000004002f8 l    d  .gnu.hash      0000000000000000              .gnu.hash
0000000000400328 l    d  .dynsym        0000000000000000              .dynsym
0000000000400460 l    d  .dynstr        0000000000000000              .dynstr
00000000004005be l    d  .gnu.version   0000000000000000              .gnu.version
00000000004005d8 l    d  .gnu.version_r 0000000000000000              .gnu.version_r
0000000000400618 l    d  .rela.dyn      0000000000000000              .rela.dyn
0000000000400648 l    d  .rela.plt      0000000000000000              .rela.plt
0000000000400720 l    d  .init  0000000000000000              .init
0000000000400738 l    d  .plt   0000000000000000              .plt
00000000004007e0 l    d  .text  0000000000000000              .text
0000000000400ba8 l    d  .fini  0000000000000000              .fini
0000000000400bb8 l    d  .rodata        0000000000000000              .rodata
...
0000000000400a96  w    F .text  0000000000000032              void swap<double>(double&, double&)
...
0000000000400a6a  w    F .text  000000000000002c              void swap<int>(int&, int&)
0000000000601058 g       *ABS*  0000000000000000              _edata
00000000004008c4 g     F .text  0000000000000151              main
0000000000400720 g     F .init  0000000000000000              _init


> objdump -t swap1 | c++filt
swap1:     file format elf64-x86-64
SYMBOL TABLE:
0000000000400238 l    d  .interp        0000000000000000              .interp
0000000000400254 l    d  .note.ABI-tag  0000000000000000              .note.ABI-tag
0000000000400274 l    d  .note.SuSE     0000000000000000              .note.SuSE
000000000040028c l    d  .note.gnu.build-id     0000000000000000              .note.gnu.build-id
00000000004002b0 l    d  .hash  0000000000000000              .hash
00000000004002f8 l    d  .gnu.hash      0000000000000000              .gnu.hash
0000000000400328 l    d  .dynsym        0000000000000000              .dynsym
0000000000400460 l    d  .dynstr        0000000000000000              .dynstr
00000000004005be l    d  .gnu.version   0000000000000000              .gnu.version
00000000004005d8 l    d  .gnu.version_r 0000000000000000              .gnu.version_r
0000000000400618 l    d  .rela.dyn      0000000000000000              .rela.dyn
0000000000400648 l    d  .rela.plt      0000000000000000              .rela.plt
0000000000400720 l    d  .init  0000000000000000              .init
0000000000400738 l    d  .plt   0000000000000000              .plt
00000000004007e0 l    d  .text  0000000000000000              .text
```

```
0000000000400ba8 l    d  .fini  0000000000000000              .fini
0000000000400bb8 l    d  .rodata        0000000000000000              .rodata
0000000000400bc0 l    d  .eh_frame_hdr  0000000000000000              .eh_frame_hdr
0000000000400c08 l    d  .eh_frame      0000000000000000              .eh_frame
0000000000600de0 l    d  .ctors 0000000000000000              .ctors
0000000000600df8 l    d  .dtors 0000000000000000              .dtors
0000000000600e08 l    d  .jcr   0000000000000000              .jcr
0000000000600e10 l    d  .dynamic       0000000000000000              .dynamic
0000000000600fe0 l    d  .got   0000000000000000              .got
0000000000600fe8 l    d  .got.plt       0000000000000000              .got.plt
0000000000601048 l    d  .data  0000000000000000              .data
0000000000601060 l    d  .bss   0000000000000000              .bss
0000000000000000 l    d  .comment.SUSE.OPTs     0000000000000000              .comment.SUSE.OPTs
0000000000000000 l    d  .comment       0000000000000000              .comment
0000000000000000 l    d  .debug_aranges 0000000000000000              .debug_aranges
0000000000000000 l    d  .debug_pubnames        0000000000000000              .debug_pubnames
0000000000000000 l    d  .debug_info    0000000000000000              .debug_info
0000000000000000 l    d  .debug_abbrev  0000000000000000              .debug_abbrev
0000000000000000 l    d  .debug_line    0000000000000000              .debug_line
0000000000000000 l    d  .debug_str     0000000000000000              .debug_str
0000000000000000 l    d  .debug_loc     0000000000000000              .debug_loc
0000000000000000 l    d  .debug_pubtypes        0000000000000000              .debug_pubtypes
0000000000000000 l    d  .debug_ranges  0000000000000000              .debug_ranges
0000000000000000 l    df *ABS*  0000000000000000              init.c
0000000000000000 l    df *ABS*  0000000000000000              initfini.c
000000000040080c l     F .text  0000000000000000              call_gmon_start
0000000000000000 l    df *ABS*  0000000000000000              crtstuff.c
0000000000600de0 l     O .ctors 0000000000000000              __CTOR_LIST__
0000000000600df8 l     O .dtors 0000000000000000              __DTOR_LIST__
0000000000600e08 l     O .jcr   0000000000000000              __JCR_LIST__
0000000000400830 l     F .text  0000000000000000              __do_global_dtors_aux
0000000000601170 l     O .bss   0000000000000001              completed.5939
0000000000601178 l     O .bss   0000000000000008              dtor_idx.5941
00000000004008a0 l     F .text  0000000000000000              frame_dummy
0000000000000000 l    df *ABS*  0000000000000000              crtstuff.c
0000000000600df0 l     O .ctors 0000000000000000              __CTOR_END__
0000000000400d08 l     O .eh_frame      0000000000000000              __FRAME_END__
0000000000600e08 l     O .jcr   0000000000000000              __JCR_END__
0000000000400b70 l     F .text  0000000000000000              __do_global_ctors_aux
0000000000000000 l    df *ABS*  0000000000000000              initfini.c
0000000000000000 l    df *ABS*  0000000000000000              swap1.cpp
0000000000601180 l     O .bss   0000000000000001              std::__ioinit
0000000000400a15 l     F .text  0000000000000040              __static_initialization_and_destruction_0(int, int)
0000000000400a55 l     F .text  0000000000000015              global constructors keyed to main
0000000000000000 l    df *ABS*  0000000000000000              elf-init.c
0000000000600fe8 l     O .got.plt       0000000000000000              .hidden _GLOBAL_OFFSET_TABLE_
0000000000600ddc l       .ctors 0000000000000000              .hidden __init_array_end
0000000000600ddc l       .ctors 0000000000000000              .hidden __init_array_start
0000000000600e10 l     O .dynamic       0000000000000000              .hidden _DYNAMIC
0000000000601048  w      .data  0000000000000000              data_start
0000000000000000       F *UND*  0000000000000000              std::basic_ostream<char, std::char_traits<char> >::opera
0000000000000000       F *UND*  0000000000000000              std::basic_ostream<char, std::char_traits<char> >::opera
0000000000400b60 g     F .text  0000000000000002              __libc_csu_fini
00000000004007e0 g     F .text  0000000000000000              _start
0000000000000000  w      *UND*  0000000000000000              __gmon_start__
0000000000000000  w      *UND*  0000000000000000              _Jv_RegisterClasses
0000000000400ba8 g     F .fini  0000000000000000              _fini
0000000000000000       F *UND*  0000000000000000              std::ios_base::Init::Init()@@GLIBCXX_3.4
0000000000000000       F *UND*  0000000000000000              __libc_start_main@@GLIBC_2.2.5
0000000000000000       F *UND*  0000000000000000              __cxa_atexit@@GLIBC_2.2.5
0000000000400798       F *UND*  0000000000000000              std::ios_base::Init::~Init()@@GLIBCXX_3.4
0000000000000000       F *UND*  0000000000000000              std::basic_ostream<char, std::char_traits<char> >& std:
0000000000400bb8 g     O .rodata        0000000000000004              _IO_stdin_used
0000000000601048 g       .data  0000000000000000              __data_start
0000000000400a96  w    F .text  0000000000000032              void swap<double>(double&, double&)
0000000000601060 g     O .bss   0000000000000110              std::cout@@GLIBCXX_3.4
```

```
0000000000601050 g     O .data  0000000000000000              .hidden __dso_handle
0000000000600e00 g     O .dtors 0000000000000000              .hidden __DTOR_END__
0000000000400ad0 g     F .text  0000000000000089              __libc_csu_init
0000000000601058 g       *ABS*  0000000000000000              __bss_start
0000000000601188 g       *ABS*  0000000000000000              _end
0000000000000000       F *UND*  0000000000000000              std::basic_ostream<char, std::char_traits<char> >::operator<<(std::
00000000004007c8       F *UND*  0000000000000000              std::basic_ostream<char, std::char_traits<char> >& std::endl<char,
0000000000400a6a  w    F .text  000000000000002c              void swap<int>(int&, int&)
0000000000601058 g       *ABS*  0000000000000000              _edata
00000000004008c4 g     F .text  0000000000000151              main
0000000000400720 g     F .init  0000000000000000              _init
```

```
> readelf -s swap1 | c++filt

Symbol table '.dynsym' contains 13 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND std::basic_ostream<char, std::char_traits<char> >::operator<<(double)@GLIBCXX_3.4 (2)
     2: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND std::basic_ostream<char, std::char_traits<char> >::operator<<(int)@GLIBCXX_3.4 (2)
     3: 0000000000000000     0 NOTYPE  WEAK   DEFAULT  UND __gmon_start__
     4: 0000000000000000     0 NOTYPE  WEAK   DEFAULT  UND _Jv_RegisterClasses
     5: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND std::ios_base::Init::Init()@GLIBCXX_3.4 (2)
     6: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND __libc_start_main@GLIBC_2.2.5 (3)
     7: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND __cxa_atexit@GLIBC_2.2.5 (3)
     8: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND _ZStlsISt11char_traitsIcE@GLIBCXX_3.4 (2)
     9: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND std::basic_ostream<char, std::char_traits<char> >::operator<<(std::basic_ostream<char, std::char_t
    10: 00000000004007c8     0 FUNC    GLOBAL DEFAULT  UND _ZSt4endlIcSt11char_trait@GLIBCXX_3.4 (2)
    11: 0000000000400798     0 FUNC    GLOBAL DEFAULT  UND std::ios_base::Init::~Init()@GLIBCXX_3.4 (2)
    12: 0000000000601060   272 OBJECT  GLOBAL DEFAULT   27 std::cout@GLIBCXX_3.4 (2)

Symbol table '.symtab' contains 93 entries:
   Num:    Value          Size Type    Bind   Vis      Ndx Name
     0: 0000000000000000     0 NOTYPE  LOCAL  DEFAULT  UND
     1: 0000000000400238     0 SECTION LOCAL  DEFAULT    1
     2: 0000000000400254     0 SECTION LOCAL  DEFAULT    2
     3: 0000000000400274     0 SECTION LOCAL  DEFAULT    3
     4: 000000000040028c     0 SECTION LOCAL  DEFAULT    4
     5: 00000000004002b0     0 SECTION LOCAL  DEFAULT    5
     6: 00000000004002f8     0 SECTION LOCAL  DEFAULT    6
     7: 0000000000400328     0 SECTION LOCAL  DEFAULT    7
     8: 0000000000400460     0 SECTION LOCAL  DEFAULT    8
     9: 00000000004005be     0 SECTION LOCAL  DEFAULT    9
    10: 00000000004005d8     0 SECTION LOCAL  DEFAULT   10
    11: 0000000000400618     0 SECTION LOCAL  DEFAULT   11
    12: 0000000000400648     0 SECTION LOCAL  DEFAULT   12
    13: 0000000000400720     0 SECTION LOCAL  DEFAULT   13
    14: 0000000000400738     0 SECTION LOCAL  DEFAULT   14
    15: 00000000004007e0     0 SECTION LOCAL  DEFAULT   15
    16: 0000000000400ba8     0 SECTION LOCAL  DEFAULT   16
    17: 0000000000400bb8     0 SECTION LOCAL  DEFAULT   17
    18: 0000000000400bc0     0 SECTION LOCAL  DEFAULT   18
    19: 0000000000400c08     0 SECTION LOCAL  DEFAULT   19
    20: 0000000000600de0     0 SECTION LOCAL  DEFAULT   20
    21: 0000000000600df8     0 SECTION LOCAL  DEFAULT   21
    22: 0000000000600e08     0 SECTION LOCAL  DEFAULT   22
    23: 0000000000600e10     0 SECTION LOCAL  DEFAULT   23
    24: 0000000000600fe0     0 SECTION LOCAL  DEFAULT   24
    25: 0000000000600fe8     0 SECTION LOCAL  DEFAULT   25
    26: 0000000000601048     0 SECTION LOCAL  DEFAULT   26
    27: 0000000000601060     0 SECTION LOCAL  DEFAULT   27
    28: 0000000000000000     0 SECTION LOCAL  DEFAULT   28
    29: 0000000000000000     0 SECTION LOCAL  DEFAULT   29
    30: 0000000000000000     0 SECTION LOCAL  DEFAULT   30
    31: 0000000000000000     0 SECTION LOCAL  DEFAULT   31
    32: 0000000000000000     0 SECTION LOCAL  DEFAULT   32
    33: 0000000000000000     0 SECTION LOCAL  DEFAULT   33
    34: 0000000000000000     0 SECTION LOCAL  DEFAULT   34
    35: 0000000000000000     0 SECTION LOCAL  DEFAULT   35
    36: 0000000000000000     0 SECTION LOCAL  DEFAULT   36
    37: 0000000000000000     0 SECTION LOCAL  DEFAULT   37
    38: 0000000000000000     0 SECTION LOCAL  DEFAULT   38
    39: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS init.c
    40: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS initfini.c
    41: 000000000040080c     0 FUNC    LOCAL  DEFAULT   15 call_gmon_start
    42: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS crtstuff.c
    43: 0000000000600de0     0 OBJECT  LOCAL  DEFAULT   20 __CTOR_LIST__
    44: 0000000000600df8     0 OBJECT  LOCAL  DEFAULT   21 __DTOR_LIST__
    45: 0000000000600e08     0 OBJECT  LOCAL  DEFAULT   22 __JCR_LIST__
    46: 0000000000400830     0 FUNC    LOCAL  DEFAULT   15 __do_global_dtors_aux
    47: 0000000000601170     1 OBJECT  LOCAL  DEFAULT   27 completed.5939
    48: 0000000000601178     8 OBJECT  LOCAL  DEFAULT   27 dtor_idx.5941
    49: 00000000004008a0     0 FUNC    LOCAL  DEFAULT   15 frame_dummy
    50: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS crtstuff.c
    51: 0000000000600df0     0 OBJECT  LOCAL  DEFAULT   20 __CTOR_END__
    52: 0000000000400d08     0 OBJECT  LOCAL  DEFAULT   19 __FRAME_END__
    53: 0000000000600e08     0 OBJECT  LOCAL  DEFAULT   22 __JCR_END__
    54: 0000000000400b70     0 FUNC    LOCAL  DEFAULT   15 __do_global_ctors_aux
    55: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS initfini.c
    56: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS swap1.cpp
    57: 0000000000601180     1 OBJECT  LOCAL  DEFAULT   27 std::__ioinit
    58: 0000000000400a15    64 FUNC    LOCAL  DEFAULT   15 _Z41__static_initializati
    59: 0000000000400a55    21 FUNC    LOCAL  DEFAULT   15 global constructors keyed to main
    60: 0000000000000000     0 FILE    LOCAL  DEFAULT  ABS elf-init.c
    61: 0000000000600fe8     0 OBJECT  LOCAL  HIDDEN   25 _GLOBAL_OFFSET_TABLE_
    62: 0000000000600ddc     0 NOTYPE  LOCAL  HIDDEN   20 __init_array_end
    63: 0000000000600ddc     0 NOTYPE  LOCAL  HIDDEN   20 __init_array_start
    64: 0000000000600e10     0 OBJECT  LOCAL  HIDDEN   23 _DYNAMIC
    65: 0000000000601048     0 NOTYPE  WEAK   DEFAULT   26 data_start
    66: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND std::basic_ostream<char, std::char_traits<char> >::operator<<(double)@@GLIBCXX_3.4
    67: 0000000000000000     0 FUNC    GLOBAL DEFAULT  UND std::basic_ostream<char, std::char_traits<char> >::operator<<(int)@@GLIBCXX_3.4
    68: 0000000000400b60     2 FUNC    GLOBAL DEFAULT   15 __libc_csu_fini
    69: 00000000004007e0     0 FUNC    GLOBAL DEFAULT   15 _start
```

```
    70: 0000000000000000      0 NOTYPE  WEAK   DEFAULT  UND __gmon_start__
    71: 0000000000000000      0 NOTYPE  WEAK   DEFAULT  UND _Jv_RegisterClasses
    72: 0000000000400ba8      0 FUNC    GLOBAL DEFAULT   16 _fini
    73: 0000000000000000      0 FUNC    GLOBAL DEFAULT  UND std::ios_base::Init::Init()@@
    74: 0000000000000000      0 FUNC    GLOBAL DEFAULT  UND __libc_start_main@@GLIBC_
    75: 0000000000000000      0 FUNC    GLOBAL DEFAULT  UND __cxa_atexit@@GLIBC_2.2.5
    76: 0000000000400798      0 FUNC    GLOBAL DEFAULT  UND std::ios_base::Init::~Init()@@
    77: 0000000000000000      0 FUNC    GLOBAL DEFAULT  UND _ZStlsISt11char_traitsIcE
    78: 0000000000400bb8      4 OBJECT  GLOBAL DEFAULT   17 _IO_stdin_used
    79: 0000000000601048      0 NOTYPE  GLOBAL DEFAULT   26 __data_start
    80: 0000000000400a96     50 FUNC    WEAK   DEFAULT   15 void swap<double>(double&, double&)
    81: 0000000000601060    272 OBJECT  GLOBAL DEFAULT   27 std::cout@@GLIBCXX_3.4
    82: 0000000000601050      0 OBJECT  GLOBAL HIDDEN   26 __dso_handle
    83: 0000000000600e00      0 OBJECT  GLOBAL HIDDEN   21 __DTOR_END__
    84: 0000000000400ad0    137 FUNC    GLOBAL DEFAULT   15 __libc_csu_init
    85: 0000000000601058      0 NOTYPE  GLOBAL DEFAULT  ABS __bss_start
    86: 0000000000601188      0 NOTYPE  GLOBAL DEFAULT  ABS _end
    87: 0000000000000000      0 FUNC    GLOBAL DEFAULT  UND std::basic_ostream<char, std::char_traits<char> >::operator<<(std::basic_ostream<char, std::char_traits<char> >&
    88: 00000000004007c8      0 FUNC    GLOBAL DEFAULT  UND _ZSt4endlIcSt11char_trait
    89: 0000000000400a6a     44 FUNC    WEAK   DEFAULT   15 void swap<int>(int&, int&)
    90: 0000000000601058      0 NOTYPE  GLOBAL DEFAULT  ABS _edata
    91: 00000000004008c4    337 FUNC    GLOBAL DEFAULT   15 main
    92: 0000000000400720      0 FUNC    GLOBAL DEFAULT   13 _init
```

Die Sektionstypen von Objektdateien:
text, data und bss

Hinweis zu verfügbaren Softwareentwicklungssystemen:
GNU g++ für Linux
cygwin für Windows
DreamSpark Premium (früher MSDNAA): VisualStudio 201x für Windows

1.5.2 Erstellen und Benutzen von statischen Bibliotheken

*.a-Bibiotheken als Sammlungen von Objektdateien

Static library

Erzeugen statischer Bibliotheken

ar Manualpage

Wo waren einmal statisch gelinkte Binaries positioniert?

```
> cat swap1.cpp
```

```
#include <iostream>
template <typename T>
/*
 * Requirements: T muss einen Kopierkonstruktor haben,
 *               T muss einen Zuweisungsoperator zu T haben.
 */
void swap(T& a, T& b)
{
   T  old_a(a);

   a = b;
   b = old_a;
}

int main(){
   int k(1);
   int l(5);
   std::cout << k << " " << l << std::endl;
   swap(k,l);
   std::cout << k << " " << l << std::endl;

   double d1(3.1415);
   double d2(15.1055);
   std::cout << d1 << " " << d2 << std::endl;
   swap(d1, d2);
   std::cout << d1 << " " << d2 << std::endl;
}
```

```
> make CXXFLAGS=-g swap1
```

```
g++ -g  swap1.cpp   -o swap1
> nm swap1 | grep swap | c++filt
0000000000400a96 W void swap<double>(double&, double&)
0000000000400a6a W void swap<int>(int&, int&)

> g++ -c swap1.cpp
> ls -al swap1.o
-rw-r--r-- 1 user1 users 4464  9. Nov 13:59 swap1.o

> ar rc libswap.a swap1.o
> ls -al libswap.a
-rw-r--r-- 1 user1 users 4650  9. Nov 14:02 libswap.a

> nm libswap.a | c++filt
0000000000000000 W void swap<double>(double&, double&)
0000000000000000 W void swap<int>(int&, int&)
                 U std::basic_ostream<char, std::char_traits<char> >::operator<<(double)
                 U std::basic_ostream<char, std::char_traits<char> >::operator<<(int)
0000000000000000 T main
```

oder ein vollständiges Beispiel:

```
> cat person.h
```

```cpp
/*
 * person.h
 */
class Person
{
 public:
  Person(){};
  ~Person(){};

  void speak(const char * sentence);
};
```

```
> cat person.cpp
```

```cpp
#include "person.h"
#include <iostream>

void Person::speak(const char * sentence)
{
  std::cout << sentence << std::endl;
}
```

```
> cat main.cpp
```

```
/*
 * main.cpp
 */

#include "person.h"
#include <iostream>

int main()
{
  Person person;
  person.speak("Hello world!");

  return 0;
}
```

```
> g++ -c person.cpp
> g++ -c main.cpp
> ar rc libperson.a person.o
> g++ -o main main.o -L. -lperson
> ldd main
        linux-vdso.so.1 =>  (0x00007fffdfbff000)
        libstdc++.so.6 => /usr/lib64/libstdc++.so.6 (0x00007f1f48ef2000)
        libm.so.6 => /lib64/libm.so.6 (0x00007f1f48c9b000)
        libgcc_s.so.1 => /lib64/libgcc_s.so.1 (0x00007f1f48a85000)
        libc.so.6 => /lib64/libc.so.6 (0x00007f1f48725000)
        /lib64/ld-linux-x86-64.so.2 (0x00007f1f491fc000)

> ls -al main
-rwxr-xr-x 1 user1 users 13015  9. Nov 14:13 main
```

Bei den impliziten make-Regeln benutzte Environment-Variablen

1.5.3 Erstellen und Benutzen einer „shared object“- Bibliothek

```
> g++ -fPIC -c person.cpp
> g++ -shared -o libperson.so person.o
> g++ -o main main.o -L. -lperson
> ls -al main
-rwxr-xr-x 1 user1 users 12570  9. Nov 16:27 main

> ldd main
        linux-vdso.so.1 =>  (0x00007fffc85fa000)
        libperson.so => not found
        libstdc++.so.6 => /usr/lib64/libstdc++.so.6 (0x00007f990e302000)
        libm.so.6 => /lib64/libm.so.6 (0x00007f990e0ab000)
        libgcc_s.so.1 => /lib64/libgcc_s.so.1 (0x00007f990de95000)
        libc.so.6 => /lib64/libc.so.6 (0x00007f990db35000)
        /lib64/ld-linux-x86-64.so.2 (0x00007f990e60c000)
> ./main
./main: error while loading shared libraries: libperson.so: cannot
   open shared object file: No such file or directory

> export LD_LIBRARY_PATH=.
> ldd main
        linux-vdso.so.1 =>  (0x00007fff6ebff000)
        libperson.so => ./libperson.so (0x00007f76ec213000)
        libstdc++.so.6 => /usr/lib64/libstdc++.so.6 (0x00007f76ebf09000)
        libm.so.6 => /lib64/libm.so.6 (0x00007f76ebcb2000)
        libgcc_s.so.1 => /lib64/libgcc_s.so.1 (0x00007f76eba9c000)
        libc.so.6 => /lib64/libc.so.6 (0x00007f76eb73c000)
        /lib64/ld-linux-x86-64.so.2 (0x00007f76ec415000)
> ./main
Hello world!
```

Oder besser (mit Versionsinformationen):
shared library HOWTO
YoLinux tutorial: libraries
Im Linuxumfeld genutzte Versionsnummern
.so Versionsnummern und Kompaibilität (im Apache-Projekt)

Why LD_LIBRARY_PATH is bad
When should I set LD_LIBRARY_PATH?
Verwaltung von Shared Libraries

Creating shared object libraries
Anatomy of Linux dynamic libraries

Workarount für fehlende .so
fix shared library load problems

1.5.4 Bibliotheksmanagement insbesondere unter verschiedenen Betriebssystemen

Using static and shared libraries across platforms
Writing and Using Libraries (and plugins)

Dynamically Loaded (DL) Libraries
plugin
dynamic loading

1.6 STL-Templatequellen unter SuSE-Linux fürs zeilenweise Debuggen auch innerhalb der STL-Routinen

	Paket	Version
☑	gcc47-c++ Der GNU C++-Compiler	4.7.1_2...3-1.1.1
☑	gcc47-c++-debuginfo Debug information for package gcc47-c++	4.7.1_2...3-1.1.1
☑	gcc47-debuginfo Debug information for package gcc47	4.7.1_2...3-1.1.1
☑	gcc47-debugsource Debug sources for package gcc47	4.7.1_2...3-1.1.1
☑	libstdc++47 Dynamische C++-Bibliotheken	4.7.1_2...3-1.1.1
☑	libstdc++47-32bit Dynamische C++-Bibliotheken	4.7.1_2...3-1.1.1
☑	libstdc++47-debuginfo Debug information for package libstdc++47	4.7.1_2...3-1.1.1
☑	libstdc++47-devel Enthält Dateien und Bibliotheken, die zum Programmieren benötigt werden	4.7.1_2...3-1.1.1
☑	libstdc++47-devel-32bit Enthält Dateien und Bibliotheken, die zum Programmieren benötigt werden	4.7.1_2...3-1.1.1
☑	glibc Die Standard Shared Libraries (aus der GNU C-Bibliothek)	2.15-22.6.4
☑	glibc-32bit Die Standard Shared Libraries (aus der GNU C-Bibliothek)	2.15-22.6.4
☑	glibc-debuginfo Debug information for package glibc	2.15-22.6.4
☑	glibc-debuginfo-32bit Debug information for package glibc	2.15-22.6.4
☑	glibc-debugsource Debug sources for package glibc	2.15-22.6.4
☑	glibc-devel Include Files and Libraries Mandatory for Development	2.15-22.6.4
☑	glibc-devel-32bit Include Files and Libraries Mandatory for Development	2.15-22.6.4
☑	glibc-devel-debuginfo Debug information for package glibc-devel	2.15-22.6.4

1.7 Automatisch überprüfte Requirements an Template-Parameter

Ein traditionelles Template-Beispiel:

```
#include <iostream>
#include <cmath>
#include <limits>

using namespace std;

template <typename T1, typename T2>
double geomMittel2(const T1& a, const T2& b)
{
    return sqrt(abs(a*b));
}

int main()
{
    cout << geomMittel2(3.0, 300.0) << endl;
    cout << geomMittel2(3, 300.0) << endl;
    cout << geomMittel2(-3, 300.0) << endl;
    cout << geomMittel2(-3, 300) << endl;
    cout << geomMittel2(3.0, 'c') << endl;
    cout << geomMittel2(3.0, "c") << endl;

    return 0;
}
```

und die Fehlermeldung für den letzten Testfall:

```
In Funktion ≫double geomMittel2(const T1&, const T2&) [with T1 = double, T2 = char [2]]≪:
geomMittel2-0.cpp:20:33:   instantiated from here
geomMittel2-0.cpp:10:25: Fehler: ungültige Operanden der Typen ≫const double≪ und ≫const char [2]≪ für binäres ≫operator*≪
```

Nach einer verbesserten Bezeichnerwahl:

```
#include <iostream>
#include <cmath>
#include <limits>

using namespace std;

template <typename ArithmeticLike1, typename ArithmeticLike2>
double geomMittel2(const ArithmeticLike1& a, const
   ArithmeticLike2& b)
{
    return sqrt(abs(a*b));
}

int main()
{
    cout << geomMittel2(3.0, 300.0) << endl;
    cout << geomMittel2(3, 300.0) << endl;
    cout << geomMittel2(-3, 300.0) << endl;
    cout << geomMittel2(-3, 300) << endl;
    cout << geomMittel2(3.0, 'c') << endl;
    cout << geomMittel2(3.0, "c") << endl;

    return 0;
}
```

Aufgabe: Wie sieht die Fehlermeldung nun aus?

1.7.1 mit Hilfe von BOOST_STATIC_ASSERT()

```
#include <iostream>
#include <cmath>
#include <limits>
#include <boost/static_assert.hpp>
#include <boost/type_traits.hpp>

using namespace std;

BOOST_STATIC_ASSERT(std::numeric_limits<int>::digits >= 32);

template <typename ArithmeticLike1, typename ArithmeticLike2>
double geomMittel2(const ArithmeticLike1& a, const
    ArithmeticLike2& b)
{
BOOST_STATIC_ASSERT(::boost::is_arithmetic<ArithmeticLike1>::
    value);
BOOST_STATIC_ASSERT(::boost::is_arithmetic<ArithmeticLike2>::
    value);

    return sqrt(abs(a*b));
}

int main()
{
    cout << geomMittel2(3.0, 300.0) << endl;
    cout << geomMittel2(3, 300.0) << endl;
    cout << geomMittel2(-3, 300.0) << endl;
    cout << geomMittel2(-3, 300) << endl;
    cout << geomMittel2(3.0, 'c') << endl;
    cout << geomMittel2(3.0, "c") << endl;

    return 0;
}
```

mit der Compiler-Fehlermeldung:

```
geomMittel2.cpp: In instantiation of ‘double geomMittel2(const ArithmeticLike1&, const ArithmeticLike2&) [with ArithmeticLike1 = double;
                                                                                            ArithmeticLike2 = char [2]]’:
geomMittel2.cpp:28:33:   required from here
geomMittel2.cpp:15:1: error: invalid application of ‘sizeof’ to incomplete type ‘boost::STATIC_ASSERTION_FAILURE<false>’
geomMittel2.cpp:17:25: error: invalid operands of types ‘const double’ and ‘const char [2]’ to binary ‘operator*’
```

Vergleiche is_arithmetic und type_traits der Boost

oder

1.7.2 mit Hilfe des c++11-Modus des g++

```
#include <iostream>
#include <cmath>
#include <limits>
#include <boost/type_traits.hpp>

using namespace std;

static_assert(std::numeric_limits<int>::digits >= 32, "int not
   enough digits");

template <typename ArithmeticLike1, typename ArithmeticLike2>
double geomMittel2(const ArithmeticLike1& a, const
   ArithmeticLike2& b)
{
static_assert(::boost::is_arithmetic<ArithmeticLike1>::value, "
   ArithmeticLike1 is not arithmetic");
static_assert(::boost::is_arithmetic<ArithmeticLike2>::value, "
   ArithmeticLike2 is not arithmetic");

    return sqrt(abs(a*b));
}

// uebersetze mit -std=c++11
// oder make CXXFLAGS="-std=c++11" ...

int main()
{
    cout << geomMittel2(3.0, 300.0) << endl;
    cout << geomMittel2(3, 300.0) << endl;
    cout << geomMittel2(-3, 300.0) << endl;
    cout << geomMittel2(-3, 300) << endl;
    cout << geomMittel2(3.0, 'c') << endl;
    cout << geomMittel2(3.0, "c") << endl;

    return 0;
}
```

mit der Compiler-Fehlermeldung:

```
geomMittel-sa2.cpp: In instantiation of ‘double geomMittel2(const ArithmeticLike1&, const ArithmeticLike2&) [with ArithmeticLike1 = double; ArithmeticLike2 = char [2]]’:
geomMittel-sa2.cpp:29:33:   required from here
geomMittel-sa2.cpp:14:1: error: static assertion failed: ArithmeticLike2 is not arithmetic
geomMittel-sa2.cpp:16:25: error: invalid operands of types ‘const double’ and ‘const char [2]’ to binary ‘operator*’
```

Vergleiche static_assert.

1.8 „horrible error messages“ bei STL-Nutzung

```
testmm.cpp:30: error: cannot convert ‘std::_Rb_tree_iterator<
    std::pair<const std::basic_string<char, std::char_traits<
    char>, std::allocator<char> >, Widget> > to ‘int in
    initialization
testmm.cpp:36: error: no matching function for call to ‘std::
    multimap<std::basic_string<char, std::char_traits<char>, std
    ::allocator<char> >, Widget, std::less<std::basic_string<
    char, std::char_traits<char>, std::allocator<char> > >, std
    ::allocator<std::pair<const std::basic_string<char, std::
    char_traits<char>, std::allocator<char> >, Widget> > >::
    insert(int)
/usr/include/c++/4.2.1/bits/stl_multimap.h:339: note:
    candidates are: typename std::_Rb_tree<_Key, std::pair<const
     _Key, _Tp>, std::_Select1st<std::pair<const _Key, _Tp> >,
    _Compare, typename _Alloc::rebind<std::pair<const _Key, _Tp>
     >::other>::iterator std::multimap<_Key, _Tp, _Compare,
    _Alloc>::insert(const std::pair<const _Key, _Tp>&) [with
    _Key = std::basic_string<char, std::char_traits<char>, std::
    allocator<char> >, _Tp = Widget, _Compare = std::less<std::
    basic_string<char, std::char_traits<char>, std::allocator<
    char> > >, _Alloc = std::allocator<std::pair<const std::
    basic_string<char, std::char_traits<char>, std::allocator<
    char> >, Widget> >]
/usr/include/c++/4.2.1/bits/stl_multimap.h:363: note:
                    typename std::_Rb_tree<_Key, std::pair<const
     _Key, _Tp>, std::_Select1st<std::pair<const _Key, _Tp> >,
    _Compare, typename _Alloc::rebind<std::pair<const _Key, _Tp>
     >::other>::iterator std::multimap<_Key, _Tp, _Compare,
    _Alloc>::insert(typename std::_Rb_tree<_Key, std::pair<const
     _Key, _Tp>, std::_Select1st<std::pair<const _Key, _Tp> >,
    _Compare, typename _Alloc::rebind<std::pair<const _Key, _Tp>
     >::other>::iterator, const std::pair<const _Key, _Tp>&) [
    with _Key = std::basic_string<char, std::char_traits<char>,
    std::allocator<char> >, _Tp = Widget, _Compare = std::less<
    std::basic_string<char, std::char_traits<char>, std::
    allocator<char> > >, _Alloc = std::allocator<std::pair<const
     std::basic_string<char, std::char_traits<char>, std::
    allocator<char> >, Widget> >]
testmm.cpp:38: error: no matching function for call to ‘std::
    multimap<int, int, intComp, std::allocator<std::pair<const
    int, int> > >::insert(int)
```

```
/usr/include/c++/4.2.1/bits/stl_multimap.h:339: note:
   candidates are: typename std::_Rb_tree<_Key, std::pair<const
    _Key, _Tp>, std::_Select1st<std::pair<const _Key, _Tp> >,
   _Compare, typename _Alloc::rebind<std::pair<const _Key, _Tp>
    >::other >::iterator std::multimap<_Key, _Tp, _Compare,
   _Alloc >::insert(const std::pair<const _Key, _Tp>&) [with
   _Key = int, _Tp = int, _Compare = intComp, _Alloc = std::
   allocator<std::pair<const int, int> >]
/usr/include/c++/4.2.1/bits/stl_multimap.h:363: note:
                   typename std::_Rb_tree<_Key, std::pair<const
    _Key, _Tp>, std::_Select1st<std::pair<const _Key, _Tp> >,
   _Compare, typename _Alloc::rebind<std::pair<const _Key, _Tp>
    >::other >::iterator std::multimap<_Key, _Tp, _Compare,
   _Alloc >::insert(typename std::_Rb_tree<_Key, std::pair<const
    _Key, _Tp>, std::_Select1st<std::pair<const _Key, _Tp> >,
   _Compare, typename _Alloc::rebind<std::pair<const _Key, _Tp>
    >::other >::iterator, const std::pair<const _Key, _Tp>&) [
   with _Key = int, _Tp = int, _Compare = intComp, _Alloc = std
   ::allocator<std::pair<const int, int> >]
```

Workaround: Postprozessing
oder besser statische Requirementsüberprüfung zur Compilezeit.

Sehr leicht können bei unpassenden Typparametern und anderen Problemen komplizierte und unverständliche Compiler-Meldungen entstehen, was einfach mit der Tatsache zusammenhängt, dass die konkreten Anforderungen an die Typparameter unbekannt sind. Die Arbeit mit C++-Templates erfordert deshalb eine lückenlose Dokumentation der Anforderungen an einen Typparameter. Durch Template-Metaprogrammierung können die meisten Anforderungen (Basisklasse, Vorhandensein von Methoden, Kopierbarkeit, Zuweisbarkeit etc.) auch in speziellen Konstrukten abgefragt werden, wodurch sich lesbarere Fehlermeldungen ergeben. Obgleich sie standardkonform sind, werden diese Konstrukte jedoch nicht von allen Compilern unterstützt. (Siehe http://de.wikipedia.org/wiki/Generische_Programmierung_in_Java Abschnitt „Das Konzept“)

Why do templates produce such horrible error messages?
In current C++, template errors are detected when a certain type argument does not support a certain operation (often expressed as the inability to convert one type to another or a failure of type deduction). It often happens deep into the instantiation tree. You need an equivalent of the stack trace to figure out where the root cause of the error is. It's called an "instantiation stack" and is dumped by the compiler upon a template error. It often spans several pages and contains unfamiliar names and implementation details of some library code.
Siehe http://bartoszmilewski.wordpress.com/2010/06/24/c-concepts-a-postmortem/: Absatz „Error Reporting“.

1.8.1 C++11 type_traits

Abschnitt 20.9.4ff.:

```
template <class T> struct is_void;
template <class T> struct is_integral;
template <class T> struct is_floating_pint;
template <class T> struct is_array;
template <class T> struct is_pointer;
template <class T> struct is_lvalue_referece;
template <class T> struct is_rvalue_reference;
template <class T> struct is_member_object_pointer;
template <class T> struct is_member_function_pointer;
template <class T> struct is_enum;
template <class T> struct is_union;
template <class T> struct is_class;
template <class T> struct is_function;

template <class T> struct is_reference;
template <class T> struct is_arithmetic;
template <class T> struct is_fundamental;
template <class T> struct is_object;
template <class T> struct is_scalar;
template <class T> struct is_compount;
template <class T> struct is_member_pointer;

template <class T> struct is_const;
template <class T> struct is_volatile;
template <class T> struct is_trivial;
template <class T> struct is_trivially_copyable;
template <class T> struct is_standard_layout;
template <class T> struct is_pod;
template <class T> struct is_literal_type;
template <class T> struct is_empty;
template <class T> struct is_polymorphic;
template <class T> struct is_abstract;
template <class T> struct is_signed;
template <class T> struct is_unsigned;
template <class T> struct is_constructible;
template <class T> struct is_default_constractible;
template <class T> struct is_copy_constructible;
template <class T> struct is_move_constructible;
template <class T, class U> struct is_assignable;
template <class T> struct is_copy_assignable;
```

```
template <class T> struct is_move_assignable;
template <class T> struct is_destructible;
...
template <class T, class U> struct is_same;
template <class Base, class Derived> struct is_base_of;
template <class From, class To> struct is_convertible;
template <class From, class To> class is_explicitly_convertible
    ;
```

1.8.2 BOOST type_traits

Boost: Type Traits

```
has_bit_and
has_bit_and_assign
has_bit_or
has_bit_or_assign
has_bit_xor
has_bit_xor_assign
has_complement
has_dereference
has_divides
has_divides_assign
has_equal_to
has_greater
has_greater_equal
has_left_shift
has_left_shift_assign
has_less
has_less_equal
has_logical_and
has_logical_not
has_logical_or
has_minus
has_minus_assign
has_modulus
has_modulus_assign
has_multiplies
has_multiplies_assign
has_negate
has_new_operator
has_not_equal_to
has_nothrow_assign
has_nothrow_constructor
```

has_nothrow_copy
has_nothrow_copy_constructor
has_nothrow_default_constructor
has_plus
has_plus_assign
has_post_decrement
has_post_increment
has_pre_decrement
has_pre_increment
has_right_shift
has_right_shift_assign
has_trivial_assign
has_trivial_constructor
has_trivial_copy
has_trivial_copy_constructor
has_trivial_default_constructor
has_trivial_destructor
has_unary_minus
has_unary_plus
has_virtual_destructor
integral_constant
integral_promotion
is_abstract
is_arithmetic
is_array
is_base_of
is_class
is_complex
is_compound
is_const
is_convertible
is_empty
is_enum
is_floating_point
is_function
is_fundamental
is_integral
is_lvalue_reference
is_member_function_pointer
is_member_object_pointer
is_member_pointer
is_object
is_pod
is_pointer

```
is_polymorphic
is_reference
is_rvalue_reference
is_same
is_scalar
is_signed
is_stateless
is_union
is_unsigned
is_virtual_base_of
is_void
is_volatile
```

1.8.3 numeric_limits als Typ-Abbildung

numeric_limits als generische Klasse
mit traits-ähnlichem Charakter für die Benutung zum Beispiel für Requirements von Tempate-Parametern:

```
#include <limits>
#include <boost/static_assert.hpp>

template <class UnsignedInt>
class myclass
{
private:
  static_assert(std::numeric_limits<UnsignedInt>::digits >= 16,
               "UnsignedInt isn't long enough");
  static_assert(std::numeric_limits<UnsignedInt>::is_specialized,
               "UnsignedInt isn't specialized");
  static_assert(std::numeric_limits<UnsignedInt>::is_integer,
               "UnsignedInt isn't integer");
  static_assert(!std::numeric_limits<UnsignedInt>::is_signed,
               "UnsignedInt isn't unsigned");

public:
   /* details here */
};
 myclass<unsigned> m1;
 //myclass<int> m2;
 myclass<unsigned char> m3;

int main()
{
 return 0;
}
```

18.3.2.3: allgemeines Template mit is_specialized==false
18.3.2.7: Spezialisierung für float, bool
numeric_limis: 18.3.2.2: alle bereitgestellten Spezialisierungen

1.9 Rückblick: typsichere Funktionsbenutzung

Der Prototypen (Signaturen) von Funtionen:

```
const double& max(const double& a, const double& b) throw();
inline static constexpr float max() noexcept { return 3.40282347E+38F; }
int myfunction (int param) throw(); // no exceptions allowed
int myfunction (int param);          // all exceptions allowed ...
```

Prototypen in Headerdateien

„Wichtig: Bei Prototypen unterscheidet C zwischen einer leeren Parameterliste und einer Parameterliste mit void . Ist die Parameterliste leer, so bedeutet dies, dass die Funktion eine nicht definierte Anzahl an Parametern besitzt. Das Schlüsselwort void gibt an, dass der Funktion keine Werte übergeben werden dürfen. “
(Funktionsprototypen in C)

C functions without prototypes

1.10 Concepts und zielführende knappe Fehlermeldungen bei der Benutzung fehlerhafter aktueller generischer Parameter: 2017 oder wann?

C++11: Features originally planned but removed or not included

Concepts (C++)

http:// www.generic-programming.org/languages/conceptcpp/tutorial/

```
template<std::CopyConstructible T>
  requires Addable<T>
  T sum(T array[], int n)
  {
    T result = 0;
    for (int i = 0; i < n; ++i)
      result = result + array[i];
    return result;
  }
```

nur für Klassen T mit:

```
auto concept CopyConstructible<typename T> {
  T::T(T const&);
  T::~T();
};
```

```
auto concept Addable<typename T, typename U = T> {
  typename result_type;
  result_type operator+(T, U);
};
```

Statt einer buchstabengetreuen Überprüfung auf Einhaltung der Konzepteigenschaften mittels der `auto`-Konzeptdefinition kann man durch `concept_maps` auch eine mittels „Übersetzung“ einzelner Operationen/Typen erreichbare Erfüllung der Konzept-Eigenschaften definieren:

```
concept Stack<typename X> {
    typename value_type;
    void push(X&, const value_type&);
    void pop(X&);
    value_type top(const X&);
    bool empty(const X&);
};

template<typename T> concept_map Stack<std::vector<T>> {
    typedef T value_type;
    void push(std::vector<T>& v, const T& x) { v.push_back(x); }
    void pop(std::vector<T>& v) { v.pop_back(); }
    T top(const std::vector<T>& v) { return v.back(); }
    bool empty(const std::vector<T>& v) { return v.empty(); }
};
```

(siehe Concept_maps, retroaktive Modellierung)

Zu weiteren Concepts vergleiche:
http://www.generic-programming.org/languages/conceptcpp/concept_web.php

Eine praktische Anwendung:

```
#include <iostream>
#include <cmath>
#include <vector>
#include <concepts>

using namespace std;

auto concept HasAbs<typename T> {
    typename result_type;
    result_type abs(const T&);
}
auto concept HasPower<typename T>{
    typename result_type;
    result_type pow(const T&, int);
}
auto concept HasPowerd<typename T>{
    requires FloatingPointLike<T>;
    double pow(const T&, const T&);
}

template <int p = 2, InputIterator InputIter, FloatingPointLike T>
requires True<p >= 1>,
    HasAbs<InputIter::value_type>,
    HasPowerd<T>,
    HasPower<HasAbs<InputIter::value_type>::result_type>,
    HasPlusAssign<T,
       HasPower<HasAbs<InputIter::value_type>::result_type>::result_type>
    T pNorm(InputIter first, InputIter last, T init)
{
    for (; first != last; first++)
    {
        init += pow(abs(*first), p);
    };
    return pow((init), (1.0/p));
}
int main()
{
    vector<double> TD (2);
    TD[0] = 200.0;
    TD[1] = 0.0;

    double res = pNorm<3>(TD.begin(), TD.end(), 0.0f);
    cout << res << " sizeof: "
         << sizeof(pNorm(TD.begin(), TD.end(), 0.0f))
         << endl;

    double TestData[] = {110.0, 10.0, 10.0};
    cout << pNorm(TestData, TestData + 3, 0.0)
         << " sizeof: " << sizeof(pNorm(TestData, TestData + 3, 0.0))
         << endl;
```

```
            double TestData2[] = {10.0, 10.0, 10.0};
            cout << pNorm<1>(TestData2, TestData2 + 3, 0.01)
                 << " sizeof: " << sizeof(pNorm<1>(TestData2, TestData2 +
                     3, 0.01
))
         << endl;

    return 0;
}
```

Dabei wird aus das Konzept `HasPlusAssign<T, U>` der C++0x Standard Library benutzt:

```
auto concept HasPlusAssign<typename T, typename U = T> {
typename result_type;
result_type operator+=(T&, const U&);
}
```

(vergleiche Foundational Concepts for the C++0x Standard Library (Revision 5),
Proposed Wording for Concepts (Revision 3),
Containers,
Algorithms (Revision 2),
Iterators (Revision 3),
Numerics (Revision 3))

Link zu conceptg++:
http: //www.generic-programming.org/software/ConceptGCC/download.php

compiler can type-check templates when they are defined, so mistakes show up earlier. Real support for Generic Programming also means that many of the template tricks that are needed in standard C++ are no longer necessary, and, yes, it provides much-improved error messages than we get with C++ compilers today.“

C++11 without Concepts
C++ Concepts: a Postmortem
Nächster C++-Standard soll 2017 kommen

1.11 Zielgerichtete Fehlermeldungen bei Nutzung einer C++-Standardbibliothek mit Konzepten

Fehlerhafte Benutzung einer generischen Funktion:

```
#include <list>
#include <algorithm>

 int main() {
   std::list<int> l;
   std::sort(l.begin(), l.end());
 }
```

g++ ohne eingeschränkte Generizität:

```
/usr/lib/gcc/i686-pc-linux-gnu/4.1.2/include/g++-v4/bits/stl_algo.h: In  -
function 'void std::sort(_RandomAccessIterator, _RandomAccessIterator) [  -
with _RandomAccessIterator = std::_List_iterator<int>]':
list-sort.c++:6: instantiated from here
/usr/lib/gcc/i686-pc-linux-gnu/4.1.2/include/g++-v4/bits/stl_algo.h:2713:  -
error: no match for 'operator-' in '__last - __first'
/usr/lib/gcc/i686-pc-linux-gnu/4.1.2/include/g++-v4/bits/stl_algo.h: In  -
function 'void std::__final_insertion_sort(_RandomAccessIterator,  -
_RandomAccessIterator) [with _RandomAccessIterator = std::_List_iterator<  -
int>]':
...
```

conceptg++ mit Konzepte benutzender Standardbibliothek:

```
list-sort.c++: In function 'int main()':
list-sort.c++:6: error: no matching function for call to 'sort(std::  -
_List_iterator<int>, std::_List_iterator<int>)'
/usr/local/lib/gcc/i686-pc-linux-gnu/4.3.0/../../../../include/c++/4.3.0/  -
bits/stl_algo.h:2872: note: candidates are: void std::sort(_Iter, _Iter)  -
[with _Iter = std::_List_iterator<int>] <where clause>
list-sort.c++:6: note: no concept map for requirement 'std::  -
MutableRandomAccessIterator<std::_List_iterator<int> >'
```

Eine Sammlung von Konzepten findet man unter ConceptC++ Specification.

Zitat: „ConceptC++ makes programming with C++ templates easier, ...

1.12 Die Boost-Bibliotheken

Boost.StaticAssert mit RandomAccessIterator, UnsignedInt, ...
The Boost Concept Check Library (BCCL)
enable_if für property based template overloading
Boost.Foreach
Math Special Functions

1.13 Orte, wo statische Zusicherungen benutzt werden

Boost.StaticAssert

Use at namespace scope
Use at function scope
Use at class scope
Use in templates

1.14 statische Zusicherungen, ... in C++11

static assertions
Range-based for-loop
25.2.2 ff.: any_of(), none_of(), for_each()

1.15 Fehlermeldungen bei uneingeschränkter Generizität (Fortsetzung von 1.8)

```
#include <vector>
#include <complex>
#include <algorithm>

int main()
 {
     std::vector<std::complex<float> > v;
     std::stable_sort(v.begin(), v.end());
 }
```

und die Fehlermeldung:

```
In file included from /usr/include/c++/4.5/algorithm:63:0,
                 from bad_error_eg.cpp:3:
/usr/include/c++/4.5/bits/stl_algo.h: In Funktion ≫void std::__insertion_sort(_RandomAccessIterator, _RandomAccessIterator) [with _RandomAccessIterator = __gnu_cxx::__norm
/usr/include/c++/4.5/bits/stl_algo.h:3358:4:   instantiated from ≫void std::__inplace_stable_sort(_RandomAccessIterator, _RandomAccessIterator) [with _RandomAccessIterator
/usr/include/c++/4.5/bits/stl_algo.h:5415:2:   instantiated from ≫void std::stable_sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<std::complex<float>*
bad_error_eg.cpp:8:41:   instantiated from here
```

```
/usr/include/c++/4.5/bits/stl_algo.h:2103:4: Fehler: no match for ≫operator<≪ in ≫__i.__gnu_cxx::__normal_iterator<_Iterator, _Container>::operator* [wit
/usr/include/c++/4.5/bits/stl_algo.h: In Funktion ≫void std::__merge_without_buffer(_BidirectionalIterator, _BidirectionalIterator, _BidirectionalIterator,
/usr/include/c++/4.5/bits/stl_algo.h:3364:7:   instantiated from ≫void std::__inplace_stable_sort(_RandomAccessIterator, _RandomAccessIterator) [with _Rand
/usr/include/c++/4.5/bits/stl_algo.h:5415:2:   instantiated from ≫void std::stable_sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<std:
bad_error_eg.cpp:8:41:   instantiated from here
/usr/include/c++/4.5/bits/stl_algo.h:2963:4: Fehler: no match for ≫operator<≪ in ≫__middle.__gnu_cxx::__normal_iterator<_Iterator, _Container>::operator*
/usr/include/c++/4.5/bits/stl_algo.h: In Funktion ≫void std::__unguarded_linear_insert(_RandomAccessIterator) [with _RandomAccessIterator = __gnu_cxx::__no
/usr/include/c++/4.5/bits/stl_algo.h:2111:6:   instantiated from ≫void std::__insertion_sort(_RandomAccessIterator, _RandomAccessIterator) [with _RandomAcc
/usr/include/c++/4.5/bits/stl_algo.h:3358:4:   instantiated from ≫void std::__inplace_stable_sort(_RandomAccessIterator, _RandomAccessIterator) [with _Rand
/usr/include/c++/4.5/bits/stl_algo.h:5415:2:   instantiated from ≫void std::stable_sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<std:
bad_error_eg.cpp:8:41:   instantiated from here
/usr/include/c++/4.5/bits/stl_algo.h:2064:7: Fehler: no match for ≫operator<≪ in ≫__val < __next.__gnu_cxx::__normal_iterator<_Iterator, _Container>::ope
In file included from /usr/include/c++/4.5/vector:61:0,
                 from bad_error_eg.cpp:1:
/usr/include/c++/4.5/bits/stl_algobase.h: In Funktion ≫_ForwardIterator std::lower_bound(_ForwardIterator, _ForwardIterator, const _Tp&) [with _ForwardItera
/usr/include/c++/4.5/bits/stl_algo.h:2975:4:   instantiated from ≫void std::__merge_without_buffer(_BidirectionalIterator, _BidirectionalIterator, _Bidirec
/usr/include/c++/4.5/bits/stl_algo.h:3364:7:   instantiated from ≫void std::__inplace_stable_sort(_RandomAccessIterator, _RandomAccessIterator) [with _Rand
/usr/include/c++/4.5/bits/stl_algo.h:5415:2:   instantiated from ≫void std::stable_sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<std:
bad_error_eg.cpp:8:41:   instantiated from here
/usr/include/c++/4.5/bits/stl_algobase.h:976:4: Fehler: no match for ≫operator<≪ in ≫__middle.__gnu_cxx::__normal_iterator<_Iterator, _Container>::operat
In file included from /usr/include/c++/4.5/algorithm:63:0,
                 from bad_error_eg.cpp:3:
/usr/include/c++/4.5/bits/stl_algo.h: In Funktion ≫_FIter std::upper_bound(_FIter, _FIter, const _Tp&) [with _FIter = __gnu_cxx::__normal_iterator<std::com
/usr/include/c++/4.5/bits/stl_algo.h:2982:4:   instantiated from ≫void std::__merge_without_buffer(_BidirectionalIterator, _BidirectionalIterator, _Bidirec
/usr/include/c++/4.5/bits/stl_algo.h:3364:7:   instantiated from ≫void std::__inplace_stable_sort(_RandomAccessIterator, _RandomAccessIterator) [with _Rand
/usr/include/c++/4.5/bits/stl_algo.h:5415:2:   instantiated from ≫void std::stable_sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<std:
bad_error_eg.cpp:8:41:   instantiated from here
/usr/include/c++/4.5/bits/stl_algo.h:2461:4: Fehler: no match for ≫operator<≪ in ≫__val < __middle.__gnu_cxx::__normal_iterator<_Iterator, _Container>::o
/usr/include/c++/4.5/bits/stl_algo.h: In Funktion ≫_OIter std::merge(_IIter1, _IIter1, _IIter2, _IIter2, _OIter) [with _IIter1 = std::complex<float>*, _IIt
/usr/include/c++/4.5/bits/stl_algo.h:2838:4:   instantiated from ≫void std::__merge_adaptive(_BidirectionalIterator, _BidirectionalIterator, _Bidirectional
/usr/include/c++/4.5/bits/stl_algo.h:3315:7:   instantiated from ≫void std::__stable_sort_adaptive(_RandomAccessIterator, _RandomAccessIterator, _Pointer,
/usr/include/c++/4.5/bits/stl_algo.h:5417:2:   instantiated from ≫void std::stable_sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<std:
bad_error_eg.cpp:8:41:   instantiated from here
/usr/include/c++/4.5/bits/stl_algo.h:5299:4: Fehler: no match for ≫operator<≪ in ≫__first2.__gnu_cxx::__normal_iterator<_Iterator, _Container>::operator*
/usr/include/c++/4.5/bits/stl_algo.h: In Funktion ≫_BidirectionalIterator3 std::__merge_backward(_BidirectionalIterator1, _BidirectionalIterator1, _Bidirec
/usr/include/c++/4.5/bits/stl_algo.h:2847:4:   instantiated from ≫void std::__merge_adaptive(_BidirectionalIterator, _BidirectionalIterator, _Bidirectional
/usr/include/c++/4.5/bits/stl_algo.h:3315:7:   instantiated from ≫void std::__stable_sort_adaptive(_RandomAccessIterator, _RandomAccessIterator, _Pointer,
/usr/include/c++/4.5/bits/stl_algo.h:5417:2:   instantiated from ≫void std::stable_sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<std:
bad_error_eg.cpp:8:41:   instantiated from here
/usr/include/c++/4.5/bits/stl_algo.h:2740:4: Fehler: no match for ≫operator<≪ in ≫* __last2 < __last1.__gnu_cxx::__normal_iterator<_Iterator, _Container>
/usr/include/c++/4.5/bits/stl_algo.h: In Funktion ≫_OIter std::merge(_IIter1, _IIter1, _IIter2, _IIter2, _OIter) [with _IIter1 = __gnu_cxx::__normal_iterat
/usr/include/c++/4.5/bits/stl_algo.h:3163:4:   instantiated from ≫void std::__merge_sort_loop(_RandomAccessIterator1, _RandomAccessIterator1, _RandomAccess
/usr/include/c++/4.5/bits/stl_algo.h:3261:4:   instantiated from ≫void std::__merge_sort_with_buffer(_RandomAccessIterator, _RandomAccessIterator, _Pointer
/usr/include/c++/4.5/bits/stl_algo.h:3312:4:   instantiated from ≫void std::__stable_sort_adaptive(_RandomAccessIterator, _RandomAccessIterator, _Pointer,
/usr/include/c++/4.5/bits/stl_algo.h:5417:2:   instantiated from ≫void std::stable_sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<std:
bad_error_eg.cpp:8:41:   instantiated from here
/usr/include/c++/4.5/bits/stl_algo.h:5299:4: Fehler: no match for ≫operator<≪ in ≫__first2.__gnu_cxx::__normal_iterator<_Iterator, _Container>::operator*
/usr/include/c++/4.5/bits/stl_algo.h: In Funktion ≫_OIter std::merge(_IIter1, _IIter1, _IIter2, _IIter2, _OIter) [with _IIter1 = std::complex<float>*, _IIt
/usr/include/c++/4.5/bits/stl_algo.h:3163:4:   instantiated from ≫void std::__merge_sort_loop(_RandomAccessIterator1, _RandomAccessIterator1, _RandomAccess
/usr/include/c++/4.5/bits/stl_algo.h:3263:4:   instantiated from ≫void std::__merge_sort_with_buffer(_RandomAccessIterator, _RandomAccessIterator, _Pointer
/usr/include/c++/4.5/bits/stl_algo.h:3312:4:   instantiated from ≫void std::__stable_sort_adaptive(_RandomAccessIterator, _RandomAccessIterator, _Pointer,
/usr/include/c++/4.5/bits/stl_algo.h:5417:2:   instantiated from ≫void std::stable_sort(_RAIter, _RAIter) [with _RAIter = __gnu_cxx::__normal_iterator<std:
bad_error_eg.cpp:8:41:   instantiated from here
/usr/include/c++/4.5/bits/stl_algo.h:5299:4: Fehler: no match for ≫operator<≪ in ≫* __first2 < * __first1≪
```

C++11:

25.4.1.2 `stable_sort` **[stable.sort]**

```
template<class RandomAccessIterator>
  void stable_sort(RandomAccessIterator first, RandomAccessIterator last);

template<class RandomAccessIterator, class Compare>
  void stable_sort(RandomAccessIterator first, RandomAccessIterator last,
                   Compare comp);
```

1 *Effects:* Sorts the elements in the range `[first,last)`.

2 *Requires:* `RandomAccessIterator` shall satisfy the requirements of `ValueSwappable` (17.6.3.2). The type of `*first` shall satisfy the requirements of `MoveConstructible` (Table 20) and of `MoveAssignable` (Table 22).

3 *Complexity:* It does at most $N \log^2(N)$ (where N `== last - first`) comparisons; if enough extra memory is available, it is $N \log(N)$.

4 *Remarks:* Stable.

SGI:
stable_sort

Algorithms | Function
Category: algorithms | Component type: function

Prototype

Stable_sort is an overloaded name; there are actually two stable_sort functions.

```
template <class RandomAccessIterator>
void stable_sort(RandomAccessIterator first, RandomAccessIterator last);

template <class RandomAccessIterator, class StrictWeakOrdering>
void stable_sort(RandomAccessIterator first, RandomAccessIterator last,
                 StrictWeakOrdering comp);
```

Description

`Stable_sort` is much like `sort`: it sorts the elements in `[first, last)` into ascending order, meaning that if `i` and `j` are any two valid iterators in `[first, last)` such that `i` precedes `j`, then `*j` is not less than `*i`. `Stable_sort` differs from `sort` in two ways. First, `stable_sort` uses an algorithm that has different run-time complexity than `sort`. Second, as the name suggests, `stable_sort` is stable: it preserves the relative ordering of equivalent elements. That is, if `x` and `y` are elements in `[first, last)` such that `x` precedes `y`, and if the two elements are equivalent (neither `x < y` nor `y < x`) then a postcondition of `stable_sort` is that `x` still precedes `y`. [1]

The two versions of `stable_sort` differ in how they define whether one element is less than another. The first version compares objects using `operator<`, and the second compares objects using a function object `comp`.

Definition

Defined in the standard header algorithm, and in the nonstandard backward-compatibility header algo.h.

Requirements on types

For the first version, the one that takes two arguments:

- `RandomAccessIterator` is a model of Random Access Iterator.
- `RandomAccessIterator` is mutable.
- `RandomAccessIterator`'s value type is LessThan Comparable.
- The ordering relation on `RandomAccessIterator`'s value type is a *strict weak ordering*, as defined in the LessThan Comparable requirements.

iterator_traits
associated types

1.16 Verbesserte Fehlermeldungen bei Nutzung von StaticAssert

1.16.1 RandomAccessIterator

Zunächst die uneingeschränkt generische Variante:

```
#include <iostream>
#include <vector>
#include <set>
#include <complex>
#include <algorithm>
#include <iterator>
#include <boost/static_assert.hpp>
#include <boost/type_traits.hpp>

template <typename RandomAccessIterator >
RandomAccessIterator foo(RandomAccessIterator from,
                         RandomAccessIterator to)
{
   // this template should only be used with
   // random access iterators...
   //
   // ...
   reverse(from, to);
   return from;
};

int main()
{
      std::vector<float> v;
      // std::set<float> v;

      v.insert(v.end(),3.14);
      v.insert(v.end(),15.15);
      foo(v.begin(), v.end());
      copy(v.begin(), v.end(), std::ostream_iterator<float>(
                                               std::cout, " "));
      std::cout << std::endl;

}
```

wird einwandfrei übersetzt

```
> make CXXFLAGS="-std=c++11" ra2
```

```
g++ -std=c++11 ra2.cpp -o ra2
```

und funktioniert einwandfrei, für

```
int main()
{
      // std::vector<float> v;
      std::set<float> v;
      //...
```

erscheint jedoch keine vernünftige Fehlermeldung

```
> make CXXFLAGS="-std=c++11" ra2
/usr/include/c++/4.7/bits/stl_algobase.h: In instantiation of ‘static void std::__iter_swap<_BoolType>::
/usr/include/c++/4.7/bits/stl_algobase.h:139:7:   required from ‘void std::iter_swap(_ForwardIterator1, 
/usr/include/c++/4.7/bits/stl_algo.h:1428:6:   required from ‘void std::__reverse(_BidirectionalIterator
/usr/include/c++/4.7/bits/stl_algo.h:1474:7:   required from ‘void std::reverse(_BIter, _BIter) [with _B
ra2.cpp:25:4:   required from ‘RandomAccessIterator foo(RandomAccessIterator, RandomAccessIterator) [wit
ra2.cpp:36:28:   required from here
/usr/include/c++/4.7/bits/stl_algobase.h:90:11: error: assignment of read-only location ‘__a.std::_Rb_tr
/usr/include/c++/4.7/bits/stl_algobase.h:91:11: error: assignment of read-only location ‘__b.std::_Rb_tr
```

RandomAccessIterator

Durch ein geeignetes statisches Assert der Art

```
#include <iostream>
#include <algorithm>
#include <iterator>
#include <vector>
#include <set>
#include <complex>
#include <boost/static_assert.hpp>
#include <boost/type_traits.hpp>

template <typename RandomAccessIterator >
RandomAccessIterator foo(RandomAccessIterator from,
                         RandomAccessIterator to)
{
   // this template can only be used with
   // random access iterators...
   typedef typename std::iterator_traits<
         RandomAccessIterator >::iterator_category cat;
   static_assert(
      (::boost::is_convertible<
         cat,
         const std::random_access_iterator_tag&>::value),
      "no random access iterator");
```

```
   //
   // ...
   reverse(from, to);
   return from;
};

int main()
{
      // std::vector<float> v;
      std::set<float> v;

      v.insert(v.begin(),3.14);
      v.insert(v.begin(),15.15);
      foo(v.begin(), v.end());
      copy(v.begin(), v.end(), std::ostream_iterator<float>(std
         ::cout, " "));
      std::cout << std::endl;
}
```

wird jedoch der falsche aktuelle generische Parametertyp gemeldet:

```
make CXXFLAGS="-std=c++11" ra2
g++ -std=c++11 -g ra2.cpp -o ra2
ra2.cpp: In instantiation of ‘RandomAccessIterator foo(RandomAccessIterator, RandomAccessIterat
ra2.cpp:36:28:   required from here
ra2.cpp:18:4: error: static assertion failed: no random access iterator
make: *** [ra2] Fehler 1
```

1.16.2 Nicht instantiierbare Klassen

```
#include <iostream>
#include <algorithm>
#include <boost/static_assert.hpp>
#include <boost/type_traits.hpp>

template <typename T>
struct abstractClass
{
        static_assert(false, "This class may not be instantiated!");
        // ...
};

int main()
{
      abstractClass<int> ac;
      std::cout << std::endl;
}
```

Beachte eventuell: http://www.boost.org/doc/libs/1_52_0/doc/html/boost_staticassert.html#boost_staticassert.templates

1.16.3 Erzwingung gleicher Typen

```
#include <limits>
#include <boost/type_traits.hpp>
#include <boost/static_assert.hpp>

template <class UnsignedInt>
class myclass
{
private:
  static_assert(std::is_same<UnsignedInt, unsigned int>::value,
                "UnsignedInt isn't unsigned int");
public:
   /* details here */
};

 //myclass<unsigned> m1;
 //myclass<int> m2;
 //myclass<unsigned char> m3;
 myclass<unsigned long> m4;

int main()
{
 return 0;
}
```

1.16.4 Funktionen mit „(int/float/...) type promotion“-Returntyp

```
#include "promote.h"
template <typename T1, typename T2>
   typename promote_trait<T1,T2>::T_promote
         my_function(T1 x, T2 y)
{
     return  (x + y)/2.0;
}
```

mit `promote.h` ähnlich wie:

```
template <typename T1, typename T2>
struct promote_trait{
     typedef T1 T_promote;
};

template<> struct promote_trait<char, char> {
public:
        typedef int T_promote;
};
//...
```

Vergleiche: promote.h

In C++11 eleganter: automatisch bestimmter return-Typ:

```
template <typename T1, typename T2>
auto my_function(T1 x, T2 y) -> decltype((x + y)/2.0)
{
     return (x + y)/2.0;
}
```

Siehe auch BOOST promote

1.16.5 Auf Unterklassen eingeschränkte Generizität

```
template <typename ListUnterklasse>
class MyList
{
    static_assert(std::is_base_of<List,
                                   ListUnterklasse>::value,
                  "ListUnterklasse ist keine Kindklasse von List");
    // ...
}
```

Siehe C++11 Abschnitt 20.9.6 Relation between types.

Diese Typeigenschaften werden durch trickreichen Einsatz der Metaprogrammierung aus dem C++-Compiler „herausgekitzelt“: How is_base_of works? beziehungsweise Alternate implementation of is_base_of.

1.16.6 g++ type_traits Compiler Extensions

... oder sie benutzen direkt die syntaktischen Erweiterungen der „GNU Compiler Collection“ 7.9 Type Traits.

1.16.7 Type Traits in D

Andere Programmiersprachen (hier z.B. D) haben ähnliche elegantere semantische Erweiterungen, um den Compiler direkt abzufragen:

```
// Returns true if instances of type T can be added
template isAddable(T)
{   // Works by attempting to add two instances of type T
    const isAddable = __traits(compiles, (T t) { return t + t;
       });
}

int Foo(T)(T t)
    if (isAddable!(T))
{
    return 3;
}
// ...
```

Deren Anwendung für ADTs (als Requirements-Ersatz):

```
template isStack(T)
{
    const isStack =
        __traits(compiles,
          (T t)
          {   T.value_type v = top(t);
              push(t, v);
              pop(t);
              if (empty(t)) { }
          });
}

template Foo(T)
    if (isStack!(T))
{
    ...
}
```

D Template Constraints
D Traits

1.16.8 C++ *has_member* fehlt

C++ type traits to check if class has operator/member
How to decide if a template class has a certain member function?

1.16.9 SFINAE

SFINAE Warum ein fehlgehender Instantiierungsversuch keinen Compilationsfehler verursacht:

```
struct Test {
    typedef int foo;
};

template <typename T>
void f(typename T::foo) {} // Definition #1

template <typename T>
void f(T) {}               // Definition #2

int main() {
    f<Test>(10); // Call #1.
    f<int>(10);  // Call #2. Without error (SFINAE)
}
```

C++: SFINAE

SFINAE bei der nützlichen Trait-Arbeit:

```
template <typename T>
        struct has_iterator
        {
            template <typename U>
            static char test(typename U::iterator* x);

            template <typename U>
            static long test(U* x);

            static const bool value = sizeof(test<T>(0)) == 1;
        };
// ...
cout << has_iterator<int>::value << endl;
```

C++ SFINAE examples: IsClassT

arguments. For each function template, if the argument deduction and checking succeeds, the *template-arguments* (deduced and/or explicit) are used to synthesize the declaration of a single function template specialization which is added to the candidate functions set to be used in overload resolution. If, for a given function template, argument deduction fails, no such function is added to the set of candidate functions for that template. The complete set of candidate functions includes all the synthesized declarations and all of

1.16.10 C++11: Traits mit decltype statt sizeof()-Tricks

Detect operator support with decltype/SFINAE

1.16.11 Überladene Templatefunktionen

Bedingte Compilation mittels `enable_if` und SFINAE:

`template <bool B, class T = void> struct enable_if;`	If `B` is `true`, the member typedef `type` shall equal `T`; otherwise, there shall be no member typedef `type`.

1.16.11.1 enable_if-Funktionen

```
#include <iostream>
#include <cmath>
#include <limits>

using namespace std;

template <typename ArithmeticLike1, typename ArithmeticLike2>
typename std::enable_if<std::is_arithmetic<ArithmeticLike1>::value,
                        double>::type
  geomMittel2(const ArithmeticLike1& a, const ArithmeticLike2& b)
{
    return sqrt(abs(a*b));
}

// uebersetze mit -std=c++11
// oder g++ CXXFLAGS="-std=c++11" ...

int main()
{
    cout << geomMittel2(3.0, 300.0) << endl;
    cout << geomMittel2(3, 300.0) << endl;
    cout << geomMittel2(-3, 300.0) << endl;
    cout << geomMittel2(-3, 300) << endl;
    cout << geomMittel2(3.0, 'c') << endl;
    // cout << geomMittel2(3.0, "c") << endl;

    return 0;
}
```

1.16.11.2 enable_if-Funktionsüberladen

3.2 Overlapping enabler conditions

```
template <class T>
typename enable_if<std::is_integral<T>::value, void>::type
foo(T t) {}

template <class T>
typename enable_if<std::is_arithmetic<T>::value, void>::type
foo(T t) {}
```

Beide foo()-Deklarationen schließen sich nicht gegenseitig aus, erzeugen also mehrdeutigen Code. Durch Kombination ähnlich ... possible to use std::enable_if to ... kann das vermieden werden:

```
struct A
{
    template <typename T>
    typename std::enable_if<std::is_integral<T>::value, T>::type foo()
    {
        std::cout << "integral" << std::endl;
        return T();
    }

    template <typename T>
    typename std::enable_if<!std::is_integral<T>::value, T>::type foo()
    {
        std::cout << "not integral" << std::endl;
        return T();
    }
}
}
```

Function Overloading Based on Arbitrary Properties of Types

1.16.11.3 bedingte „template class specializations“

3.1 Enabling template class specializations

```
template <class T, class Enable = void>
class A { ... };

template <class T>
class A<T, typename enable_if<std::is_integral<T>::value>::type> { ... };

template <class T>
class A<T, typename enable_if<std::is_float<T>::value>::type> { ... };
```

Ein Beispiel:

```
#include <iostream>
#include <vector>
using namespace std;

template <typename T, typename Enable = void>
struct A { A(){ cout<< "is something other ..." << endl;} };

template <typename T>
struct A<T, typename enable_if<is_floating_point<T>::value>::type> {
A(){ cout<< "is floatingpoint" << endl;}
};

template <typename T>
struct A<T, typename enable_if<is_integral<T>::value>::type> {
A(){ cout<< "is integral" << endl;}
};
```

```
template <typename T>
struct A<T, typename enable_if<!is_pod<T>::value>::type> {
A(){ cout<< "is no pod" << endl;}
};

template <typename T>
struct A<T, typename enable_if<(is_enum<T>::value)&&(is_scalar<T>::value)
    >::type> {
A(){ cout<< "is enum and scalar" << endl;}
};

int main(){
  typedef vector<string> vektortype1;
  typedef int* IntPointerType;
  enum Farbe {ROT, GELB, GRUEN, BLAU};

  A<char>();
  A<signed>();
  A<float>();
  A<vektortype1>();
  A<Farbe>();
  A<IntPointerType>();
}
```

und die Ergebnisse:

```
is integral
is integral
is floatingpoint
is no pod
is enum and scalar
is something other ...
```

Siehe auch: std::conditional

1.17 Template-Deklarationen zur Erzeugung von Objektdateien mit einer Ansammlung von Template-Instanzen

```
#include <iostream>
#include <cmath>
using namespace std;

template <typename ArithmeticLike1, typename ArithmeticLike2>
double geomMittel2(const ArithmeticLike1& a,
                   const ArithmeticLike2& b)
{
    return sqrt(abs(a*b));
}

template double geomMittel2<short, float>(const short&, const float&);
template double geomMittel2<int, float>(const int&, const float&);
template double geomMittel2<long, float>(const long&, const float&);
template double geomMittel2<float, float>(const float&, const float&);
template double geomMittel2<double, float>(const double&, const float&);
template double geomMittel2<long double, float>(const long double&, const
    float&);
// ...
template double geomMittel2<short, double>(const short&, const double&);
template double geomMittel2<int, double>(const int&, const double&);
template double geomMittel2<long, double>(const long&, const double&);
template double geomMittel2<float, double>(const float&, const double&);
template double geomMittel2<double, double>(const double&, const double&);
template double geomMittel2<long double, double>(const long double&, const
     double&);
// ...
template double geomMittel2<short, long double>(const short&, const long
    double&);
template double geomMittel2<int, long double>(const int&, const long
    double&);
template double geomMittel2<long, long double>(const long&, const long
    double&);
template double geomMittel2<float, long double>(const float&, const long
    double&);
template double geomMittel2<double, long double>(const double&, const long
     double&);
template double geomMittel2<long double, long double>(const long double&,
    const long double&);
```

Besser: Eine Sammlung von Objektdateien, die jeweils (nur) eine Instantiierung enthält, damit die erzeugte Bibliothek nur die benötigten Kompilationseinheiten einbinden läßt.

1.18 Wo ist die Template-Instanz?

Abschnitt 7.5: Where's the template?

Abschnitt 7.9: GNU-Compilerunterstützung für Type Traits

g++-Compileroptionen mit Template-Relevanz:

```
-fno-implicit-templates
-fno-implicit-inline-templates
-fno-pretty-templates
-frepo
```

(siehe g++-Manual, Kapitel 3).

1.19 C++11 extern template

C++11 extern template
N1448

1.20 Generic Programming

www.generic-programming.org mit:

- (viele/meherere/...) konkrete Implementierungen `->` größtallgemeine Templateversion (Lifting), Requirements
- Muster immer wieder gemeinsam auftretender Requirements: Concepts
- hierarchische Sortierung der Concepts der Anwendungsdomain

problem domains of generic libraries

Example generic algorithms/concepts:

- generische Algorithmen mit „Requirements on Types“:
  sort()
  power()
  accumulate()
  ...
  fill()
- Concepts:
  Associative Container
  Assignable
  ...
  Default Constructible

1.21 Generic Programming in ConceptC++

http://www.generic-programming.org/languages/conceptcpp/

Concepts mit:

1. functions, operators, constructors, ...
2. associated types (return_type, value_type, difference_type, ...)

(Concepts können Verfeinerungen anderer Concepsts sein (Vererbung))

concept_maps weisen Typen als konzeptmodellierend aus und beschreiben eine eventuell nichtbuchstabengetreue, per Abblilung vermittelte Konzepterfüllung (Morphismus). Sie ermöglichen retroaktives Modellieren.

Requirement-Klauseln ermöglichen vollständige zielgerichtete Fehlermeldungen bei Konzeptverletzung sowohl bei Instantiierungsversuch eines Templates mit einem falschen generischen Parameter als auch bei der Nutung von mehr als der durch Requirement-Klauseln geforderten Eigenschaften in der Template-Implementierung.

Konzeptbasiertes Funktionsüberladen ohne `enable_if` möglich.

C++-Standardbibliothek mit Konzepten.

ConceptGCC Download

1.22 Concepts, concept_maps, axioms

`void fill(ForwardIterator first, ForwardIterator last, const T& value)`

wie es in C++11 ist: 25.3.6
wie es hätte sein können: 25.2.6
im SGI STL-Manual

Siehe Concepts, concept maps, axioms
Aus der konzeptnutzenden STL:

```
template<ForwardIterator Iter, class V>
        requires Assignable<Iter::value_type,V>
        void fill(Iter first, Iter last, const V& v);
```

und die Benutzung:

```
fill(0, 9, 9.9);
                // error: int is not a ForwardIterator

fill(&v[0], &v[9], 9.9);
                      // ok: int* is a ForwardIterator
```

Fehlermeldung bei der Implementierung mit unzureichender Requirementliste:

```
template<ForwardIterator Iter, class V>
        requires Assignable<Iter::value_type,V>
void fill(Iter first, Iter last, const V& v)
{
        while (first!=last) {
                *first = v;
                first=first+1;  // error: + not defined
                                // for Forward_iterator
        }
}
```

Concept based overloading:

```
// iterator-based standard sort (with concepts):
template<Random_access_iterator Iter>
        requires Comparable<Iter::value_type>
void sort(Iter first, Iter last); // use the usual implementation

// container-based sort:
template<Container Cont>
        requires Comparable<Cont::value_type>
void sort(Cont& c)
{
        sort(c.begin(),c.end());     // simply call the iterator
            version
}

void f(vector<int>& v)
{
        sort(v.begin(), v.end());    // one way
        sort(v);                     // another way
        // ...
}
```

concept_maps:
Zeiger sind Vorbild für Iteratoren, ihnen fehlt jedoch der assoziierte Typ `value_type`. Dem kann man mit einer `concept_map` abhelfen:

```
template<typename T>
concept_map ForwardIterator<T*> {
        typedef T value_type;
};
```

Axioms:

```
concept Semigroup<typename Op, typename T> : CopyConstructible<T>
   {
        T operator()(Op, T, T);
        axiom Associativity(Op op, T x, T y, T z) {
                op(x, op(y, z)) <=> op(op(x, y), z);
        }
}

concept Monoid<typename Op, typename T> : Semigroup<Op, T> {
        T identity_element(Op);
        axiom Identity(Op op, T x) {
                op(x, identity_element(op)) <=> x;
                op(identity_element(op), x) <=> x;
        }
}
// in concept TotalOrder:
axiom Transitivity(Op op, T x, T y, T z)
{
        if (op(x, y) && op(y, z)) op(x, z) <=> true;
                                // conditional equivalence
}
```

1.23 ConceptC++-Tutorial

vergleiche http://www.generic-programming.org/languages/conceptcpp/tutorial/

Ausgangspunkt: ein oder mehrere konkrete Algorithmen

```
double sum(double array[], int n)
{
  double result = 0;
  for (int i = 0; i < n; ++i)
    result = result + array[i];
  return result;
}
```

Erster Verallgemeinerungsschritt:

```
template<typename T>
T sum(T array[], int n)
{
  T result = 0;
  for (int i = 0; i < n; ++i)
    result = result + array[i];
  return result;
}
```

führt beim ersten Instantiierungsversuch

```
struct pod
{
  int i;
};

int main()
{
  pod values[3] = { {1}, {2}, {3} };
  sum(values, 3);
  return 0;
}
```

zu Fehlermeldungen:

```
> conceptg++ array1-1.C
array1-1.cc: In function 'T sum(T*, int) [with T = pod]':
array1-1.cc:19:   instantiated from here
array1-1.cc:5: error: conversion from 'int' to non-scalar type 'pod' requested
array1-1.cc:7: error: no match for 'operator+' in 'result + *((+(((unsigned int)i) * 4u)) + array)'
```

Die Spezifikation eines notwendigen Konzepts:

```
#include <concepts>
template<std::CopyConstructible T>
T sum(T array[], int n)
{
  T result = 0;
  for (int i = 0; i < n; ++i)
    result = result + array[i];
  return result;
}
```

Jetzt lautet die Fehlermeldung:

```
> conceptg++ array2.C

array2.cpp: In function 'T sum(T*, int)':
array2.cpp:5: error: conversion from 'int' to non-scalar type 'T' requested
array2.cpp:7: error: no match for 'operator+' in 'result + array[i]'
```

Vervollständigung des Sets der nötigen Konzepte:

```
template<std::CopyConstructible T>
  requires Addable<T>
  T sum(T array[], int n)
  {
    T result = 0;
    for (int i = 0; i < n; ++i)
      result = result + array[i];
    return result;
  }
```

Fehlermeldung:

```
array3.cpp: In function 'T sum(T*, int)':
array3.cpp:10: error: conversion from 'int' to non-scalar type 'T' requested
array3.cpp:12: error: no match for 'operator=' in 'result = Addable<T>::operator+(result, array[i])'
```

Erneute Vervolllständigung des Sets der benötigten Konzepte:

```
template<std::CopyConstructible T>
  requires Addable<T>, Assignable<T>
  T sum(T array[], int n)
  {
    T result = 0;
    for (int i = 0; i < n; ++i)
      result = result + array[i];
    return result;
  }
```

Immer noch Fehler:

```
array4.cpp: In function 'T sum(T*, int)':
array4.cpp:14: error: conversion from 'int' to non-scalar type 'T' requested
```

Letzte Erweiterung der benötigten Konzepte:

```
auto concept IntConstructible<typename T> {
  T::T(int);
};

template<std::CopyConstructible T>
  requires Addable<T>, Assignable<T>, IntConstructible<T>
  T sum(T array[], int n)
  {
    T result = 0;
    for (int i = 0; i < n; ++i)
      result = result + array[i];
    return result;
  }
```

und fehlerlose Übersetzung. Wir haben das Konzept für die generische Funktion `sum()` zusammengestellt.
Bemerkung: Nach Muster der STL (siehe zum Beispiel `accumulate()` wäre die folgende generische Version besser:

```
template<std::CopyConstructible T>
  requires Addable<T>, Assignable<T>
  T sum(T array[], int n, T result)
  {
    for (int i = 0; i < n; ++i)
      result = result + array[i];
    return result;
  }
```

Generische Programmierung ist die Programmierung mit Concepts!

Zweiter Verallgemeinerungsschritt: (Zeiger statt Felder)

```
template<std::CopyConstructible T>
  requires Addable<T>, Assignable<T>
  T sum(T* first, T* last, T result)
  {
    for (; first != last; ++first)
      result = result + *first;
    return result;
  }
```

Übersetzung ohne Fehlermeldung!

Dritter Verallgemeinerungsschritt: (Iteratoren statt Zeiger)

```
template<ForwardIterator Iter>
  requires Addable<Iter::value_type>, Assignable<Iter::value_type>
  Iter::value_type sum(Iter first, Iter last, Iter::value_type result)
  {
    for (; first != last; ++first)
      result = result + *first;
    return result;
  }
```

mit dem Konzept

```
concept ForwardIterator<typename Iter> {
  typename value_type;

  Iter& operator++(Iter& x);

  value_type& operator*(Iter);

  bool operator==(Iter, Iter);
  bool operator!=(Iter, Iter);
};
```

der `STL`.Übersetzung der Implementierung erfolgreich.

Jedoch Instantiierung mittels

```
...
double TestData[] = { 110.0, 10.0, 10.0};
std::cout << sum(TestData, TestData + 3, 0.0f)
...
```

führt zur Fehlermeldung, dass Zeiger keine Forwarditeratoren sin.Die `concept_map`

```
concept_map ForwardIterator<double*> {
  typedef double value_type;
};
```

behebt diese Unkenntnis.

Um alle Zeiger zu Forwarditeratoren zu machen, kann man folgende Konzeptmap einführen:

```
template<typename T>
concept_map ForwardIterator<T*> {
  typedef T value_type;
};
```

Retroaktive Konzepterfüllung:
Soll Die Klasse `Color`

```
class Color {
public:
   Color();
   Color mix(const Color& other) const;

   // ...
};
```

das Konzept `Addable` erfüllen, ist das durch

```
concept_map Addable<Color> {
  Color operator+(const Color& x, const Color& y) { return x.mix(y); }
};
```

erreichbar.

Vierter Verallgemeinerungsschritt: sum() result type different to Iter::value_type

```
template<ForwardIterator Iter, Assignable T>
   requires Addable<T>
  T sum(Iter first, Iter last, T result)
  {
    for (; first != last; ++first)
      result = result + *first;
    return result;
  }
```

Fehlermeldung:

```
op1.cpp: In function 'T sum(Iter, Iter, T)':
op1.cpp:26: error: no match for 'operator+' in 'result + * first'
op1.cpp:3: note: candidates are: T Addable<T>::operator+(const T&, const T&)
```

Neue Konzeptmap:

```
auto concept Addable<typename T, typename U = T> {
  T operator+(T x, U y);
};
template<ForwardIterator Iter, Assignable T>
requires Addable<T, value_type>
T sum(Iter first, Iter last, T result)
{
  for (; first != last; ++first)
    result = result + *first;
  return result;
}
```

Fehlerfrei!

Aufgabe: Überlege eine allgemeinere `sum`-Version, die Container statt mittels + mit einer beliebigen zweiargumentigen Operation `op(,)` verjüngt.

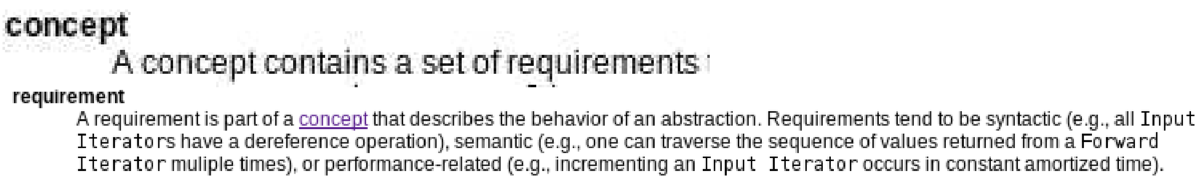
ConceptC++ führt den Programmierer generischer Funktionen oder Klassen Schritt für Schritt zur ausreichenden Deklaration der benötigten Eigenschaften der formalen generischen Parameter. Nach einmaliger erfolgreicher Übersetzung sind später keine Überraschungen wegen fehlenden Operationen mehr zu erwarten! Das erreicht ConceptC++ dadurch, dass es eine minimale Klasse, die nur genau die in allen Concepts genannten Operationen enthält (einen Archetyp) erzeut und für einen Testinstantiierungsversuch benutzt: Die Fehlermeldungen bei Nutzung von nicht in der Liste der Concepts genannte Operationen, die im Code der generischen Funktion/Klasse benutzt werden, sahen Sie oben.
Eine Sammlung von Konzepten findet man unter ConceptC++ Specification.

1.24 C++11: was aus C++03 ist nicht mehr da?

Features removed or deprecated:

„sequence point“, export template, NNN() throw(std::bad_alloc), auto_ptr, unary_function

1.25 aktueller Workaround: Nutzung von Typetraits statt von Concepts



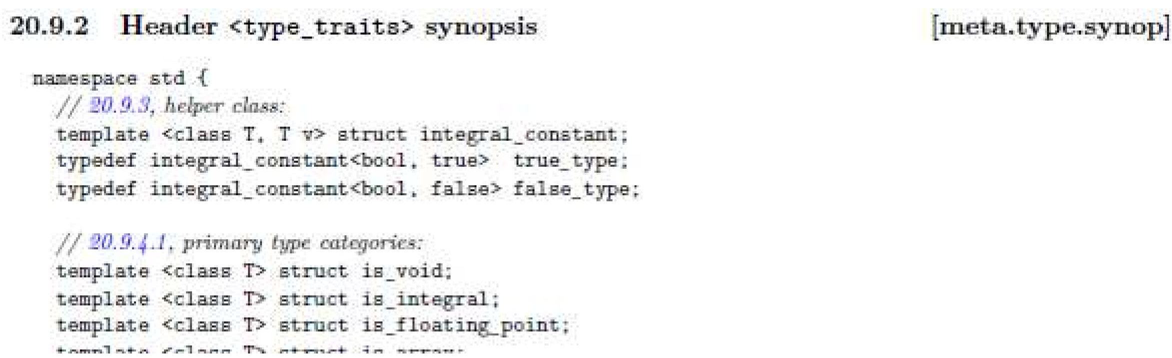
concept

A concept contains a set of requirements

requirement

A requirement is part of a concept that describes the behavior of an abstraction. Requirements tend to be syntactic (e.g., all `Input Iterators` have a dereference operation), semantic (e.g., one can traverse the sequence of values returned from a `Forward Iterator` muliple times), or performance-related (e.g., incrementing an `Input Iterator` occurs in constant amortized time).

(aus: Generic Programming Glossary)



20.9.2 Header <type_traits> synopsis [meta.type.synop]

```
namespace std {
  // 20.9.3, helper class:
  template <class T, T v> struct integral_constant;
  typedef integral_constant<bool, true>  true_type;
  typedef integral_constant<bool, false> false_type;

  // 20.9.4.1, primary type categories:
  template <class T> struct is_void;
  template <class T> struct is_integral;
  template <class T> struct is_floating_point;
```

std::integral_constant

Ein Workaround-Concept als Kombination mehrerer Traiteigenschaften an generische Parameter:

```
template<typename Iter, typename T>
struct is_summable:
  std::integral_constant<bool,
    NNN::is_input_iterator<Iter>::value &&
    std::is_assignable<T,T>::value &&
    boost::has_plus_assign<
                              T,
                              iterator_traits<iter>::value_type,
                              T
                             >::value
  >
{};
```

(Implementierungsidee ähnlich /usr/include/c++/4.7/type_traits)

Leider ist weder in BOOST noch in C++11 eine trait-Metafunktion is_input_iterator <> vordefiniert. In http://calder.sdml.cs.kent.edu/svn/origin/old/sandbox/iterators/include/origin/iterator/traits.hpp war sie noch vorhanden.
Siehe auch http://neoscientists.org/ tschwinger/boostdev/concept_traits/libs/concept_traits/doc/ (inzwischen nicht mehr in BOOST enthalten).

Also bleibt nur die Möglichkeit, gemäß 1.16.1 vorzugehen oder eine eigene Metafunktion nach den Ideen von 1.16.1 oder
http://stackoverflow.com/questions/8751460/how-to-restrict-an-iterator-to-being-a-forward-iterator
zu schreiben:

```
template <typename It>
typename std::enable_if<
    is_same<typename std::iterator_traits<It>::iterator_category,
            std::forward_iterator_tag>::value,
    bool>::type ...
```

oder besser (warum?):

```
template <typename It>
typename std::enable_if<std::is_base_of<std::forward_iterator_tag,
                              typename std::iterator_traits<It>::
                                  iterator_category>::value,
                         bool>::type ...
```

(aus: http://stackoverflow.com/questions/8751460/how-to-restrict-an-iterator-to-being-a-forward-iterator)

1.26 Assoziierte Typen

associated type

An associated type is a type that is used to describe the requirements of a concept, but is not actually a parameter to the concept. For instance, the reference type returned when dereferencing an Input Iterator is expressed as an associated type. In languages that do not directly support associated types, type parameters can be used instead at some cost to brevity.
(aus: http://www.generic-programming.org/about/glossary.php)

```
<class Iterator> struct iterator_traits {
  typedef typename Iterator::difference_type difference_type;
  typedef typename Iterator::value_type value_type;
  typedef typename Iterator::pointer pointer;
  typedef typename Iterator::reference reference;
  typedef typename Iterator::iterator_category iterator_category;
}
```

Associated Types

value_type, difference_type, ... in iterator_traits, ...:

```
namespace std {
template<class Iterator> struct iterator_traits {
typedef typename Iterator::difference_type difference_type;
typedef typename Iterator::value_type value_type;
typedef typename Iterator::pointer pointer;
typedef typename Iterator::reference reference;
typedef typename Iterator::iterator_category iterator_category;
};
\\ ...
template<class T> struct iterator_traits<T*> {
typedef ptrdiff_t difference_type;
typedef T value_type;
typedef T* pointer;
typedef T& reference;
typedef random_access_iterator_tag iterator_category;
};
// ...
}
```

Fallweise je nach Iteratortyp unterschiedlicher Code:
Neben der SFINE-Lösung vom Ende des vorherigen Abschnitts:

```
struct input_iterator_tag { };
struct output_iterator_tag { };
struct forward_iterator_tag : public input_iterator_tag { };
struct bidirectional_iterator_tag : public forward_iterator_tag { };
struct random_access_iterator_tag : public bidirectional_iterator_tag { };
```

Eine Hierarchie von Tags und Tag-Dispatching:

```
#include <iostream>
#include <vector>
#include <list>
#include <iterator>
```

```cpp
template< class BDIter >
void alg(BDIter, BDIter, std::bidirectional_iterator_tag)
{
    std::cout << "alg() called for bidirectional iterator\n";
}

template <class RAIter>
void alg(RAIter, RAIter, std::random_access_iterator_tag)
{
    std::cout << "alg() called for random-access iterator\n";
}

template< class Iter >
void alg(Iter first, Iter last)
{
    alg(first, last,
        typename std::iterator_traits<Iter>::iterator_category());
}

int main()
{
    std::vector<int> v;
    alg(v.begin(), v.end());

    std::list<int> l;
    alg(l.begin(), l.end());

//    std::istreambuf_iterator<char> i1(std::cin), i2;
//    alg(i1, i2); // compile error: no matching function for call
}
```

Beispiel eines eigenen assoziierten Typs:

```cpp
template <typename T1, typename T2>
struct promote_trait{
    typedef T1 T_promote;
};
template<> struct promote_trait<char, unsigned char> {
public:
        typedef int T_promote;
};
template<> struct promote_trait<short int, long> {
public:
        typedef long T_promote;
};
// ...
```

Siehe: promote_trait

1.27 Archetypen

http://www.generic-programming.org/languages/cpp/techniques.php#archetypes

Der Workaround „Nutzung von Traits statt Concepts“ versagt bei der Unterstützung des Autors generischer Konstrukte durch Nutzeffekte von Archetypen!

1.28 Generic Programming Techniques of the BOOST Libraries

Survey of some of the generic programming techniques used in the boost libraries

Anatomy of a Concept
Traits
C++ type_traits
BOOST type_traits
Tag dispatching
Adaptors
Type generators
Metaprogramming
Object generators
Policy classes
Policy-based design

Weitere C++ Template-Technologien:
Curiously Recurring Template Pattern
Restricted Template Expansion
Parameterized Base Class

1.29 POD-Typen

POD Types
C++11: POD = “trivial type“ or “standard-layout“

Move-Semantik für pod-Daten/Copy-Semantik für non-pod-Daten:

```
template<typename T>
void copy(T const* source,T* dest,unsigned count)
{
    static_assert(std::is_pod<T>::value,"T must be a POD");
    memcpy(dest,source,count*sizeof(T));
}

// ... oder besser pod/non-pod sensitives copy():

template<typename T>
typename std::enable_if<std::is_pod<T>::value,void>::type
copy(T const* source,T* dest,unsigned count)
{
    memcpy(dest,source,count*sizeof(T));
}

template<typename T>
typename std::enable_if<!std::is_pod<T>::value,void>::type
copy(T const* source,T* dest,unsigned count)
{
    for(unsigned i=0;i<count;++i)
    {
        *dest++=*source++;
    }
}
```

aus: pod/non-pod overloading in: Checking Concepts without Concepts in C++

1.30 Eigene Klassen-Tags und Tag-Dispatching

Alternativ Tag-Dispatching:

```
template <bool> struct podness {};
typedef podness<true> pod_tag;
typedef podness<false> non_pod_tag;

template <typename T> void f2(T, pod_tag) { /* POD */ }
template <typename T> void f2(T, non_pod_tag) { /* non-POD */ }

template <typename T>
void f(T x)
{
    // Dispatch to f2 based on tag.
    f2(x, podness<std::is_pod<T>::value>());
}
```

oder fallweise spezialisierte Klassen:

```
emplate <typename T, bool> struct f2;

template <typename T>
struct f2<T, true> { static void f(T) { /* POD */ } };

template <typename T>
struct f2<T, false> { static void f(T) { /* non-POD */ } };

template <typename T>
void f(T x)
{
    // Select the correct partially specialised type.
    f2<T, std::is_pod<T>::value >::f(x);
}
```

(aus: Tag dispatch versus static methods on partially specialised classes)

1.31 Für die Template-Programmierung interessante Neuerungen in C++11

constexpr
initialize lists
type inference: auto, decltype
range-based for-loop insbesondere bei der Existenz von Iteratoren:
- foreach and custom iterator
- Creating my own Iterators
- How to implement an STL-style iterator and avoid common pitfalls
- iterator library
- Iterator categories
- Custom Iterator in C++
- How to realize a custom implementation of a std-like iterator?

alternative function syntax
override and final
u9 string literals
defaulted and deleted special member functions
alias templates
variadic templates
C++11 - New features - Variadic templates

1.32 Curiously recurring template pattern

CRTP ist die Technologie, in der eine Kindklasse einer generischen Elternklasse den Zugriff auf sich selbst (mittel aktuellem Templateparameter) erlaubt.

```
template <typename T>
struct counter
{
    static int objects_created;
    static int objects_alive;

    counter()
    {
        ++objects_created;
        ++objects_alive;
    }
protected:
    ~counter() // objects should never be removed through pointers of this
        type
    {
        --objects_alive;
    }
};
template <typename T> int counter<T>::objects_created( 0 );
template <typename T> int counter<T>::objects_alive( 0 );

class X : counter<X>
{
    // ...
};

class Y : counter<Y>
{
    // ...
};
```

(aus Curiously recurring template pattern, 16.3 The Curiously Recurring Template Pattern (CRTP))

1.33 Objektorientierte Entwurfsmuster

Design Patterns
Entwurfsmuster

1.34 Sprechweisen bei C++(11)-Programmkonstrukten

Make C++ easy to teach and to learn without ...
More C++ Idioms

Effective C++, Third Edition, 2005; More Effective C++, 1996; Effective STL, 2001

1.35 Type Generator

Type Generator
type generators

1.36 Object Generator

object generators
std::pair

1.37 Parameterized Base Class

Parameterized Base Class
Mixin-Based Programming in C++

1.38 Barton-Nackman Trick (Restricted Template Expansion)

More C++ Idioms: Barton-Nackman trick
Wiki: Barton–Nackman trick

1.39 Die Boost Concept Check Library (BCCL)

Using Concept Checks:

```
#include <boost/concept_check.hpp>

template <class T>
void generic_library_function(T x)
{
  BOOST_CONCEPT_ASSERT((EqualityComparable<T>));
  // ...
};

template <class It>
class generic_library_class
{
  BOOST_CONCEPT_ASSERT((RandomAccessIterator<It>));
  // ...
};
//... BOOST_CONCEPT_ASSERT()
//     only for things seeable in the
//     template function definition
```

oder

```
#include <boost/concept/requires.hpp>
#include <boost/concept_check.hpp>

template<typename RanIter>
BOOST_CONCEPT_REQUIRES(
     ((Mutable_RandomAccessIterator<RanIter>))
     ((LessThanComparable<typename Mutable_RandomAccessIterator<RanIter>::
         value_type>)),
     (void)) // return type
     stable_sort(RanIter, RanIter);
//... otherwise
```

1.39.1 Difference of Draft C++ Cocepts and BCCL

What's the difference between C++0x concepts and The Boost Concept Check Library:

- Compiler brauchen Templates bis zur entgültigen Instantiierung nicht zu übersetzen, also auch nicht syntaktisch zu analysieren. Das Auftreten möglicher Fehlermeldungen ist deshalb bis zur Instantiierung aufgeschoben. Um eine vollständige Testabdeckung zu erreichen, benötigt man ein „Urmuster“ des Gebrauchs aller nach Konzept vorgeschriebenen Operationen, die testcompiliert vorhandene fehlende Operationsdefinitionen aufdecken würde: einen **Archetyp** des Konzepts.

  Die ursprünglich in den C++0x geplanten Konzepte hätten Archtypen automatisch erzeugt und benutzt, somit die Templatedefinition automatisch vollständig typgechecked. Das bisherige C++-template-Handling läßt mögliche in der Dokumentation einer Template-Bibliothek unerwähne Requirements eines generischen Objekts lange unentdeckt und frustriert zu unvorhergesehenen Zeiten dessen Benutzer mit einer bis dahin nie aufgetretenen Fehlermeldung(skaskade): Motivierendes BCCL-Beispiel.

Bei Benutzung der BCCL hat man eigene Konzepte selbst mit Archetypen auszustatten und diese testzucompilieren (siehe Abschmitt 1.21.3). Die in der BCCL vordefinierten für die STL nötigen Konzepte sind in der Datei `boost/concept_archetype.hpp` mit Archetypen ausgestattet.

Zum Beispiel das Konzept `InputIterator` mit den geforderten Operationen `++i, (void)i++, *i++,*i; Defaultkonstruktor, operator=, operator-> (TrivialIterator); Kopierkonstruktor, swap() (Assignable); operator==, operator!= (EqualtityComparable); Defaultkonstruktor (DefaultConstructible)` (vgl. STL InputIterator) und dem folgenden Archetyp dafür:

```
// ==========================================================================

// Iterator Archetype Classes

template <class T, int I = 0>
class input_iterator_archetype
{
private:
  typedef input_iterator_archetype self;
public:
  typedef std::input_iterator_tag iterator_category;
  typedef T value_type;
  struct reference {
    operator const value_type&() const { return static_object<T>::
        get(); }
  };
  typedef const T* pointer;
  typedef std::ptrdiff_t difference_type;
  self& operator=(const self&) { return *this;  }
  bool operator==(const self&) const { return true; }
  bool operator!=(const self&) const { return true; }
  reference operator*() const { return reference(); }
  self& operator++() { return *this; }
  self operator++(int) { return *this; }
};
```

- BCCL unterstützt die Überprüfung von semantischen Requirements wie z.B. Benutzbarkeit in Multipass-Algorithmen ... **nicht**!
- BCCL unterstützt das Syntaxremappping (temporäres renaming, Context_maps) **nicht**.
- BCCL unterstützt Kontext-basiertes Überladen **nicht**. (Ausweg: `enable_if` mit Concept Traits)

1.39.2 In der Boost-Bibliothek vordefinierte (STL-)Konzepte

Zur Referenz: boost/concept_check.hpp

Basic Concept Checking Classes

Zum Unterschied von `Assignable` und `SGIAssignable`:

```
template <class TT>
struct AssignableConcept
  {
    void constraints() {
#if !defined(_ITERATOR_) // back_insert_it broken for VC++ STL
      a = a;              // require assignment operator
#endif
      const_constraints(a);
    }
    void const_constraints(const TT& b) {
#if !defined(_ITERATOR_) // back_insert_it broken for VC++ STL
      a = b;              // const required for arg to assignment
#endif
    }
    TT a;
  };
```

im Vergleich zu:

```
// The SGI STL version of Assignable requires copy constructor and
   operator=
  template <class TT>
  struct SGIAssignableConcept
  {
    void constraints() {
      TT b(a);
#if !defined(_ITERATOR_) // back_insert_it broken for VC++ STL
      a = a;              // require assignment operator
#endif
      const_constraints(a);
      ignore_unused_variable_warning(b);
    }
    void const_constraints(const TT& b) {
      TT c(b);
#if !defined(_ITERATOR_) // back_insert_it broken for VC++ STL
      a = b;              // const required for arg to assignment
#endif
      ignore_unused_variable_warning(c);
    }
    TT a;
  };
```

Iterator Concept Checking Classes

```
template <class TT, class ValueT>
  struct OutputIteratorConcept
  {
```

```
    void constraints() {
      function_requires< AssignableConcept<TT> >();
      ++i;           // require preincrement operator
      i++;           // require postincrement operator
      *i++ = t;      // require postincrement and assignment
    }
    TT i, j;
    ValueT t;
  };
```

Function Object Concept Checking Classes

```
template <class Func, class Return>
  struct GeneratorConcept
  {
    void constraints() {
      const Return& r = f(); // require operator() member fct
      ignore_unused_variable_warning(r);
    }
    Func f;
  };
```

Container Concept Checking Classes

```
template <class Container>
  struct ContainerConcept
  {
    typedef typename Container::value_type value_type;
    typedef typename Container::difference_type difference_type;
    typedef typename Container::size_type size_type;
    typedef typename Container::const_reference const_reference;
    typedef typename Container::const_pointer const_pointer;
    typedef typename Container::const_iterator const_iterator;

    void constraints() {
      function_requires< InputIteratorConcept<const_iterator> >();
      function_requires< AssignableConcept<Container> >();
      const_constraints(c);
    }
    void const_constraints(const Container& c) {
      i = c.begin();
      i = c.end();
      n = c.size();
      n = c.max_size();
      b = c.empty();
    }
    Container c;
    bool b;
    const_iterator i;
    size_type n;
  };
```

1.40 Ein Blick zurück (2003..2008) — und vorwärts 2017? Usage-Pattern oder Pseudosignatur

(Am Anfang) „Usage Pattern“-FallstudienAnsatz:

Stroustrup: N1510 (2003)

```
template<class Value_type> struct Forward_iterator {
  static void constraints(Forward_iterator p)
  {
    Forward_iterator q = p; p = q; // can be copied
    p++; ++p;                      // can be incremented
    Value_type v = *p;             // points to Value_types
  }
  // ...
}
// ...
concept Element {
  constraints(Element e1, Element e2) {
    bool b =e1<e2;          // Elements can be compared using <
                            // and the result can be used as a
                            // bool
    swap(e1,e2);            // Elements can be swapped
  }
};
// ...
concept Add {               // We can copy and add Adds
  constraints(Add x) {
    Add y = x; x = y; x = x+y; Add xx = x+y;
  }
};

// ...
```

Der Pseudosignatur-Ansatz führt zunächst zu Problemen bei ähnlichen unterschiedlichen Signaturen.

Var<>-Platzhalter, where, &&(2006):

Stroustrup: Specifying C++ Concepts

```
concept Mutable_fwd<typename Iter, typename T> {
  Var<Iter> p;          // a variable of type Iter.
  Var<const T> v;       // a variable of type const T.

  Iter q = p;           // an Iter must be copy-able

  bool b = (p != q);    // must support != operation,
                        // and the resulting expression
                        // must be convertible to bool
  ++p;                  // must support pre-increment, no
                        // requirements on the result type

  *p = v;               // must be able to dereference p,
                        // and assign a const T to the
                        // result of that dereference; no
                        // requirements on the result type
};
//...
concept Small<typename T, int N>
  where sizeof(T) <= N
{ };
// ...
concept C<typename X>
  where C1<X> && C2<X>
{ };
// ...
concept Mutable_fwd<typename Iter, typename T> {
  Var<Iter> p;       // placeholder for variable of type Iter.
  Var<const T> v;
  Var<T> v2;
  // ... as before ...
  *p = v;            // we can write to *p
  v2 = *p;           // we can read from *p
};
// ...
```

```
concept Forward_iterator<typename Iter> {
  Var<Iter> p;               // a variable of type Iter.
  typename Iter::value_type  // must have a named member
                             // associated type value_type.
  Iter q = p;                // an Iter must be copy-able
  bool b = (p != q);         // must support == and !=
  b = (p == q);              // operations, and the resulting
                             // expressions must be convertible
                             // to bool.
  ++p;                       // must support pre- and
  p++;                       // post-increment operations, no
                             // assumption on the result type
};
// ...
concept Copy_constructible<typename T> {
  Var<T> a;
  T b = a;          // copy construction
  T c(a);           // direct copy construction
};

concept Assignable<typename T, typename U = T> {
  Var<T> a;
  Var<const U> b;
  a = b;          // copy (non-destructive read)
};

concept Movable<typename T, typename U = T> {
  Var<T> a;
  Var<U> b;
  a = b;          // potentially-destructive read
};

concept Equality_comparable<typename T, typename U = T> {
  Var<const T> a;
  Var<const U> b;
  bool eq = (a == b);
  bool neq = (a != b);
};
// ...
concept Container<typename X> {
  X::X(int n);
  X::~X();
  bool X::empty() const;
}
```

1.41 Creating Own Boost Concept Checking Classes

1.41.1 Ein Beispiel

Example

```
// #include <type_traits>
template <class X>
struct InputIterator
  : Assignable<X>, EqualityComparable<X>
{
 private:
    typedef std::iterator_traits<X> t;
 public:
    typedef typename t::value_type value_type;
    typedef typename t::difference_type difference_type;
    typedef typename t::reference reference;
    typedef typename t::pointer pointer;
    typedef typename t::iterator_category iterator_category;

    BOOST_CONCEPT_ASSERT((SignedInteger<difference_type>));
    BOOST_CONCEPT_ASSERT((Convertible<iterator_category,
                                      std::input_iterator_tag>));

    BOOST_CONCEPT_USAGE(InputIterator)
    {
        X j(i);             // require copy construction
        same_type(*i++,v); // require postincrement-
                            // dereference returning value_type
// or in C++11:
//       static_assert(is_same(*i++,v)::value);
        X& x = ++j;         // require preincrement returning X&
    }

 private:
    X i;
    value_type v;

    // Type deduction will fail unless the arguments have the
    // same type.
    template <typename T>
    void same_type(T const&, T const&);
};
```

Kochrezept:

- Concept Checking „Template Class“ mit Namen des Konzepts erstellen
- Notwendige Vater-Konzepte mittels Vererbung spezifizieren (hier: `Assignable` und `EqualitiyComparable`)
- Nötige assoziierte Typen mittels `typedef` als Membertype definieren
- Durch `BOOST_CONCEPT_ASSERT()` nötige Einschränkungen an die assoziierten Typen formulieren
- Mittels `BOOST_CONCEPT_USAGE()` die geforderten Eigenschaften (Operationen) der das Konzept erfüllenden Klassen (als Usage-Pattern) spezifizieren
- Für `BOOST_CONCEPT_USAGE()` nötige Objektdeklarationen als Datamember der „Concept Checking Class“ und eventuell nötige Funktionsdeklarationen (wie hier `same_type(.,.)`) vornehmen

1.41.2 Erstellung eines zugehörigen Archetypes

Concept Covering and Archetypes
archetypes
see: 5 Concept Covering

Ein Beispiel:

```
template <class T>
class input_iterator_archetype
{
private:
  typedef input_iterator_archetype self;
public:
  typedef std::input_iterator_tag iterator_category;
  typedef T value_type;
  struct reference {
    operator const value_type&() const { return static_object<T>::get(); }
  };
  typedef const T* pointer;
  typedef std::ptrdiff_t difference_type;
  self& operator=(const self&) { return *this;  }
  bool operator==(const self&) const { return true; }
  bool operator!=(const self&) const { return true; }
  reference operator*() const { return reference(); }
  self& operator++() { return *this; }
  self operator++(int) { return *this; }
};
```

Die Testabdeckungsüberprüfung kann durch einen Instantiierungsversuch der Archetypen der Requirements aller generischen Algorithmen erreicht werden, zum Beispiel:

```
  typedef less_than_comparable_archetype<
      sgi_assignable_archetype<> > ValueType;
  random_access_iterator_archetype<ValueType> ri;
  std::stable_sort(ri, ri);
```

1.42 Programmieren mit Konzepten

Minimiere die Requirements an die Input-Parameter generischer Komponenten, um deren Wiederverwendbarkeit zu steigern. Damit erreicht man die größtmögliche Allgemeinheit!

Konzepte (Kombinationen von Requirements) sind ein Sprachmechanismus, der es gestattet, dem Compiler (oder zur Zeit wenigstens dem Benutzer einer generischen Bibliothek in Kommentarform) verbindlich mitzuteilen, welche Typeigenschaften ein generischer Algorithmus (ein Template-Konstrukt) benutzen darf beziehungsweise welche Eigenschaften ein Typ besitzen muß, damit er als aktueller generischer Parameter für eine Template-Instantiierung benutzt werden darf.

Table 1. Concepts, constraints, and axioms

Concepts		*Constraints*	
Regularity	*Iterators*	*Operators*	*Language*
Comparable	Iterator	Equal	Same
Ordered	Forward_iterator	Less	Common
Copyable	Bidirectional_iterator	Logical_and	Derived
Movable	Random_access_iterator	Logical_or	Convertible
Regular		Logical_not	Signed_int
		Callable	
Functional	*Types*	*Initialization*	*Other*
Function	Boolean	Destructible	Procedure
Operation		Constructible	Input_iterator
Predicate		Assignable	Output_iterator
Relation			
Axioms			
Equivalence_relation			
Strict_weak_order			
Strict_total_order			
Boolean_algebra			

```
concept Ordered< Regular T> {
    requires constraint Less<T>;
    requires axiom Strict_total_order<less<T>, T>;
    requires axiom Greater<T>;
    requires axiom Less_equal<T>;
    requires axiom Greater_equal<T>;
}
```

We factor out the axioms just to show that we can, and because they are examples of axioms that might find multiple uses:

```
template<typename T>
axiom Greater(T x, T y) {
    (x>y) == (y<x);
}
template<typename T>
axiom Less_equal(T x, T y) {
    (x<=y) == !(y<x);
}
template<typename T>
axiom Greater_equal(T x, T y) {
    (x>=y) == !(x<y);
}
```

2 Metaprogrammierung

Metaprogramming is the writing of computer programs that write or manipulate other programs (or themselves) as their data, or that do part of the work at compile time that would otherwise be done at runtime. In some cases, this allows programmers to minimize the number of lines of code to express a solution (hence reducing development time), or it gives programs greater flexibility to efficiently handle new situations without recompilation. ...
aus: Metaprogramming

2.1 Metafunktionen

```
promote_trait <.,.>::T_promote
numeric_limits <.>::max()
iterator_traits <.>::value_type
```

Metafunktionen (Metaprogrammierung) sind uns schon an diversen Stellen begegnet:
`promote_trait<T1,T2>::T_promote` in

```
template <typename T1, typename T2>
   typename promote_trait<T1,T2>::T_promote my_function(T1 x, T2 y)
//          ----------------------------------
{
\\...
}
```

stellt den mit `T1, T2` assoziierten Typ `T_promote` bereit (vergleiche Abschnitt 1.16.4).

```
  cout << "Minimum value for int: " << numeric_limits<int>::min() << endl;
//                                     ----------------------------
  cout << "Maximum value for int: " << numeric_limits<int>::max() << endl;
//                                     ----------------------------
  cout << "int is signed: " << numeric_limits<int>::is_signed << endl;
//                             --------------------------------
  cout << "Non-sign bits in int: " << numeric_limits<int>::digits << endl;
//                                    -----------------------------
  cout << "int has infinity: " << numeric_limits<int>::has_infinity << endl;
//                                ------------------------------------
```

druckt Eigenschaften der numerischen Typen mittels Typfunktionen aus. Siehe

```
static constexpr T min() noexcept;
static constexpr T max() noexcept;
static constexpr bool is_signed;
static constexpr int digits;
static constexpr bool has_infinity;
```

im Standard http://www.open-std.org/jtc1/sc22/wg21/docs/papers/2011/n3242.pdf beziehungsweise in http://publib.boulder.ibm.com/infocenter/comphelp/v9v111/index.jsp?topic=/com.ibm.xlcpp9.aix.doc/standlib/header_limits.htm.

```
template <class InputIterator>
iterator_traits<InputIterator>::value_type
last_value(InputIterator first, InputIterator last) {
//...
}
```

greift auf den `InputIterator` assoziierten `value_type` zu, siehe
http://www.sgi.com/tech/stl/iterator_traits.html.

„A metafunction is a construct to map some types or constants to other entities like types, constants, functions, or objects at compile time. The name metafunction comes from fact that they can be regarded as part of a meta-programming language that is evaluated during compilation.“ (http://trac.seqan.de/wiki/Tutorial/Metafunctions)

Run time, compile time vs. runtime, mit dem GCC zur ausführbaren Datei (Binary)

Implementiert wurden sie im geschichtlichen Verlauf durch **enum**, **static const**, integral_constant <> beziehungsweise constexpr-Konstruktionen:

```
                                                        // vor C++03
#include <iostream>

template<int i>
class fact {
  public:
    enum { result = i * fact<i-1>::result };
};

template<>class fact<1> {
  public:
    enum { result = 1 };
};

int main(){

   std::cout << fact<5>::result << std::endl;
}

///////////////////////////////////////////////

#include <iostream>                     // C++03

template<int i>
class fact {
  public:
    static const long long result = i * fact<i-1>::result;
};

template<>class fact<1> {
  public:
    static const long long result = 1;
};

int main(){

   std::cout << fact<5>::result << std::endl;
};

////////////////////////////////////////////////
```

```
#include <iostream>                          // ab C++11
#include <type_traits>

template <unsigned n>
struct fact : std::integral_constant<int,n * fact<n-1>::value> {};

template <>
struct fact<0> : std::integral_constant<int,1> {};

int main() {
  std::cout << fact<5>::value;  // constexpr (no calculations on runtime)
  return 0;
}

///////////////////////////////////////////////

#include <iostream>                          // oder

constexpr long long fact(int value) {
  return (value==0) ? 1 : value * fact(value-1);
};



int main(){

    std::cout <<  fact(5) << std::endl;
    return 0;
}
```

2.2 Metafunktionen in /usr/include/c++/4.7/type_traits und Feldlängen

Metafunktion `integral_constant` in `type_traits`:

```
  /// integral_constant
  template<typename _Tp, _Tp __v>
    struct integral_constant
    {
      static constexpr _Tp                  value = __v;
      typedef _Tp                           value_type;
      typedef integral_constant<_Tp, __v>   type;
      constexpr operator value_type() { return value; }
    };

  /// The type used as a compile-time boolean with true value.
  typedef integral_constant<bool, true>     true_type;

  /// The type used as a compile-time boolean with false value.
  typedef integral_constant<bool, false>    false_type;
```

```
  template<typename _Tp, _Tp __v>
    constexpr _Tp integral_constant<_Tp, __v>::value;
(http://publib.boulder.ibm.com/infocenter/comphelp/v9v111/index.jsp?topic=/com.ibm.xlcpp9.aix.doc/standlib/header_type_traits.htm)

  /// is_array
  template<typename>
    struct is_array
    : public false_type { };

  template<typename _Tp, std::size_t _Size>
    struct is_array<_Tp[_Size]>
    : public true_type { };

  template<typename _Tp>
    struct is_array<_Tp[]>
    : public true_type { };

/////////////////////////////////////////////

  /// is_unsigned
  template<typename _Tp>
    struct is_unsigned
    : public __and_<is_arithmetic<_Tp>, __not_<is_signed<_Tp>>>::type
    { };

/////////////////////////////////////////////

  /// Define a member typedef @c type only if a boolean constant is true.
  template<bool, typename _Tp = void>
    struct enable_if
    { };

  // Partial specialization for true.
  template<typename _Tp>
    struct enable_if<true, _Tp>
    { typedef _Tp type; };

/////////////////////////////////////////////
```

Benutzung von Nontype-Templateparametern für die Länge von Containern:

```
#include <iostream>
#include <numeric>

template <typename Type, size_t n>
Type sum(const Type (&tp)[n])
{
    return std::accumulate(tp, tp+n, Type());
}

int main()
{
    int x[10];
    for(int l = 0; l < 10; l++)
        x[l] = l;

    std::cout << sum(x) << std::endl;

    return(0);
}
```

Nontype template parameter
What does template <**unsigned int** N> mean?

2.3 Factorial, Combinations, IF, id, add und die Rekursion statt der Schleife

Template-Metaprogrammierung:

```
template <int N>
struct Factorial
{
    enum { value = N * Factorial<N - 1>::value };
};

template <>
struct Factorial<0>
{
    enum { value = 1 };
};

// Factorial<4>::value == 24
// Factorial<0>::value == 1
void foo()
{
    int x = Factorial<4>::value; // == 24
    int y = Factorial<0>::value; // == 1
}

//                n!
// C(k,n) = ------------
//              k! (n-k)!

template <int k, int n>
struct Combinations
{
    enum { RET = Factorial<n>::RET/(Factorial<k>::RET*Factorial<n-k>::RET)
        };
};

cout << Combinations<2,4>::RET << endl;
```

Templates mit zwei non-type int-Parametern statt eines nicht erlaubten non-type float-Parameters: C++ Template Metaprogramming.

Bedingte Typauswahl:

```
// IF
template <bool condition, class Then, class Else>
struct IF
{
    typedef Then RET;
};

template <class Then, class Else>
struct IF<false, Then, Else>
{
    typedef Else RET;
};

// if sizeof(int) < sizeof(long) then use long else use int
IF< sizeof(int)<sizeof(long), long, int >::RET  i;
```

C++-Metaprogrammierung:

```
template <unsigned int x>
struct id
{
enum { value = x };
};

template <unsigned int x, unsigned int y>
struct add
{
enum { value = x + y };
};

//...

template <int x>
struct id_static
{
static const int value = x;
};

template <int x>
struct id_static_constexpr
{
static constexpr int value = x;
};
```

2.4 Rechnende Compiler:

Erwin Unruh: Die Entdeckung des rechnenden Compilers:

```
// Erwin Unruh, untitled program,
// ANSI X3J16-94-0075/ISO WG21-462, 1994.

template <int i>
struct D
{
    D(void *);
    operator int();
};

template <int p, int i>
struct is_prime
{
    enum { prim = (p%i) && is_prime<(i>2?p:0), i>::prim };
};

template <int i>
struct Prime_print
{
    Prime_print<i-1>    a;
    enum { prim = is_prime<i,i-1>::prim };
    void f() { D<i> d = prim; }
};

struct is_prime<0,0> { enum { prim = 1 }; };
struct is_prime<0,1> { enum { prim = 1 }; };
struct Prime_print<2>
{
    enum { prim = 1 };
    void f() { D<2> d = prim; }
};

void foo()
{
    Prime_print<10> a;
}

// output:
// unruh.cpp 30: conversion from enum to D<2> requested in Prime_print
// unruh.cpp 30: conversion from enum to D<3> requested in Prime_print
// unruh.cpp 30: conversion from enum to D<5> requested in Prime_print
// unruh.cpp 30: conversion from enum to D<7> requested in Prime_print
// unruh.cpp 30: conversion from enum to D<11> requested in Prime_print
// unruh.cpp 30: conversion from enum to D<13> requested in Prime_print
// unruh.cpp 30: conversion from enum to D<17> requested in Prime_print
// unruh.cpp 30: conversion from enum to D<19> requested in Prime_print
```

constexpr is_prime_recursive

2.5 Typfunktionen: längerer Datentyp, IfThenElse-Werte

Typfunktionen liefern anstelle eines Datenwertes (einer Konstanten) einen oder mehrere Datentypen *oder* sind von Datentypen abhängig:

```
template <int bits>
struct number_type
{
  typedef int type;
};
template <>
struct number_type <16>
{
  typedef short type;
};
template <>
struct number_type <8>
{
  typedef char type;
};
template <typename arg>
struct bitsize
{
  enum { value = sizeof(arg) * 8 };
};
template <typename arg>
struct bigger_type
{
  typedef typename number_type<bitsize<arg>::value * 2 >::type type;
};
```

Bedingte Werte:

```
template <bool cond , int true_part , int false_part >
struct IfThenElse ;
template <int true_part , int false_part >
struct IfThenElse <true , true_part , false_part >
{
enum { value = true_part };
};
template <int true_part , int false_part >
struct IfThenElse <false , true_part , false_part >
{
enum { value = false_part };
};
```

2.6 Template Nontype Parameter

Abschnitt 14.3.2: Template non-type arguments
Abschnitt 5.19: Constant expressions
Non-type template parameters
Was sind die Voraussetzungen für C++-Template-Parameter?
What are the requirements for C++ template parameters?

C++: Why can't I use float value as a template parameter?
template+floating point non type
How can I use a floating-point value as a non-type template parameter?
Why are floating point types invalid template parameter types for template functions?
c++ template parameter is ambiguous

Workaround:
Floating point arithmetic in C++ templates.

Beachte dabei auch:
ldexp() und frexp().
ieee754.h und der Zugriff auf Vorzeichen, Exponent und Mantisse:

```
#include <iostream>
#include <cmath>
#include <ieee754.h>

int main()
{
  float num = 4.0 * atan(1.0);  // PI

  ieee754_float ft;
  ft.f = num;

  std::cout << ft.ieee.negative << std::endl;
  std::cout << ft.ieee.exponent << std::endl;
  std::cout << ft.ieee.mantissa << std::endl;

  // prints:
  // 0
  // 128
  // 4788187

  ieee754_float ft2;
  ft2.ieee.negative = ft.ieee.negative;
  ft2.ieee.exponent = ft.ieee.exponent;
  ft2.ieee.mantissa = ft.ieee.mantissa;

  std::cout << ft2.f << std::endl;

  // prints:
  // 3.14159

  return 0;
}
```

2.7 Compilezeit-Fehlermeldungen in constexpr-Metafunktionen

Aus Andrzej's C++ blog:

```
constexpr int factorial( int i )
{
    return (i > 1) ? i * factorial(i - 1)
                   : 1;
}
```

oder besser:

```
constexpr int safe_factorial( int i )
{
    return (i < 0) ?                      // error condition
                     throw exception()    // error reporting
                   : factorial(i);        // real computation
}
```

Mittels einer mit selbstsprechendem Bezeichnernamen gewählten Hilfsmetafunktion:

```
constexpr int requires_nonnegative( int i )
{
  return (i < 0) ? throw exception()
                 : i;
}
```

wird die Compiler-Fehlermeldung selbsidentifizierend:

```
constexpr int safe_factorial( int i )
{
    return requires_nonnegative(i),
           factorial(i);
}
```

Eine Klasse mit Compiletime Kontruktor:

```
class Date
{
     unsigned d;
     Month m;
     unsigned y;

     public:
     constexpr Date( unsigned d, Month m, unsigned y );
     // other stuff ...
};

constexpr Date::Date( unsigned d, Month m, unsigned y )
: d( requires_goodDay(d, m, y) )
, m(m)
, y( requires_positive(y) )
{} // empty body
```

```
constexpr unsigned requires_goodDay( unsigned d, Month m, unsigned y )
{
    return (d == 0 || d > 31) ?        throw BadDayName(d)            :
           (is30day(m) && d == 31) ? throw BadDayOfMonth(d, m)      :
           (m == Feb && d >= 30) ?   throw BadDayOfMonth(d, m)      :
           (!isLeap(y) && m == Feb && d == 29) ? throw Bad29Feb(y) :
           d; // real return value
}
```

Vergleiche:
BOOST::optional
constexpr-unions
utility class to represent optional objects (Revision 2)
Parsing strings at compile-time — Part I
Parsing strings at compile-time — Part II
User-defined literals — Part I
User-defined literals — Part II
User-defined literals — Part III

2.8 Vor- und Nachteile der Metaprogrammierung

Vor- und Nachteile der Template-Metaprogrammierung:

- **Längere Übersetzungszeit und kürzere Ausführungszeit:** Da der gesamte Template-Quelltext während der Übersetzung verarbeitet, ausgewertet und eingesetzt wird, dauert die Übersetzung insgesamt länger, während der ausführbare Code dadurch an Effizienz gewinnen kann. Obwohl dieser Zusatzaufwand im Allgemeinen sehr gering ausfällt, kann er auf große Projekte oder Projekte, in denen intensiv Templates eingesetzt werden, großen Einfluss auf die Dauer der Übersetzung besitzen.
- **Kürzerer Quelltext:** Templatemetaprogrammierung erlaubt es dem Programmierer, sich auf die Architektur des Programms zu konzentrieren und dem Compiler die Erzeugung von jeglichen Implementierungen, die vom aufrufenden Quelltext benötigt werden, zu überlassen. Daher kann Templatemetaprogrammierung zu kürzerem Quelltext und erhöhter Wartbarkeit führen.
- **Schlechtere Lesbarkeit:** Verglichen mit konventioneller C++-Programmierung wirken Syntax und Schreibweisen der Templatemetaprogrammierung ungewohnt. Fortgeschrittene oder sogar die meiste nicht-triviale Templatemetaprogrammierung kann daher schwer zu verstehen sein. Dadurch können Metaprogramme von Programmierern, die in Templatemetaprogrammierung unerfahren sind, schwer zu pflegen sein. Letzteres hängt allerdings auch davon ab, wie die Templatemetaprogrammierung im speziellen Fall umgesetzt wurde.
- **Geringere Portierbarkeit:** Die Portierbarkeit von Quelltext, der von Template-Metaprogrammierung starken Gebrauch macht, kann auf Grund von Unterschieden zwischen den verschiedenen Compilern eingeschränkt sein.
- **Ungewohnter Programmierstil:** Durch die rein-funktionale Struktur der Templates wären zwar theoretisch Optimierungen wie etwa in Haskell (Glasgow Haskell Compiler) möglich, praktisch werden solche Vorteile jedoch von keinem Compiler ausgenutzt und statt dessen verursacht diese Struktur in erster Linie (insbesondere für Programmierer, die strukturierte Programmierung aus C++ gewohnt sind) schwer verständlichen Code.
- **Schlechte Fehlermeldungen und schlechte Debuggbarkeit**

2.9 C++11 Metaprogramming Examples

```
// Here are a few tricks I've used with the trunk versions of clang and libc++
// with C++11 compilation turned on. Some might be obvious, some not, but at
// least they are some kind of improvement over their C++03 counterparts.
//
// Public domain.
// ==========================================================================
// 1) Using variadic class templates recursively, like in the definitions for
// "add<T...>" here:

#include <type_traits>

// A few convenience aliases first
template <typename T, T N> using ic = std::integral_constant<T, N>;
template <int N>           using int_ = std::integral_constant<int, N>;

// Sum any number of integral constants:
template <typename... Args> struct add;
template <>
struct add<>
       : ic<int, 0> {};

template <typename A>
struct add<A>
       : ic<decltype(+A::value), A::value> {};

template <typename A, typename B, typename... More>
struct add<A, B, More...>
       : add<ic<decltype(A::value + B::value),
                       A::value + B::value>, More...> {};

// --- example ---------------------------------------------------------------

add<>::value; // 0
add<int_<1>>::value; // 1
add<int_<1>, int_<2>>::value; // 3
add<int_<1>, int_<2>, int_<3>>::value; // 6
add<int_<1>, int_<2>, int_<3>, int_<4>>::value; // 10
// etc.

// ==========================================================================
// 2a) With decltype, the "sizeof(yes_type)" trick is no longer needed for
// implementing traits. This one tests whether there is a type T::type
// defined:

using std::true_type;
using std::false_type;

namespace detail {
          template <typename T, typename Type=typename T::type>
          struct has_type_helper;

          template <typename T> true_type has_type_test(has_type_helper<T> *);
          template <typename T> false_type has_type_test(...);

}

template <typename T>
         struct has_type : decltype(detail::has_type_test<T>(nullptr)) {};

// --- example ---------------------------------------------------------------

has_type<int>::value;                                   // false
has_type<std::is_integral<int>>::value;                 // true, said type is "bool"
has_type<std::integral_constant<int,1>>::value;         // true, said type is "int"
```

```
// ---------------------------------------------------------------------------------
// 2b) This trait tests whether T is an integral constant:

namespace detail {

          template <typename T, decltype(T::value)>
                   struct integral_constant_helper;

          template <typename T> true_type integral_constant_test(
                                 integral_constant_helper<T,T::value> *);

          template <typename T> false_type integral_constant_test(...);
}

template <typename T>
         struct is_integral_constant
               : decltype(detail::integral_constant_test<T>(nullptr)) {};

// --- example -------------------------------------------------------------------
is_integral_constant<int>::value;                              // false
is_integral_constant<std::is_integral<int>>::value;            // true
is_integral_constant<std::integral_constant<int,1>>::value; // true

// =================================================================================

// 3) Selection of the first matching type from a list of cases (or "pattern
// matching", if you will):

   template <typename... When> struct match;
   template <> struct match<> { static constexpr bool value = false; };
   template <typename When, typename... More> struct match<When, More...>
            : std::conditional<When::value, When, match<More...>>::type {};

// 'match' is meant to be used together with 'when', 'otherwise' and
// friends:

         template <bool Cond, typename Then=void> struct when_c;
         template <typename Then> struct when_c<true, Then> {
                  typedef Then type;
                  static constexpr bool value = true;
         };

         template <typename Then> struct when_c<false, Then> {
                  static constexpr bool value = false;
         };

         template <bool Cond, typename Then=void>
                  struct when_not_c : when_c<!Cond, Then> {};

         template <typename Cond, typename Then=void>
                  struct when : when_c<Cond::value, Then> {};

         template <typename Cond, typename Then=void>
                  struct when_not : when_not_c<Cond::value, Then> {};

         template <typename Then> struct otherwise {
                  typedef Then type;
                  static constexpr bool value = true;
         };

// --- example -------------------------------------------------------------------

struct fizz {};
struct buzz {};
struct fizzbuzz {};
```

```
template <int N>
    struct game : match<
        when_c<N % 3 == 0 && N & 5 == 0, fizzbuzz>,
        when_c<N % 3 == 0, fizz>,
        when_c<N % 5 == 0, buzz>,
        otherwise< int_c<N>>
    > {};

game<1>::type;   // int_<1>
game<2>::type;   // int_<2>
game<3>::type;   // fizz
game<4>::type;   // int_<4>
game<5>::type;   // buzz
game<6>::type;   // fizz
game<7>::type;   // int_<7>
game<8>::type;   // int_<8>
game<9>::type;   // fizz
game<10>::type;  // buzz
game<11>::type;  // int_<11>
game<12>::type;  // fizz
game<13>::type;  // int_<13>
game<14>::type;  // int_<14>
game<15>::type;  // fizzbuzz
game<16>::type;  // int_<16>

// ==========================================================================
// 4a) Variadic template template parameters. For instance,
// boost::mpl::quoteN<...> can be reimplemented with just:

   template <template <typename...> class F>
       struct quote {
           template <typename... Args> struct apply : F<Args...> {};
       };

// --------------------------------------------------------------------------
// 4b) Here's another use for variadic template template parameters. Of course,
// the standard library offers std::tuple_size<T> for getting the number of
// elements in a tuple. But that metafunction cannot be used for any other
// tuple-like class. Suppose we defined boost::mpl::vector like:

   template <typename... T>
          struct vector {};

// By using a variadic template template, we can define a metafunction which
// works equally for both std::tuple<T...> as well as vector<T...>:

   template <typename T>
          struct size {}; // (no size defined by default)

   template <template <typename...> class C, typename... T>
          struct size<C<T...>> : ic<std::size_t, sizeof...(T)> {};

   template <typename T> struct size<T &> : size<T> {};
   template <typename T> struct size<T &&> : size<T> {};
   template <typename T> struct size<T const> : size<T> {};
   template <typename T> struct size<T volatile> : size<T> {};
   template <typename T> struct size<T const volatile> : size<T> {};

// --- example --------------------------------------------------------------

   size<tuple<int, int> &>::value;        // 2
   size<vector<int, int, int>>::value;    // 3
   size<vector<> const &>::value;         // 0

// ==========================================================================
// 5) Using nested variadic templates to get many template parameter packs to
```

```
// play with:

namespace detail {
        template <typename A> struct con;
        template <typename... T> struct con<vector<T...>> {
                template <typename B> struct cat;
                template <typename... U> struct cat<vector<U...>> {
                        typedef vector<T..., U...> type;
                };
        };
}

template <typename A, typename B>
        struct concat : detail::con<A>::template cat<B> {};

// --- example ---------------------------------------------------------------

struct a; struct b; struct c; struct d; struct e;
concat<vector<a, b>, vector<c, d, e>>::type; // vector<a, b, c, d, e>

// ===========================================================================
// 6) Defining function result and result type at once.

#define RETURNS(...) decltype((__VA_ARGS__)) { return (__VA_ARGS__); }

// --- example ---------------------------------------------------------------

template <typename A, typename B>
auto plus(A const & a, B const & b) -> RETURNS(a + b)

// It can't be used with recursive definitions like here, though:

struct mul_ {
      int operator()() const { return 1; }

      template <typename A>
      A operator()(A const & a) const { return a; }

      // template <typename A, typename B, typename... C>
      // auto operator()(A const & a, B const & b, C const &... c) const ->
      // RETURNS(mul_()(a * b, c...))

      // --> Error: invalid use of incomplete type mul_

      // std::declval helps, but duplicates the multiplication part:
      template <typename A, typename B, typename... C>
      auto operator()(A const & a, B const & b, C const &... c) const ->
      decltype(std::declval<mul_>()(a * b, c...)) {
           return mul_()(a * b, c...);
      }
};

constexpr mul_ mul = {}; // global function object

// --- example ---------------------------------------------------------------

mul();                // 1
mul(10);              // 10
mul(10, -20, 30.0);   // -6000.0

// ===========================================================================
// 7) Counted template recursion. The function "apply_tuple(f, t)" calls the
// function (function object) "f" with the elements of the tuple "t" as
// arguments. (To simplify things a bit, I omitted the perfect forwarding
// support in this example.)
//
```

```
// The count is tracked with a total number of iterations N, and the running
// index I. R is the precalculated result type.

namespace detail {
   template <typename R, std::size_t N, std::size_t I=0>
          struct apply_tuple {
                 template <typename F, typename T, typename... Args>
                 R operator()(F f, T const & t, Args const &... args) const {
                   typedef apply_tuple<R, N, I + 1> next;
                   return next()(f, t, args..., std::get<I>(t));
                 }

          };

  template <typename R, std::size_t N> struct apply_tuple<R, N, N> {
         template <typename F, typename T, typename... Args>
         R operator()(F f, T const &, Args const &... args) const {
           return f(args...);
         }
  };
}

template <typename F, typename... T>
decltype(std::declval<F>()(std::declval<T const &>()...))
apply_tuple(F f, std::tuple<T...> const & t) {
             typedef decltype(std::declval<F>()(std::declval<T const &>()...))
                     result;
             return detail::apply_tuple<result, sizeof...(T)>()(f, t);

}

// --- example ---------------------------------------------------------------
int f(int a, int b) { return a + b; }
apply_tuple(f, std::make_tuple(10, 20)); // 30

auto t = std::make_tuple(10, -20, 30.0);
apply_tuple(mul, t); // -6000.0
```

(aus C++11 metaprogramming)

2.10 Fortgeschrittene Metaprogrammierung

2.10.1 Domain specific language extensions: C++11 Compile-time rational arithmetic

Bruch-Arithmetik mit Zähler/Nenner aus `intmax_t`.

```
namespace std {
// 20.10.3, class template ratio
template <intmax_t N, intmax_t D = 1> class ratio;
// 20.10.4, ratio arithmetic
template <class R1, class R2> using ratio_add = see below;
template <class R1, class R2> using ratio_subtract = see below;
template <class R1, class R2> using ratio_multiply = see below;
template <class R1, class R2> using ratio_divide = see below;
// 20.10.5, ratio comparison
template <class R1, class R2> struct ratio_equal;
template <class R1, class R2> struct ratio_not_equal;
template <class R1, class R2> struct ratio_less;
template <class R1, class R2> struct ratio_less_equal;
template <class R1, class R2> struct ratio_greater;
template <class R1, class R2> struct ratio_greater_equal;
// 20.10.6, convenience SI typedefs
typedef ratio<1, 1000000000000000000000000> yocto; // see below
typedef ratio<1, 1000000000000000000000> zepto; // see below
typedef ratio<1, 1000000000000000000> atto;
typedef ratio<1, 1000000000000000> femto;
typedef ratio<1, 1000000000000> pico;
typedef ratio<1, 1000000000> nano;
typedef ratio<1, 1000000> micro;
typedef ratio<1, 1000> milli;
typedef ratio<1, 100> centi;
typedef ratio<1, 10> deci;
typedef ratio< 10, 1> deca;
typedef ratio< 100, 1> hecto;
typedef ratio< 1000, 1> kilo;
typedef ratio< 1000000, 1> mega;
typedef ratio< 1000000000, 1> giga;
typedef ratio< 1000000000000, 1> tera;
typedef ratio< 1000000000000000, 1> peta;
typedef ratio< 1000000000000000000, 1> exa;
typedef ratio< 1000000000000000000000, 1> zetta; // see below
typedef ratio<1000000000000000000000000, 1> yotta; // see below
}
```

```
namespace std {
```

```
template <intmax_t N, intmax_t D = 1>
class ratio {
public:
typedef ratio<num, den> type;
static constexpr intmax_t num;
static constexpr intmax_t den;
};
}

static_assert(ratio_add<ratio<1,3>, ratio<1,6>>::num == 1, "1/3+1/6
    == 1/2");
static_assert(ratio_add<ratio<1,3>, ratio<1,6>>::den == 2, "1/3+1/6
    == 1/2");
static_assert(ratio_multiply<ratio<1,3>, ratio<3,2>>::num == 1, "
    1/3*3/2 == 1/2");
static_assert(ratio_multiply<ratio<1,3>, ratio<3,2>>::den == 2, "
    1/3*3/2 == 1/2");
```

2.10.2 Unrolled Loops: Durch Rekursion wegoptimierte Schleifen

Schleifen ohne Verwaltungsoverhead:
Tailrekursion statt Iteration
Ausgangspunkt (laufzeit-iterativ):

```
template <typename T>
inline T dot_product (T* a, T* b, int dim)
{
  T result = T();
  for (int i = 0; i < dim; i++)
  {
    result += a[i] * b[i];
  }
  return result;
}
```

Optimiert (Compilezeit-tailrekursive Metafunktion)

```
template <int N, typename T>
struct dotproduct_s
{
  static T result (T* a, T* b)
  {
    return (*a)*(*b) + dotproduct_s<N-1,T>::result(a+1, b+1);
  };
};
template <typename T>
struct dotproduct_s<1, T>
{
  static T result (T* a, T* b)
  {
    return (*a)*(*b);
  };
};
template <int N, typename T>
inline T dotproduct(T* a, T* b)
{
  return dotproduct_s<N, T>::result(a, b);
}
int main ()
{
int a [3] = {1, 2, 3};
int b [3] = {4, 5, 6};
std :: cout << dot_product(a, b, 3) << std :: endl ;
std :: cout << dotproduct<3>(a, b) << std :: endl ;
return 0;
}
```

Codedissassembly:

```
Listing: Mit Schleife (dot_product)
push ebp
mov ebp , esp
push edi
push esi
```

```
push ebx
mov edi , DWORD PTR [ ebp +8]
mov esi , DWORD PTR [ ebp +12]
mov ebx , DWORD PTR [ ebp +16]
mov ecx , 0
mov edx , 0
cmp ecx , ebx
jge L32
L30 :
mov eax , DWORD PTR [ edi + edx *4]
imul eax , DWORD PTR [esi +edx *4]
add ecx , eax
inc edx
cmp edx , ebx
jl L30
L32 :
mov eax , ecx
pop ebx
pop esi
pop edi
pop ebp
ret
```

```
Listing: Ohne Schleife (dotproduct_s)
push ebp
mov ebp , esp
push ebx
mov edx , DWORD PTR [ ebp +8]
mov ebx , DWORD PTR [ ebp +12]
mov eax , DWORD PTR [ edx ]
imul eax , DWORD PTR [ebx ]
mov ecx , DWORD PTR [ edx +4]
imul ecx , DWORD PTR [ebx +4]
mov edx , DWORD PTR [ edx +8]
imul edx , DWORD PTR [ebx +8]
add ecx , edx
add eax , ecx
pop ebx
pop ebp
ret
```

Acht Anweisungen statt 18 Anweisungen.
(Metaprogrammierung Seite 45ff.)

Endrekursion
Tailrekursion

2.10.3 Expression templates

C++ Expression templates:
Expression templates are a category of C++ template meta programming which delays evaluation of subexpressions until the full expression is known, so that optimizations (especially the elimination of temporaries) can be applied. (lazy evaluation)
Zum Beispiel:
statt `x = a + b + c` der Aufruf von `Expression<Expression<Array,plus,Array>,plus,Array>` mit

```
struct plus {
  static int apply(int a, int b) {
    return (a + b); }
};

template < typename L, typename OpTag, typename R >
struct Expression {
  Expression(L const& l, R const& r) : l(l), r(r) {}
    int operator[](unsigned index) const {
      return OpTag::apply(l[index],r[index]);
    }
    L const& l;
    R const& r;
};

template< typename L, typename R >
Expression<L,plus,R> operator+(L const& l, R const& r) {
  return Expression<L,plus,R>(l,r);
}
...
// verzoegerte Ausdrucksauswertung (lazy evaluation)
// --- sofort wird nur der Parsbaum aufgebaut ---
// bis zur Aktivierung von operator=
template<typename Expr> {
Array& Array::operator=(Expr const& x) {
  for(unsigned i = 0; i < this->size(); ++i) {
    (*this)[i] = x[i];
  return (*this);
}
```

(Metaprogrammierung)

Matrixdimension	Zeit (nicht opt.)[s]	Zeit (opt.)[s]
100x100	1.776	1.059
200x200	7.204	4.237
300x300	17.091	9.796
400x400	30.305	18.087
500x500	46.842	28.154
600x600	85.316	54.125
700x700	114.167	73.604

Dr.Dobbs: Expression Templates
A. Langer: Expression Templates
Blitz++

2.11 Nachteile der Metaprogrammierung (Forts.)

Metaprogrammierung-Nachteile Seite 52
Metaprogrammierung-Nachteile Seite 17

2.12 Die BOOST Metaprogramming Library MPL

Will man selbst Metafunktionsbibliotheken schreiben sollte man die MPL nutzen:
MPL

2.13 Metaprogramme für die Manipulation von Typen in C++

Typelists
Metafunktionen für Container (Sequenzen, Listen, ...) von Typen:

```
template<class List1, class List2>
struct TypeListAppend
{
    typedef TypeList<typename List1::Head, typename TypeListAppend<
       typename List1::Tail, List2 >::Result> Result;
};
template<class List2>
struct TypeListAppend<NullType, List2>
{
    typedef List2 Result;
};
// Auf die Implementierung von TypeListBeforePivot und TypeListAfterPivot
    soll hier verzichtet werden
template<class List, template<typename A, typename B> class Comparator>
struct TypeListSort
{
    typedef typename TypeListAppend<
                        typename TypeListSort<
                            typename TypeListBeforePivot<
                                typename List::Tail,
                                typename List::Head,
                                Comparator>::Result,
                            Comparator>::Result,
                        TypeList<
                            typename List::Head,
                            typename TypeListSort<
                                typename TypeListAfterPivot<
                                    typename List::Tail,
                                    typename List::Head,
                                    Comparator>::Result,
                                Comparator>::Result
                            >
                        >::Result Result;
};
```

Funktionale Programmierung
Lisp
Scheme
Scala

2.14 Spracherweiterung Maßeinheiten

2.14.1 Eine Softwarekatastrophe und ihr Einfluß auf neue Programmiersprachen

Anlaß: 1999 verpasste die NASA-Sonde Mars Climate Orbiter den Landeanflug auf den Mars, weil die Programmierer das falsche Maßsystem verwendeten - Pfund x Sekunde statt Newton x Sekunde. Die NASA verlor dadurch die Sonde.

Einheiten können durch geeignete Klassen (`Euro, Franken, Pfund,` ... statt `double`) mit (automatisch durchgefürten) Typkonversionen ähnlich wie in

```
class Euro
{
private:
  double Wert;
public:
  Euro() : Wert(0.0) {};
  Euro(double w) : Wert(w) {};
  Euro(const Euro &e) : Wert(e.Wert) {};
  Euro(DM dw);
  double ZeigeWert() const { return Wert; };
  friend Euro operator+(Euro a, Euro b);
  friend Euro operator-(Euro a, Euro b);
  friend Euro operator*(Euro a, double d);
  friend Euro operator/(Euro a, double d);
  friend bool operator<(Euro a, Euro b);
  friend ostream&  operator<<(ostream& os, const Euro& e);
};
Euro::Euro(DM dw)
{
  Wert = dw.ZeigeWert() / 1.95583;
}
```

realisiert werden.

Flexibler ist es jedoch, wenn die Programmiersprache Maßeinheiten unterstützt:

- Units und Dimensions in Fortress:

$$kineticEnergy(m : \mathbb{R}\ \underline{\mathrm{kg}}, v : \mathbb{R}\ \underline{\mathrm{m/s}}) : \mathbb{R}\ \underline{\mathrm{kg\ m^2/s^2}} = (m\ v^2)/2$$

encoded as `kg_`
and rendered in
roman font

`m_`	*is rendered as*	m	`s_`	*is rendered as*	s
`km_`	*is rendered as*	km	`kg_`	*is rendered as*	kg
`V_`	*is rendered as*	V	`kW_`	*is rendered as*	kW
`_v`	*is rendered as*	**v**	`_foo13`	*is rendered as*	$\mathbf{foo}_{13}$

$$v : \mathbb{R}\ \mathrm{m/s} = (3\,\mathrm{meters} + 4\,\mathrm{meters})/5\,\mathrm{seconds}$$

Corre

$$v : \mathbb{R}\ \mathrm{m/s} = (\underline{3\,\mathrm{meters} + 4\,\mathrm{seconds}})/5\,\mathrm{seconds}$$

static error

$$v : \mathbb{R}\ \mathrm{m/s} = (\underline{3\,\mathrm{meters} + 4\,\mathrm{meters})/5}$$

static error

$$kineticEnergy(3.14\,\mathrm{kg}, \underline{32\,\mathrm{f/s}\ \mathtt{in}\ \mathrm{m/s}})$$

unit conversion

- Units und Dimensions in der Programmiersprache F#

```
let gravityOnEarth = 9.81<m/s^2>   // Beschleunigung
let heightOfDrop   = 3.5<m>        // Laenge
let speedOfImpact  = sqrt(2.0 * gravityOnEart * heightOfDrop)
```

C++11 bleibt leider bei den SI-Skalierfaktoren

```
// 20.10.6, convenience SI typedefs
typedef ratio<1, 1000000000000000000000000> yocto; // see below
typedef ratio<1, 1000000000000000000000> zepto; // see below
typedef ratio<1, 1000000000000000000> atto;
typedef ratio<1, 1000000000000000> femto;
typedef ratio<1, 1000000000000> pico;
typedef ratio<1, 1000000000> nano;
typedef ratio<1, 1000000> micro;
typedef ratio<1, 1000> milli;
typedef ratio<1, 100> centi;
typedef ratio<1, 10> deci;
typedef ratio< 10, 1> deca;
typedef ratio< 100, 1> hecto;
typedef ratio< 1000, 1> kilo;
typedef ratio< 1000000, 1> mega;
typedef ratio< 1000000000, 1> giga;
typedef ratio< 1000000000000, 1> tera;
typedef ratio< 1000000000000000, 1> peta;
typedef ratio< 1000000000000000000, 1> exa;
typedef ratio< 1000000000000000000000, 1> zetta; // see below
typedef ratio<1000000000000000000000000, 1> yotta; // see below
```

stehen, was die Unterstützung von Maßeinheiten angeht.

Kann uns da Metaprogrammierung helfen?

2.14.2 DSLs

In software development and domain engineering, a domain-specific language (DSL) is a programming language or specification language dedicated to a particular problem domain, a particular problem representation technique, and/or a particular solution technique. The concept isn't new—special-purpose programming languages and all kinds of modeling/specification languages have always existed, but the term has become more popular due to the rise of domain-specific modeling.

Scala DSLs
DSLs
C++ template metaprogramming for DSLs

2.14.3 Ausflug in die Domain des technische-wissenschaftlichen Rechnens: Units and Measure in F#

Introducing Units:

```
[<Measure>] type kg
[<Measure>] type m
[<Measure>] type s

let gravityOnEarth = 9.81<m/s^2>
let heightOfMyOfficeWindow = 3.5<m>

let speedOfImpact = sqrt(2.0 * gravityOnEarth * heightOfMyOfficeWindow)
...
```

`speedOfImpact` hat die Einheit `<m/s>`.
Der Fehler

```
let speedOfImpact = sqrt(2.0 * gravityOnEarth + heightOfMyOfficeWindow)
...
```

führt zur Compiler-Fehlermeldung
`The unit measure 'm' does not match the unit measure 'm/s^2'.`

`Unit Conversions:`

```
...
let heightOfMyOfficeWindow = 11.5<ft>
let FeedPerMetre = 3.28084<ft/m>
...
let heightOfMyOfficeWindowInMetres = heightOfMyOfficeWindow /
   FeedPerMetre
...
type float = float<1>
...
```

Generic Units
Parameterized Types

2.14.4 SI-Einheitssystem

Dezimale Vielfache und Teile der SI-Einheiten: Seite 23
Sieben Dimensionen von Meßgrößen: Seite 9
Basiseinheiten, abgeleitete Einheiten, ...: Seite 18, 19, 20, 21, 24, 27, 29ff.

2.14.5 Boost.Units

Automatische Einheiten-Dimensionsrechnung in C++

```
#include <complex>
#include <iostream>

#include <boost/typeof/std/complex.hpp>

#include <boost/units/systems/si/energy.hpp>
#include <boost/units/systems/si/force.hpp>
#include <boost/units/systems/si/length.hpp>
#include <boost/units/systems/si/electric_potential.hpp>
#include <boost/units/systems/si/current.hpp>
#include <boost/units/systems/si/resistance.hpp>
#include <boost/units/systems/si/io.hpp>

using namespace boost::units;
using namespace boost::units::si;

quantity<energy>
work(const quantity<force>& F, const quantity<length>& dx)
{
    return F * dx; // Defines the relation: work = force * distance.
}

int main()
{
    /// Test calculation of work.
    quantity<force>     F(2.0 * newton); // Define a quantity of force.
    quantity<length>    dx(2.0 * meter); // and a distance,
    quantity<energy>    E(work(F,dx));  // and calculate the work done.

    std::cout << "F  = " << F << std::endl
              << "dx = " << dx << std::endl
              << "E  = " << E << std::endl
              << std::endl;

    /// Test and check complex quantities.
    typedef std::complex<double> complex_type; // double real and
       imaginary parts.
```

```
    // Define some complex electrical quantities.
    quantity<electric_potential, complex_type> v = complex_type(12.5,
       0.0) * volts;
    quantity<current, complex_type>            i = complex_type(3.0,
       4.0) * amperes;
    quantity<resistance, complex_type>         z = complex_type(1.5,
       -2.0) * ohms;

    std::cout << "V   = " << v << std::endl
              << "I   = " << i << std::endl
              << "Z   = " << z << std::endl
              // Calculate from Ohm's law voltage = current *
                 resistance.
              << "I * Z = " << i * z << std::endl
              // Check defined V is equal to calculated.
              << "I * Z == V? " << std::boolalpha << (i * z == v) <<
                 std::endl
              << std::endl;
    return 0;
}
```

produziert folgende Ausgabe:

```
F  = 2 N
dx = 2 m
E  = 4 J

V   = (12.5,0) V
I   = (3,4) A
Z   = (1.5,-2) Ohm
I*Z = (12.5,0) V
I*Z == V? true
```

Boost.Units benutzt Metafunktionen, um quantity<.>-Werte mit automatischer Dimensionsanalyse zu ermöglichen:

```
quantity<length> L = 2.0*meters;                     // quantity of
    length
quantity<time>   E = 14.5*seconds;                   // quantity of
    time
// mit:
// template<class Unit,class Y = double> class quantity;
//
```

Conversions

Pool von vordefinierten Konstanten
alphabetische Liste der Grundeinheiten

Meßungenauigkeiten und Fehlerfortpflanzung:

```
quantity<length,measurement<double> >
    u(measurement<double>(1.0,0.0)*meters),
    w(measurement<double>(4.52,0.02)*meters),
    x(measurement<double>(2.0,0.2)*meters),
    y(measurement<double>(3.0,0.6)*meters);
```

mit den Ergebniswerten (Fehlerbalken):

```
x+y-w         = 0.48(+/-0.632772) m
w*x           = 9.04(+/-0.904885) m^2
x/y           = 0.666667(+/-0.149071) dimensionless

...

w*y^2/(u*x)^2 = 10.17(+/-3.52328) m^-1
w/(u*x)^(1/2) = 3.19612(+/-0.160431) dimensionless
```

Dabei wurde die folgende Benutzererweiterung verwendet:

```
// Boost.Units - A C++ library for zero-overhead dimensional
   analysis and
// unit/quantity manipulation and conversion
//
// Copyright (C) 2003-2008 Matthias Christian Schabel
// Copyright (C) 2008 Steven Watanabe
//
// Distributed under the Boost Software License, Version 1.0. (
   See
// accompanying file LICENSE_1_0.txt or copy at
// http://www.boost.org/LICENSE_1_0.txt)

#ifndef BOOST_UNITS_MEASUREMENT_HPP
#define BOOST_UNITS_MEASUREMENT_HPP

#include <cmath>
#include <cstdlib>
#include <iomanip>
#include <iostream>

#include <boost/io/ios_state.hpp>
#include <boost/units/static_rational.hpp>

namespace boost {
```

```
namespace units {

namespace sqr_namespace /**/ {

template<class Y>
Y sqr(Y val)
{ return val*val; }

} // namespace

using sqr_namespace::sqr;

template<class Y>
class measurement
{
    public:
        typedef measurement<Y>                 this_type;
        typedef Y                              value_type;

        measurement(const value_type& val = value_type(),
                    const value_type& err = value_type()) :
            value_(val),
            uncertainty_(std::abs(err))
        { }

        measurement(const this_type& source) :
            value_(source.value_),
            uncertainty_(source.uncertainty_)
        { }

        //~measurement() { }

        this_type& operator=(const this_type& source)
        {
            if (this == &source) return *this;

            value_ = source.value_;
            uncertainty_ = source.uncertainty_;

            return *this;
        }

        operator value_type() const    { return value_; }

        value_type value() const       { return value_; }
        value_type uncertainty() const { return uncertainty_; }
```

```
        value_type lower_bound() const { return value_-
           uncertainty_; }
        value_type upper_bound() const { return value_+
           uncertainty_; }

        this_type& operator+=(const value_type& val)
        {
            value_ += val;
            return *this;
        }

        this_type& operator-=(const value_type& val)
        {
            value_ -= val;
            return *this;
        }

        this_type& operator*=(const value_type& val)
        {
            value_ *= val;
            uncertainty_ *= val;
            return *this;
        }

        this_type& operator/=(const value_type& val)
        {
            value_ /= val;
            uncertainty_ /= val;
            return *this;
        }

        this_type& operator+=(const this_type& /*source*/);
        this_type& operator-=(const this_type& /*source*/);
        this_type& operator*=(const this_type& /*source*/);
        this_type& operator/=(const this_type& /*source*/);

    private:
        value_type          value_,
                            uncertainty_;
};

}

}

#if BOOST_UNITS_HAS_BOOST_TYPEOF
```

```
BOOST_TYPEOF_REGISTER_TEMPLATE(boost::units::measurement, 1)

#endif

namespace boost {

namespace units {

template<class Y>
inline
measurement<Y>&
measurement<Y>::operator+=(const this_type& source)
{
    uncertainty_ = std::sqrt(sqr(uncertainty_)+sqr(source.
       uncertainty_));
    value_ += source.value_;

    return *this;
}

template<class Y>
inline
measurement<Y>&
measurement<Y>::operator-=(const this_type& source)
{
    uncertainty_ = std::sqrt(sqr(uncertainty_)+sqr(source.
       uncertainty_));
    value_ -= source.value_;

    return *this;
}

template<class Y>
inline
measurement<Y>&
measurement<Y>::operator*=(const this_type& source)
{
    uncertainty_ = (value_*source.value_)*
              std::sqrt(sqr(uncertainty_/value_)+
                        sqr(source.uncertainty_/source.value_));
    value_ *= source.value_;

    return *this;
}
```

```
template<class Y>
inline
measurement<Y>&
measurement<Y>::operator/=(const this_type& source)
{
    uncertainty_ = (value_/source.value_)*
              std::sqrt(sqr(uncertainty_/value_)+
                        sqr(source.uncertainty_/source.value_));
    value_ /= source.value_;

    return *this;
}

// value_type op measurement
template<class Y>
inline
measurement<Y>
operator+(Y lhs,const measurement<Y>& rhs)
{
    return (measurement<Y>(lhs,Y(0))+=rhs);
}

template<class Y>
inline
measurement<Y>
operator-(Y lhs,const measurement<Y>& rhs)
{
    return (measurement<Y>(lhs,Y(0))-=rhs);
}

template<class Y>
inline
measurement<Y>
operator*(Y lhs,const measurement<Y>& rhs)
{
    return (measurement<Y>(lhs,Y(0))*=rhs);
}

template<class Y>
inline
measurement<Y>
operator/(Y lhs,const measurement<Y>& rhs)
{
    return (measurement<Y>(lhs,Y(0))/=rhs);
}
```

```
// measurement op value_type
template<class Y>
inline
measurement<Y>
operator+(const measurement<Y>& lhs,Y rhs)
{
    return (measurement<Y>(lhs)+=measurement<Y>(rhs,Y(0)));
}

template<class Y>
inline
measurement<Y>
operator-(const measurement<Y>& lhs,Y rhs)
{
    return (measurement<Y>(lhs)-=measurement<Y>(rhs,Y(0)));
}

template<class Y>
inline
measurement<Y>
operator*(const measurement<Y>& lhs,Y rhs)
{
    return (measurement<Y>(lhs)*=measurement<Y>(rhs,Y(0)));
}

template<class Y>
inline
measurement<Y>
operator/(const measurement<Y>& lhs,Y rhs)
{
    return (measurement<Y>(lhs)/=measurement<Y>(rhs,Y(0)));
}

// measurement op measurement
template<class Y>
inline
measurement<Y>
operator+(const measurement<Y>& lhs,const measurement<Y>& rhs)
{
    return (measurement<Y>(lhs)+=rhs);
}

template<class Y>
inline
measurement<Y>
operator-(const measurement<Y>& lhs,const measurement<Y>& rhs)
```

```
{
    return (measurement<Y>(lhs)-=rhs);
}

template<class Y>
inline
measurement<Y>
operator*(const measurement<Y>& lhs,const measurement<Y>& rhs)
{
    return (measurement<Y>(lhs)*=rhs);
}

template<class Y>
inline
measurement<Y>
operator/(const measurement<Y>& lhs,const measurement<Y>& rhs)
{
    return (measurement<Y>(lhs)/=rhs);
}

/// specialize power typeof helper
template<class Y,long N,long D>
struct power_typeof_helper<measurement<Y>,static_rational<N,D> >
{
    typedef measurement<
        typename power_typeof_helper<Y,static_rational<N,D> >::
           type
    > type;

    static type value(const measurement<Y>& x)
    {
        const static_rational<N,D>  rat;

        const Y m = Y(rat.numerator())/Y(rat.denominator()),
                newval = std::pow(x.value(),m),
                err = newval*std::sqrt(std::pow(m*x.uncertainty
                   ()/x.value(),2));

        return type(newval,err);
    }
};

/// specialize root typeof helper
template<class Y,long N,long D>
struct root_typeof_helper<measurement<Y>,static_rational<N,D> >
{
```

```
    typedef measurement<
        typename root_typeof_helper<Y,static_rational<N,D> >::
           type
    > type;

    static type value(const measurement<Y>& x)
    {
        const static_rational<N,D>  rat;

        const Y m = Y(rat.denominator())/Y(rat.numerator()),
                newval = std::pow(x.value(),m),
                err = newval*std::sqrt(std::pow(m*x.uncertainty
                   ()/x.value(),2));

        return type(newval,err);
    }
};

// stream output
template<class Y>
inline
std::ostream& operator<<(std::ostream& os,const measurement<Y>&
   val)
{
    boost::io::ios_precision_saver precision_saver(os);
    boost::io::ios_flags_saver flags_saver(os);

    os << val.value() << "(+/-" << val.uncertainty() << ")";

    return os;
}

} // namespace units

} // namespace boost

#endif // BOOST_UNITS_MEASUREMENT_HPP
```

2.14.6 Erweiterung des C++-Typsystems durch Units

... mit Hilfe der Boost MPL-Library (Implementierungsidee der Boost.Units-Bibliothek):
Dimensions:

```
// die sieben Grundeinheiten:
typedef int dimension[7]; // m  l  t  ...
dimension const mass      = {1, 0, 0, 0, 0, 0, 0};
dimension const length    = {0, 1, 0, 0, 0, 0, 0};
dimension const time      = {0, 0, 1, 0, 0, 0, 0};
...
// und die abgeleiteten Einheiten:
dimension const force  = {1, 1, -2, 0, 0, 0, 0};
...
```

Diese Dimensionen sind jedoch alle vom gleichen C++-Typ, führen also nicht zu den gewünschten Fehlermeldungen bei Dimensionsrechnungsabweichungen. Mit Hilfe des Datentyps vector_c der MPL ändert sich das:

```
#include <boost/mpl/vector_c.hpp>

typedef mpl::vector_c<int,1,0,0,0,0,0,0> mass;
typedef mpl::vector_c<int,0,1,0,0,0,0,0> length; // or position
typedef mpl::vector_c<int,0,0,1,0,0,0,0> time;
typedef mpl::vector_c<int,0,0,0,1,0,0,0> charge;
typedef mpl::vector_c<int,0,0,0,0,1,0,0> temperature;
typedef mpl::vector_c<int,0,0,0,0,0,1,0> intensity;    // in cd
typedef mpl::vector_c<int,0,0,0,0,0,0,1> angle;        // oder mol
// abgeleitete Einheiten:
typedef mpl::vector_c<int,0,1,-1,0,0,0,0> velocity;     // l/t
typedef mpl::vector_c<int,0,1,-2,0,0,0,0> acceleration; // l/(t2)
typedef mpl::vector_c<int,1,1,-1,0,0,0,0> momentum;     // ml/t
typedef mpl::vector_c<int,1,1,-2,0,0,0,0> force;        // ml/(t2)
...
typedef mpl::vector_c<int,0,0,0,0,0,0,0> scalar;
...
```

Quantities:

```
template <class T, class Dimensions>
struct quantity
{
    explicit quantity(T x)
        : m_value(x)
    {}

    T value() const { return m_value; }
 private:
    T m_value;
};
...
quantity<float,length> l( 1.0f );
quantity<float,mass>   m( 2.0f );
...
m = l;      // compile-time type error
```

Quantity-Arithmetik (value und dimension):
add/subtract:

```
template <class T, class D>
quantity<T,D>
operator+(quantity<T,D> x, quantity<T,D> y)
{
  return quantity<T,D>(x.value() + y.value());
}

template <class T, class D>
quantity<T,D>
operator-(quantity<T,D> x, quantity<T,D> y)
{
  return quantity<T,D>(x.value() - y.value());
}

// ...

quantity<float,length> len1( 1.0f );
quantity<float,length> len2( 2.0f );

len1 = len1 + len2;     // OK
len1 = len2 + quantity<float,mass>( 3.7f ); // error
```

multiplicate:

```
template <class T, class D1, class D2>
quantity<
    T
  , typename mpl::transform<D1,D2,plus_f>::type   // new dimensions
>
operator*(quantity<T,D1> x, quantity<T,D2> y)
{
    typedef typename mpl::transform<D1,D2,plus_f>::type dim;
    return quantity<T,dim>( x.value() * y.value() );
}
// mit MPL-Hilfe:
template <class OtherDimensions>
quantity(quantity<T,OtherDimensions> const& rhs)
  : m_value(rhs.value())
{
    BOOST_STATIC_ASSERT((
       mpl::equal<Dimensions,OtherDimensions>::type::value
    ));
}
```

divide:

```
template <class T, class D1, class D2>
quantity<
    T
  , typename mpl::transform<D1,D2,mpl::minus<_1,_2> >::type
>
operator/(quantity<T,D1> x, quantity<T,D2> y)
{
   typedef typename
     mpl::transform<D1,D2,mpl::minus<_1,_2> >::type dim;

   return quantity<T,dim>( x.value() / y.value() );
}
```

MPL-Metafunktionsklasse:
The most basic way to formulate a compile-time function so that it can be treated as polymorphic metadata; that is, as a type. A metafunction class is a class with a nested metafunction called apply.

Gewöhnungsbedürftige Syntax der Metaprogrammierung: MPL-ManualSeite 99

```
typedef vector<int,char,long,short,char,short,double,long> types;
typedef count<types, short>::type n;
BOOST_MPL_ASSERT_RELATION( n::value, ==, 2 );
```

(Werte des Metaprogramms werden durch `typedef`s an „Typnamen-Aliases" gebunden, ...)

2.14.7 Nachteile von DSLs

- meist Nischensprachen, häufig fehlende Sprachstandards, fehlende freie Implementierungen, ...
- hoher Aufwand für das Erlernen der nur in wenigen Fällen benutzbaren DSL
- Risiko, dass der Anwender zusätzlich viel Entwicklung in der Hostsprache (hier C++) statt der DSL selbst erledigen muß.
- Risiko des Bindens an den Anbieter einer Nischensprache
- Risiko des zukünftigen Vermeidens der Entwicklung von Problemlösungen in etablierten allgemeinen Hochsprachen
- hoher Aufwand der Spezifikation, Entwicklung und Wartung der DSL
- Schwierigkeit, die langfristig benötigten Eigenschaften der DSL richtig abzuschätzen
- Risiko der schleichenden Entwicklung der DSL zu einer allgemeinen Programmiersprache
- Schwierigkeit der Findung des der DSL angemessenen Abstraktionsniveaus
- Hoher Anspruch an die Kompetenz der Entwickler des DSLs

(Nachteil DSLs)

2.15 Literaturhinweise zum Metaprogrammieren

C++ Template Metaprogramming: Concepts, Tools, and Techniques from Boost ans Beyond
Generative Programming — Methods, Tools and Applications, Kapitel 10 Static Metaprogramming in C++

3 Template template-Parameter, Policy-basiertes Klassendesign

3.1 Templates als Template-Parameter

Template Template-Parameter:

```
template <template <typename, typename> class Container, typename Type>
class Example
{
  Container<Type, std::allocator <Type> > baz;
};

// Beispiel der Verwendung:
//
// statt xxxxxx<std::deque<int>, int> ...

Example <std::deque, int> example;
```

3.2 Policies

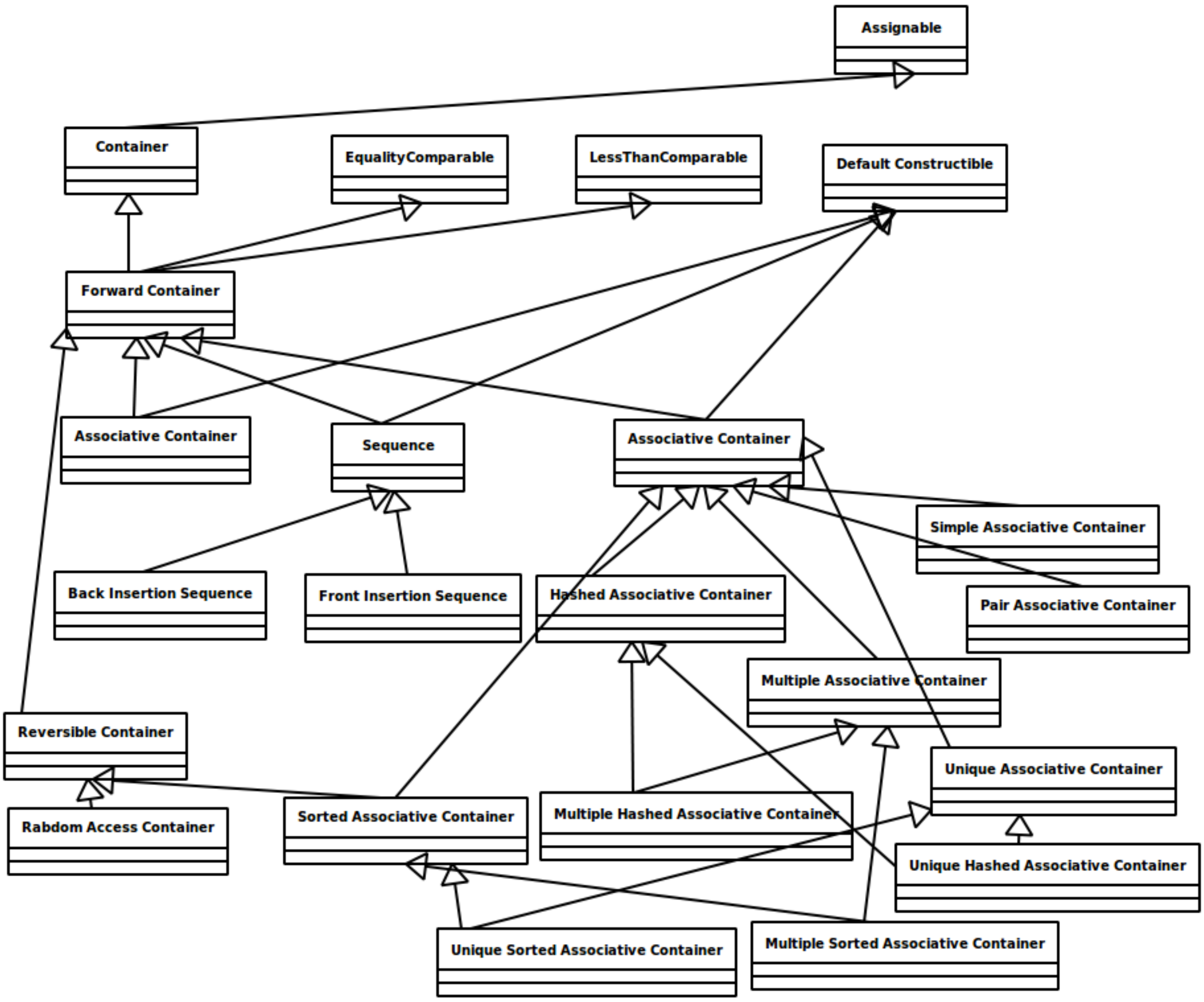
Policies bei der Template-Metaprogrammierung:
„Policies sind Klassen-Templates, die dazu dienen, Verhalten auszulagern.“

Ein Beispiel:

```
struct MultiThreadingPolicy {
  typedef /*...*/ Mutex;
  struct Lock {
    Lock(Mutex& mtx) : mtx_(mtx) {lock(mtx_);}
    ~Mutex() {unlock(mtx_);}
    Mutex& mtx_;
  };
};
struct SingleThreadingPolicy {
  class Mutex {};
  struct Lock {
    Lock(Mutex&) {}
    ~Mutex() {}
  };
};
//
// Ein Algorithmus koennte jetzt so aussehen:
//
```

```
template< class ThreadingPolicy >
void f(typename ThreadingPolicy::Mutex& mtx)
{
  // ...
  if( needToTouchThreadSensibleData() ) {
    typename ThreadingPolicy::Lock lock(mtx); // lock mutex
    // thread-safe section
  }
  // ...
}
```

STL-Container:



Policies (Implementierungsvarianten/-verhaltensweisen) der STL-Container:

```
assoziativ/nichtassoziativ
sortiert/unsortiert
hashed/ohne hash
unique/multiple
```

Andere Policies:

```
threadsave
errorhandling (exception, errno, ...)
allocator (threadsave, singleclient, malloc-based, ...)
...
```

STL Allocators

Policy based Design:

Implementiert wird durch eine zur Compilezeit durchgeführte Template-Instantiierung der gewünschten Policy-Ausprägungen der Template-Kindklasse aller Policies:

```
template < typename output_policy, typename language_policy >
class HelloWorld : public output_policy, public language_policy
{
    using output_policy::Print;
    using language_policy::Message;

public:
    //behaviour method
    void Run()
    {
        //two policy methods
        Print( Message() );
    }
};

#include <iostream>

class HelloWorld_OutputPolicy_WriteToCout
{
 protected:
    template< typename message_type >
    void Print( message_type message )
    {
        std::cout << message << std::endl;
    }
};

#include <string>

class HelloWorld_LanguagePolicy_English
{
 protected:
    std::string Message()
    {
        return "Hello, World!";
    }
};

class HelloWorld_LanguagePolicy_German
{
 protected:
    std::string Message()
    {
        return "Hallo Welt!";
    }
};

int main()
```

```
{
    /* example 1 */
    typedef HelloWorld<HelloWorld_OutputPolicy_WriteToCout,
        HelloWorld_LanguagePolicy_English> my_hello_world_type;

    my_hello_world_type hello_world;
    hello_world.Run(); // Prints "Hello, World!"

   /* example 2
    * does the same but uses another policy, the language has changed
    */
    typedef HelloWorld< HelloWorld_OutputPolicy_WriteToCout,
        HelloWorld_LanguagePolicy_German > my_other_hello_world_type;

    my_other_hello_world_type hello_world2;
    hello_world2.Run(); // Prints "Hallo Welt!"
}
```

Seite 8: ThreadingPolicy
CreationPolicy
Generic Pool Design: CreationPolicy, ExpirationPolicy
Boost numeric conversions: OverflowhHandler, Float2IntRounder, RawConverter, UserRangeChecker
Policies and the STL: AllocationPolicy, CharTPolicy
Policy-basiertes Klassendesign, CreationPolicy, Seite 16: CheckingPolicy, ThreadingPolicy

3.3 Entwurfsmuster Strategie

Policies als Compile-Time-Variante des Strategie-Designmusters
C++ Design Pattern: What is a Design Pattern?
Einführung in Design Patterns: 4.4 Das Strategy Pattern
Strategy pattern
The Strategy design motif
Implementing the Strategy Pattern
Design patterns
Entwurfsmuster Iterator
Wikibook Entwurfsmuster

3.4 Orthogonale Policy-Dimensionen

A Case for Orthogonality in Design
Orthogonality

Policies sollten minimale orthogonale Implementierungsvarianten sein.

3.5 Policies (Fortsetzung)

Policy-based design in C++

3.6 A Policy-Based flex_string Implementation

A Policy-Based basic_string Implementation

4 Aspektorientiertes Programmiern in komplexen Unternehmensanwendungen

Policy-basiertes Design = Template-gesteuerte statische Wahl einer Implementierungsvariante durch den entwickelden Bibliotheksbenutzer.

Aspect-Oriented Programming (AOP) = Ergänzung einer Programmiersprache um neue Sprachmittel (aspekt, advice) zur lokalisierten übersichtlichen, wartbaren und insbesondere erweiterbaren Codierung von Querschnittsanforderungen (= Cross-Cutting Concerns (CCC))

AOP:
Aspect-Oriented Programming (AOP) complements Object-Oriented Programming (OOP) by providing another way of thinking about program structure. The key unit of modularity in OOP is the class, whereas in AOP the unit of modularity is the aspect. Aspects enable the modularization of concerns such as transaction management that cut across multiple types and objects.

AOP als Ergänzung des OOP
Code Scattering der Wirkungsstellen einzelner Belange/Anforderungen
Seite 21: Aspectual Decomposition, Aspectual Recomposition
I want my AOP!:

- Aspectual decomposition: Decompose the requirements to identify crosscutting and common concerns. You separate module-level concerns from crosscutting system-level concerns. For example, in the aforementioned credit card module example, you would identify three concerns: core credit card processing, logging, and authentication.
- Concern implementation: Implement each concern separately. For the credit card processing example, you'd implement the core credit card processing unit, logging unit, and authentication unit.
- Aspectual recomposition: In this step, an aspect integrator specifies recomposition rules by creating modularization units – aspects. The recomposition process, also known as weaving or integrating, uses this information to compose the final system. For the credit card processing example, you'd specify, in a language provided by the AOP implementation, that each operation's start and completion be logged. You would also specify that each operation must clear authentication before it proceeds with the business logic.

Weitere Beispiele von Aspekten:

- logging
- object counting
- locking
- errorhandling
- creational OO design patterns

  - Singleton
  - ...
- structural design patterns
  - Proxy
  - ...
- behavioral design patterns
  - Strategy
  - ...
- Class/Component Scale Aspects
- Application Scale Aspect
- Enterprise Scale Aspect
- Director Design Pattern
- ...

(aus: AspectJ Cookbook: Aspect Oriented Solutions to Real-World Problems)

Scattering und Tangling Code

Needed an AOP language with:

- implementation of concerns: Mapping an individual requirement into code so that a compiler can translate it into executable code. Since implementation of concerns takes the form of specifying procedures, you can to use traditional languages like C, C++, or Java with AOP.

```
.NET Framework languages (C# / VB.NET)[10]
ActionScript[11]
Ada[12]
AutoHotkey[13]
C / C++[14]
COBOL[15]
The Cocoa Objective-C frameworks[16]
ColdFusion[17]
Common Lisp[18]
Delphi[19][20][21]
Delphi Prism[22]
e (IEEE 1647)
Emacs Lisp[23]
Groovy
Haskell[24]
Java[25]
    AspectJ
JavaScript[26]
Logtalk[27]
Lua[28]
Matlab[29]
make[30]
ML[31]
PHP[32]
Racket[33]
```

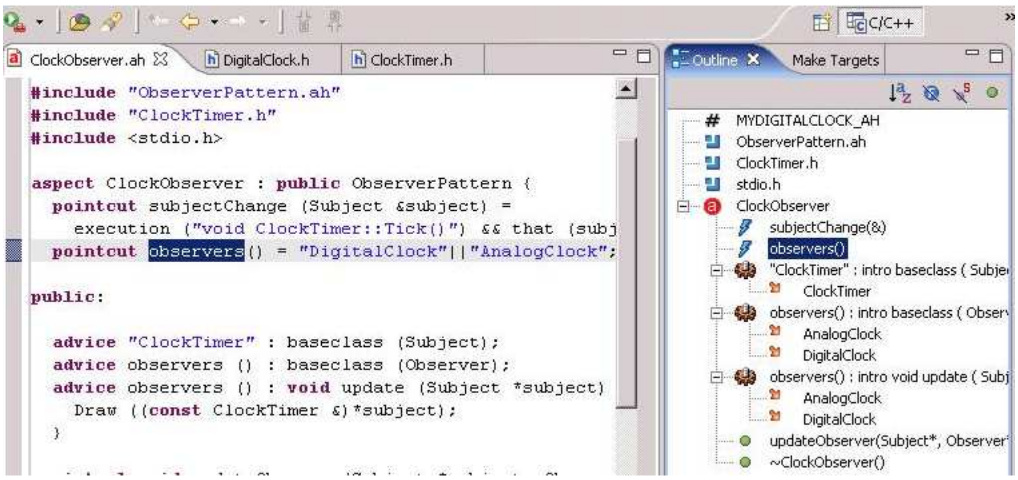
```
Perl[34]
Prolog[35]
Python[36]
Ruby[37][38][39]
Squeak Smalltalk[40][41]
UML 2.0[42]
XML[43]
```

(aus: AOP Implementations)

- Weaving rules specification: How to compose independently implemented concerns to form the final system. For this purpose, an implementation needs to use or create a language for specifying rules for composing different implementation pieces to form the final system. The language for specifying weaving rules could be an extension of the implementation language, or something entirely different.
- Recompile the whole enterprise application.

AOP vocabulary: join point, pointcut, advice
AspectC++ Quick Reference
AspectC++ Home

Aspect-Oriented Programming with C++ and AspectC++
An Introduction to AOP
Eclipse AspectC/C++ Development Tools



(aus: Screenshots)

Nachteile:
Schlechte Unterstützung beim Debuggen, Profilen, ...
(mögliche) Codeexplosion beim Aspekt-Einweben
Setzt AOP-Begriffe und -Ideologien als Bekannt voraus (dann allerdings leicht erlernbar))
Erfordert Pattern-Matching-Erfahrungen (Filterdefinition)
Erfordert Recompilation der in der Regel riesigen Unternehmensapplikationen
Probleme der Abhängigkeit von der Reihenfolge des Einwebens(?)
evtl. schlecht lesbarer neu entstehender Code
Sind wirklich alle relevanten Codestellen mit Advices geändert worden? (fehlende direkte Sprachkonstruckte von C++, z.B. Annotationen mit Aspekt-Bezug, ...)

Vorteile:
Schnell und einfach aufzusetzen
selektiv einsetzbar
keine Modifikation der Originalquellen nötig
leicht entfernbar
gute Performance

AOP-Implemetierung

http://en.wikipedia.org/wiki/Aspect-oriented_programming#Implementation

Code Injection
Bytecode Instrumentation
Dynamic Bytecode Instrumentation

The Design and Implementation of AspectC++
Advances in AOP with AspectC++

Entwicklungsstand:
(siehe Entwicklungsstand der aspektorientierten Programmierung)

- noch in den Kinderschuhen (erfaßt unter anderem nur selbst Compiliertes, nicht jedoch lediglich Benutztes, ...)
- Realisierung des AOP noch unausgereift (Patchlisten, ...)
- Bis zu akzeptabler Reife dürfte es noch einige Jahre und einige Programmiersprachengenerationen dauern
- hohe Abstraktion und völlig andere ungewohnte Herangehensweise stellt hohe Anforderungen an den (zukünftigen) Entwickler