C++ PROGRAMMING

Lecture 4

Secure Software Engineering Group
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CONTENTS

Operators

- `=` `operator=`
- `+` `operator+`
- `-` `operator-`
- `*` `operator*`
- `/` `operator/`
- `==` `operator==`
- `[]` `operator[]`
- `<` `operator<`
- `>` `operator>`
- `<=` `operator<=`
- And lots of others

Operator overloading

- Operators have a certain meaning

```
int sum = 4 + 5;
```

  - `+` is the mathematical plus that sums up numbers
- But operators can be overloaded
  - An overloaded operator may has more than one meaning
  - Meaning depends on context (type(s) it is applied to)
  - Overloading operators is a powerful instrument
    - It allows you to write code / implement algorithms exactly like shown in maths text books
- Have you ever used an overloaded operator?
  - Yes, remember the character output stream `std::cout` and `std::string`

Operator overloading

- Rather natural use of `+` for strings

```
std::string a = "AAAA";
std::string b = "BBB";
std::string result = a + b;
```

- Overloaded operators should be thoroughly designed
  - Should behave as expected
  - Do not implement

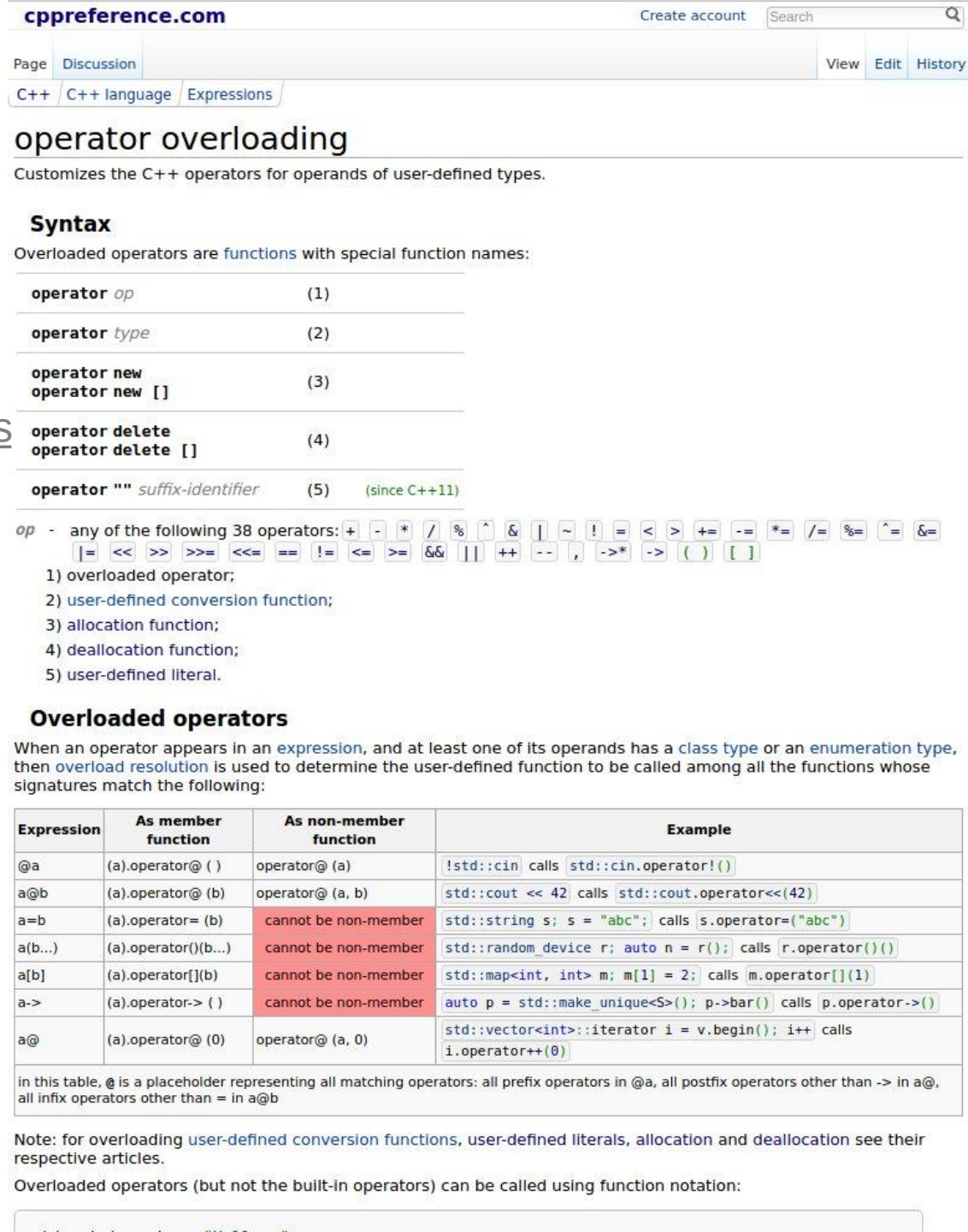
```
std::string a = "AAAA";
std::string b = "BBB";
std::string result = a + b;
```

to delete the contents of `a` and `b` and fill `result` with `"I am a very funny guy."`

Operator overloading

- What operators can be overloaded?
  - Please refer to

    http://en.cppreference.com/w/cpp/language/operators
  - If you design a data type only overload operators …
    - that are useful
    - whose meaning is clear
  - Do not overload all operators or as much as possible
  - Custom operators?
    - E.g. `operator**`
      - Pythons power operator
        - Arbitrary defined operators would be possible
          - But are not intuitive



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C++ / C++ language / Expressions

operator overloading

Customizes the C++ operators for operands of user-defined types.

Syntax

Overloaded operators are functions with special function names:

operator *op*	(1)	
operator *type*	(2)	
operator new **operator new []**	(3)	
operator delete **operator delete []**	(4)	
operator "" *suffix-identifier*	(5)	(since C++11)

op - any of the following 38 operators: `+` `-` `*` `/` `%` `^` `&` `|` `~` `!` `=` `<` `>` `+=` `-=` `*=` `/=` `%=` `^=` `&=` `|=` `<<` `>>` `>>=` `<<=` `==` `!=` `<=` `>=` `&&` `||` `++` `--` `,` `->*` `->` `( )` `[ ]`

1) overloaded operator;
2) user-defined conversion function;
3) allocation function;
4) deallocation function;
5) user-defined literal.

Overloaded operators

When an operator appears in an expression, and at least one of its operands has a class type or an enumeration type, then overload resolution is used to determine the user-defined function to be called among all the functions whose signatures match the following:

Expression	As member function	As non-member function	Example
@a	(a).operator@ ( )	operator@ (a)	`!std::cin` calls `std::cin.operator!()`
a@b	(a).operator@ (b)	operator@ (a, b)	`std::cout << 42` calls `std::cout.operator<<(42)`
a=b	(a).operator= (b)	cannot be non-member	`std::string s; s = "abc";` calls `s.operator=("abc")`
a(b...)	(a).operator()(b...)	cannot be non-member	`std::random_device r; auto n = r();` calls `r.operator()()`
a[b]	(a).operator[](b)	cannot be non-member	`std::map<int, int> m; m[1] = 2;` calls `m.operator[](1)`
a->	(a).operator-> ( )	cannot be non-member	`auto p = std::make_unique<S>(); p->bar()` calls `p.operator->()`
a@	(a).operator@ (0)	operator@ (a, 0)	`std::vector<int>::iterator i = v.begin(); i++` calls `i.operator++(0)`

in this table, **@** is a placeholder representing all matching operators: all prefix operators in @a, all postfix operators other than -> in a@, all infix operators other than = in a@b

Note: for overloading user-defined conversion functions, user-defined literals, allocation and deallocation see their respective articles.

Overloaded operators (but not the built-in operators) can be called using function notation:

Simple example: `operator<<`

- Definition inside type definition

```
#include <iostream>
struct Type {
  Type(int i, double d) : i(i), d(d) {}
  int i;
  double d;
  friend std::ostream&
    operator<< (std::ostream& os,
                const Type &t) {
    return os << t.i << " and " << t.d;
  }
};

int main() {
  Type t(1, 2.222);
  std::cout << t << '\n';
  return 0;
}
```

- Definition outside type definition

```
#include <iostream>
struct Type {
  Type(int i, double d) : i(i), d(d) {}
  int i;
  double d;
};
std::ostream& operator<< (std::ostream& os,
                          const Type &t) {
  return os << t.i << " and " << t.d;
}

int main() {
  Type t(1, 2.222);
  std::cout << t << '\n';
  return 0;
}
```

Operator overloading

- Remember our Vec3 type

```
class Vec3 {
private:
  double x;
  double y;
  double z;
public:
  Vec3() : x(0), y(0), z(0) { }
  Vec3(double x, double y, double z) : x(x), y(y), z(z) { }
  size_t size() { return 3; }
  double euclidean_length() { return sqrt(x*x+y*y+z*z); }
  friend std::ostream& operator<< (std::ostream& os, const Vec3& v){
    return os << v.x << '\n' << v.y << '\n' << v.z;
  }
};
```

- Why is `operator<<` declared as friend?
  - Obviously it is not a member function
  - It receives a Vec3 as a parameter
  - If a function / operator is declared as friend it can access a type's private data members!

```
Vec3 v1(4,5,6);
std::cout << v1 << '\n';
```

Operator overloading

- We need a `const` version of `operator[]`

```
Vec3 v;
v[1] = 12;
const Vec3 w;
double x = w[1]; // calls const version
```

- Let's overload `operator+` and `operator[]` for convenience

```
class Vec3 {
private:
  double x;
  double y;
  double z;
public:
  Vec3() : x(0), y(0), z(0) {}
  Vec3(double x, double y, double z)
        : x(x), y(y), z(z) {}
  size_t size() { return 3; }
  double euclidean_length() {
    return sqrt(x*x+y*y+z*z); }
  double& operator[] (size_t idx) {
    switch (idx) {
      case 0: return x; break;
      case 1: return y; break;
      case 2: return z; break;
      default: /* handle error */;
    }
  }
```

```
const double& operator[] (size_t idx) const {
  switch (idx) {
    case 0: return x; break;
    case 1: return y; break;
    case 2: return z; break;
    default: /* handle error */;
  }
}
friend Vec3 operator+ (Vec3 lhs, const Vec3& rhs){
  for (size_t i = 0; i < lhs.size(); ++i)
    lhs[i] += rhs[i];
  return lhs;
}
friend std::ostream& operator<< (std::ostream& os,
                                 const Vec3& v) {
  return os << v.x << " " << v.y << " " << v.z;
}
};
```

- A `const` function member or operator is one, that does not modify the data members!

Operator overloading

- Now we can use

```
int main() {
  Vec3 v1(1,2,3);
  Vec3 v2(4,5,6);
  v2[1] = 50;
  Vec3 v3 = v1 + v2;
  std::cout << v3 << '\n';
  return 0;
}
```

  - Output
    - 5 52 9

Operator overloading

- Caution: It is not a smart idea to check two doubles for equality!

- You are now able to write these yourself

```
friend Vec3 operator- (Vec3 lhs, const Vec3& rhs);
friend double operator* (const Vec3& lhs, const Vec3& rhs);
friend Vec3 operator* (Vec3 lhs, double rhs);
friend Vec3 operator% (Vec3 lhs, const Vec3& rhs);

// caution, may not be intuitive in this example!
friend bool operator< (const Vec3& lhs, const Vec3& rhs);
friend bool operator> (const Vec3& lhs, const Vec3& rhs);
friend bool operator<=(const Vec3& lhs, const Vec3& rhs);
friend bool operator>=(const Vec3& lhs, const Vec3& rhs);
friend bool operator==(const Vec3& lhs, const Vec3& rhs);
friend bool operator!=(const Vec3& lhs, const Vec3& rhs);
```

- You only have to implement `operator<` and `operator==` for comparisons
- Others can be expressed using `<` and `==`

How about custom operators?

- Again, not possible in the C++ language
- **But,** it is possible using some ugly hack
  - We will do a fun lecture later on ☺
    - I will show you some of those things

Before we continue on dynamic memory: this—a special pointer

- `this` pointer

"The keyword this is a prvalue expression whose value is the address of the implicit object parameter (object on which the non-static member function is being called). It can appear in the following contexts:

1. Within the body of any non-static member function, including member initializer list
2. within the declaration of a non-static member function anywhere after the (optional) cv-qualifier sequence, including dynamic exception specification(deprecated), noexcept specification(C++11), and the trailing return type(since C++11)
3. within default member initializer (since C++11)"

[en.cppreference.com/w/cpp/language/this]

- `this` lets you access the address of the object on which a (non-static) member function is being called on
  → address of the receiver object

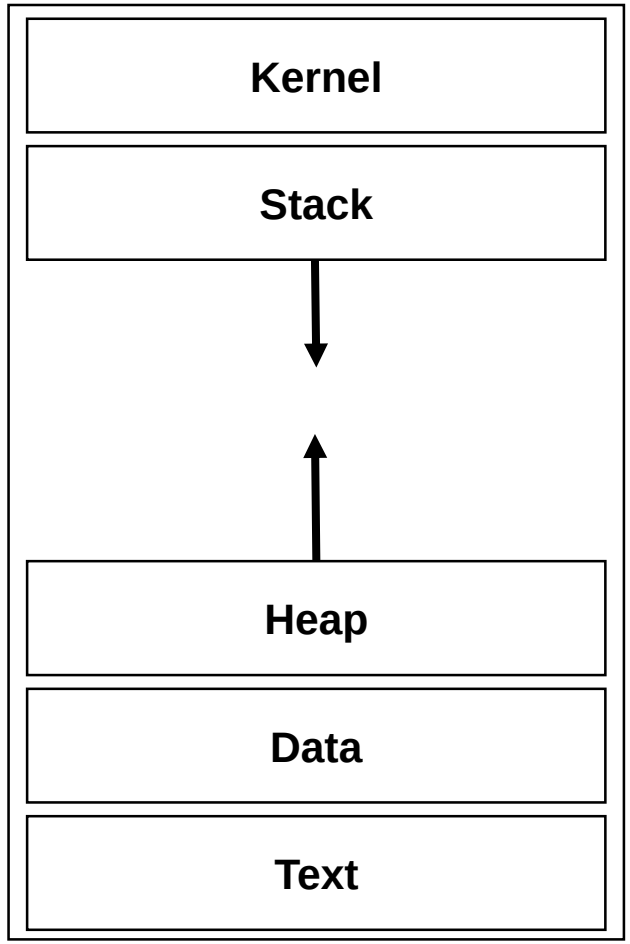
this—a special pointer: an example

```
#include <iostream>
struct X {
  void print_my_address() {
    std::cout << "the address of this object is: " << this << '\n';
  }
};
int main() {
  X a;
  a.print_my_address();
  X b;
  b.print_my_address();
  return 0;
}
```

Memory layout

- Memory layout in Linux systems (and C/C++ programs)
  - Kernel
    - Contains command-line and environment variables (OS data)
  - Stack
    - Contains function parameters and functions return address
    - Local variables
  - Heap
    - Allows allocation of huge chunks of memory
  - Data
    - Contains initialized and uninitialized (global) variables
  - Text
    - Read-only, contains program text (machine instructions)
- Memory is just a linear piece of addressable locations

- High addresses



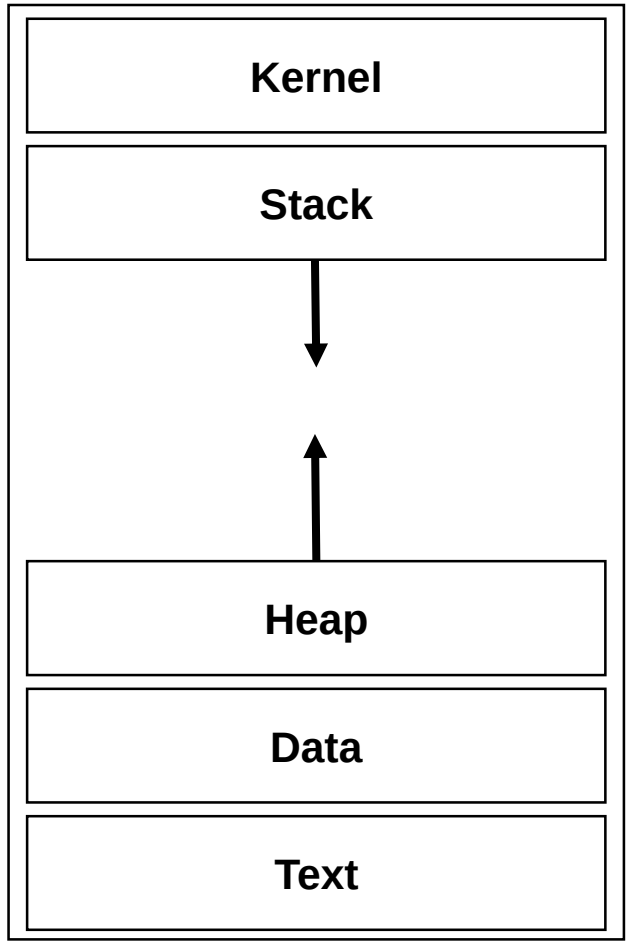
- Low addresses

Memory layout

- Please consider this website

  http://www.geeksforgeeks.org/memory-layout-of-c-program/

  - This page explains in detail why we have such a memory layout
  - I highly encourage you to read that article

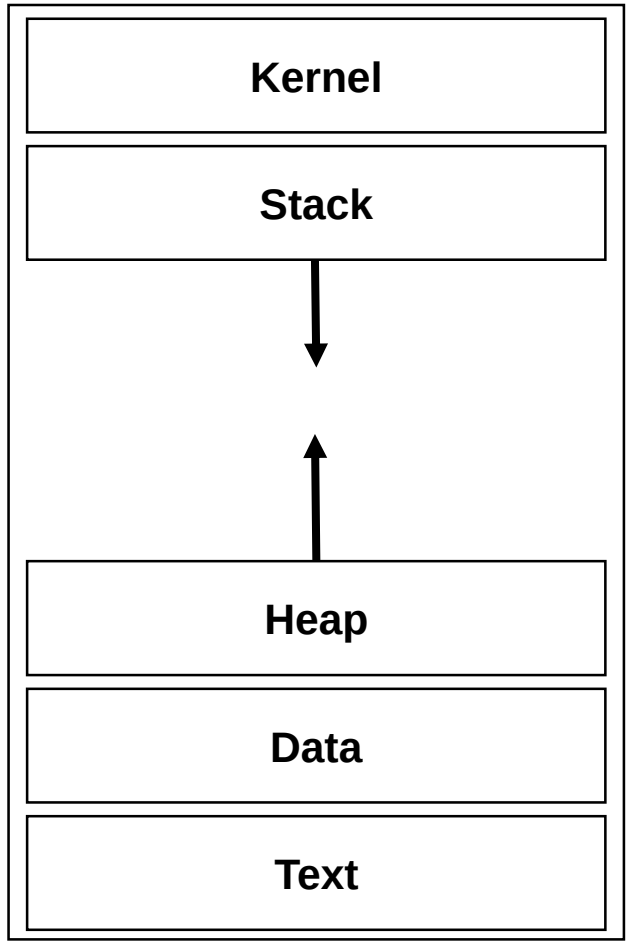


Why dynamic memory allocation?

- Consider local (stack) memory (of fixed size)

```
int buffer[10];
```

  - Problem
    - How to store more than 10 elements?
    - What if you do not know the number of elements up-front?
    - How do you store a million elements?
      - Stack size is usually limited by the operating system
        - Why? → Well, think about deallocation
    - What if data should be used in more than one scope?
  - Dynamically allocated heap memory solves these problems
    - Simply take (allocate) what you need
    - Allocate chunks of memory as large as you like (size of RAM chips)



Dynamic memory allocation

- Allocate what your RAM chips provide
  - Simply allocate what you need
  - But caution
    - You have to do the clean-up yourself
      - No garbage collector (unlike Java)!
    - Free memory after usage
      - Memory is yours until you explicitly free it:
        - **There is no out of scope!**
        - **Do not lose the memory handle!**
  - The keyword for allocation is `new`
  - The keyword for deallocation is `delete`

Dynamic memory allocation

- Remember pointers

```
int i = 42;       // integer variable i
int *i_ptr = &i; // pointer i_ptr points to i
```

- Pointers will now become really useful
  - They are inevitable even
  - Operator `new` allocates the amount of memory you need
  - But `new` cannot provide a name for the allocated memory
    - It simply returns a pointer / address to “your” memory
    - **Caution**
      - Do not lose size information!
        - Otherwise you risk undefined reads and writes!
      - Do not forget to delete the memory and do not delete twice!
        - Otherwise you leak memory or program has undefined behavior / program crash!

More on undefined behavior

- Caution the following talk may causes nightmares
- “Undefined Behavior is awesome!”, Piotr Padlewski
  - https://www.youtube.com/watch?v=ehyHyAIa5so

Allocate and delete memory

- The keyword for allocation is `new`
  - In fact it is an operator (that can even be overloaded)
  - Standard signatures are

```
void* operator new ( std::size_t count );      // for objects
void* operator new[]( std::size_t count );     // for arrays
```

    - Notice `new` is returning a `void` pointer
  - If memory cannot be allocated `new` throws an `std::bad_alloc` exception (next lecture)
- The keyword for deallocation is `delete`
  - In fact it is a operator (that can even be overloaded)
  - Standard signatures are

```
void operator delete ( void* ptr );            // for objects
void operator delete[]( void* ptr );           // for arrays
```

- Every `new` needs a `delete` ➔ otherwise your program has a leak

Allocate and delete memory

```
void* operator new ( std::size_t count );          // for objects
void* operator new[]( std::size_t count );         // for arrays
void operator delete ( void* ptr );                // for objects
void operator delete[]( void* ptr );               // for arrays
```

- Why is there a distinction between objects and arrays?
  - Just a syntactic oddity
  - Has no use at all
  - Even worse
    - Do not confuse between them
    - Do not allocate with `new` and free with `delete[]` (and vice versa)

Double free

```
philipp@pdschbrt:~/ownCloud/cppp/tmp$ ./double-free
42
*** Error in `./double-free': double free or corruption (fasttop): 0x0000000001602c20 ***
======= Backtrace: =========
/lib/x86_64-linux-gnu/libc.so.6(+0x777f5)[0x7fd1842a97f5]
/lib/x86_64-linux-gnu/libc.so.6(+0x8038a)[0x7fd1842b238a]
/lib/x86_64-linux-gnu/libc.so.6(cfree+0x4c)[0x7fd1842b658c]
./double-free[0x4008de]
/lib/x86_64-linux-gnu/libc.so.6(__libc_start_main+0xf0)[0x7fd184252840]
./double-free[0x400799]
======= Memory map: ========
00400000-00401000 r-xp 00000000 08:02 29923117                           /home/philipp/ownCloud/cppp/tmp/double-free
00600000-00601000 r--p 00000000 08:02 29923117                           /home/philipp/ownCloud/cppp/tmp/double-free
00601000-00602000 rw-p 00001000 08:02 29923117                           /home/philipp/ownCloud/cppp/tmp/double-free
015f1000-01623000 rw-p 00000000 00:00 0                                  [heap]
7fd180000000-7fd180021000 rw-p 00000000 00:00 0
7fd180021000-7fd184000000 ---p 00000000 00:00 0
7fd184232000-7fd1843f2000 r-xp 00000000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
7fd1843f2000-7fd1845f2000 ---p 001c0000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
7fd1845f2000-7fd1845f6000 r--p 001c0000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
7fd1845f6000-7fd1845f8000 rw-p 001c4000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
7fd1845f8000-7fd1845fc000 rw-p 00000000 00:00 0
```

```cpp
#include <iostream>
int main() {
  int *i = new int(13);
  *i = 42;
  std::cout << *i << '\n';
  delete i;
  delete i;
  return 0;
}
```

```cpp
int main() {
  int *i = new int(13);
  *i = 42;
  std::cout << *i << '\n';
  delete i;
  i = nullptr;
  delete i;
  return 0; }
```

Valgrind, a tool to detect memory misuse https://valgrind.org/docs/manual/quick-start.html

- Valgrind was developed by Julian Seward
  - British compiler construction specialist
- Valgrind is a tool-suite that allows for detection of memory errors
  - It runs the program under analysis multiple times
  - It stops the program many times during its execution
  - In those breaks it analyzes registers, stack, … and collects all these information
  - With help of these information it can determine whether a program has some memory issues
  - Caution: the program under analysis is executed ~100 times slower than usually
    - Analyzing big projects needs time
    - It is still worth while
- There are not many ways for detecting memory issues
  - Double delete ➔ program crashes
  - Missing delete ➔ program leaks ➔ consumes more and more memory, until crash

Clang's AddressSanitizer https://clang.llvm.org/docs/AddressSanitizer.html

- Fast memory error detector
- Uses compiler instrumentation and a run-time library (slowdown ~ 2x)
- Can detect
  - Out-of-bound accesses to heap, stack, and globals
  - Use-after-free
  - Use-after-return
  - User-after-scope
  - Double-free, invalid free
  - Memory leaks (experimental)
- Compile and link program to be instrumented

```
$ clang++ -Wall -Wextra -std=c++17 -O1 -g -fsanitize=address
  -fno-omit-frame-pointer program.cpp -o program
```

Detecting leaks

```cpp
#include <iostream>
int main() {
  int *i = new int(13);
  *i = 42;
  std::cout << *i << '\n';
  delete i;
  return 0;
}
```

```
philipp@pdschbrt:~/ownCloud/cppp/tmp$ valgrind --leak-check=full --track-origins=yes ./double-free
==30151== Memcheck, a memory error detector
==30151== Copyright (C) 2002-2015, and GNU GPL'd, by Julian Seward et al.
==30151== Using Valgrind-3.11.0 and LibVEX; rerun with -h for copyright info
==30151== Command: ./double-free
==30151==
42
==30151==
==30151== HEAP SUMMARY:
==30151==     in use at exit: 72,704 bytes in 1 blocks
==30151==   total heap usage: 3 allocs, 2 frees, 73,732 bytes allocated
==30151==
==30151== LEAK SUMMARY:
==30151==    definitely lost: 0 bytes in 0 blocks
==30151==    indirectly lost: 0 bytes in 0 blocks
==30151==      possibly lost: 0 bytes in 0 blocks
==30151==    still reachable: 72,704 bytes in 1 blocks
==30151==         suppressed: 0 bytes in 0 blocks
==30151== Reachable blocks (those to which a pointer was found) are not shown.
==30151== To see them, rerun with: --leak-check=full --show-leak-kinds=all
==30151==
==30151== For counts of detected and suppressed errors, rerun with: -v
==30151== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
philipp@pdschbrt:~/ownCloud/cppp/tmp$
```

```
$ clang++ -Wall -Wextra -std=c++17 -g no-free.cpp -o no-free
```

Detecting leaks

```cpp
#include <iostream>
int main() {
  int *i = new int(13);
  *i = 42;
  std::cout << *i << '\n';
  return 0;
}
```

```
philipp@pdschbrt:~/ownCloud/cppp/tmp$ valgrind --leak-check=full --track-origins=yes ./double-free
==29479== Memcheck, a memory error detector
==29479== Copyright (C) 2002-2015, and GNU GPL'd, by Julian Seward et al.
==29479== Using Valgrind-3.11.0 and LibVEX; rerun with -h for copyright info
==29479== Command: ./double-free
==29479==
42
==29479==
==29479== HEAP SUMMARY:
==29479==     in use at exit: 72,708 bytes in 2 blocks
==29479==   total heap usage: 3 allocs, 1 frees, 73,732 bytes allocated
==29479==
==29479== 4 bytes in 1 blocks are definitely lost in loss record 1 of 2
==29479==    at 0x4C2E0EF: operator new(unsigned long) (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==29479==    by 0x400818: main (double-free.cpp:4)
==29479==
==29479== LEAK SUMMARY:
==29479==    definitely lost: 4 bytes in 1 blocks
==29479==    indirectly lost: 0 bytes in 0 blocks
==29479==      possibly lost: 0 bytes in 0 blocks
==29479==    still reachable: 72,704 bytes in 1 blocks
==29479==         suppressed: 0 bytes in 0 blocks
==29479== Reachable blocks (those to which a pointer was found) are not shown.
==29479== To see them, rerun with: --leak-check=full --show-leak-kinds=all
==29479==
==29479== For counts of detected and suppressed errors, rerun with: -v
==29479== ERROR SUMMARY: 1 errors from 1 contexts (suppressed: 0 from 0)
philipp@pdschbrt:~/ownCloud/cppp/tmp$
```

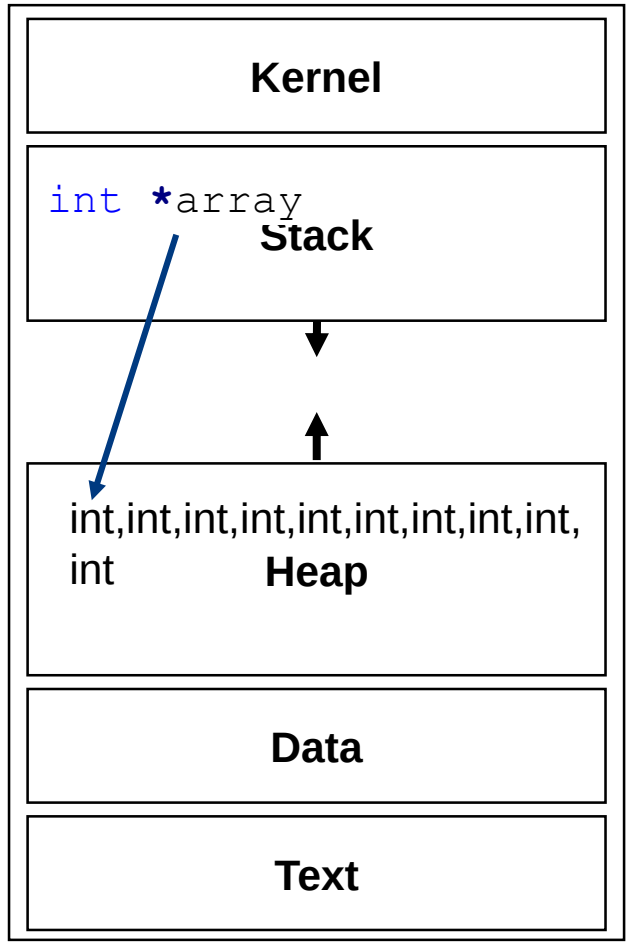
```
philipp@pdschbrt:~/ownCloud/cppp/tmp$ ./double-fre
42

=================================================
==29791==ERROR: LeakSanitizer: detected memory lea

Direct leak of 4 byte(s) in 1 object(s) allocated from:
    #0 0x4f0718 in operator new(unsigned long) /home/philipp/GIT-Repos/llvm-project-11/compiler-rt/lib/asan/asan_new_delet
e.cpp:99
    #1 0x4f3f18 in main /home/philipp/ownCloud/cppp/tmp/double-free.cpp:4:12
    #2 0x7ff29a9cb83f in __libc_start_main /build/glibc-e6zv40/glibc-2.23/csu/../csu/libc-start.c:291

SUMMARY: AddressSanitizer: 4 byte(s) leaked in 1 allocation(s).
philipp@pdschbrt:~/ownCloud/cppp/tmp$
```

```
$ clang++ -Wall -Wextra -std=c++17 -O1 -g -fsanitize=address -fno-omit-frame-pointer
  no-free.cpp -o no-free
```

Dynamically allocated arrays

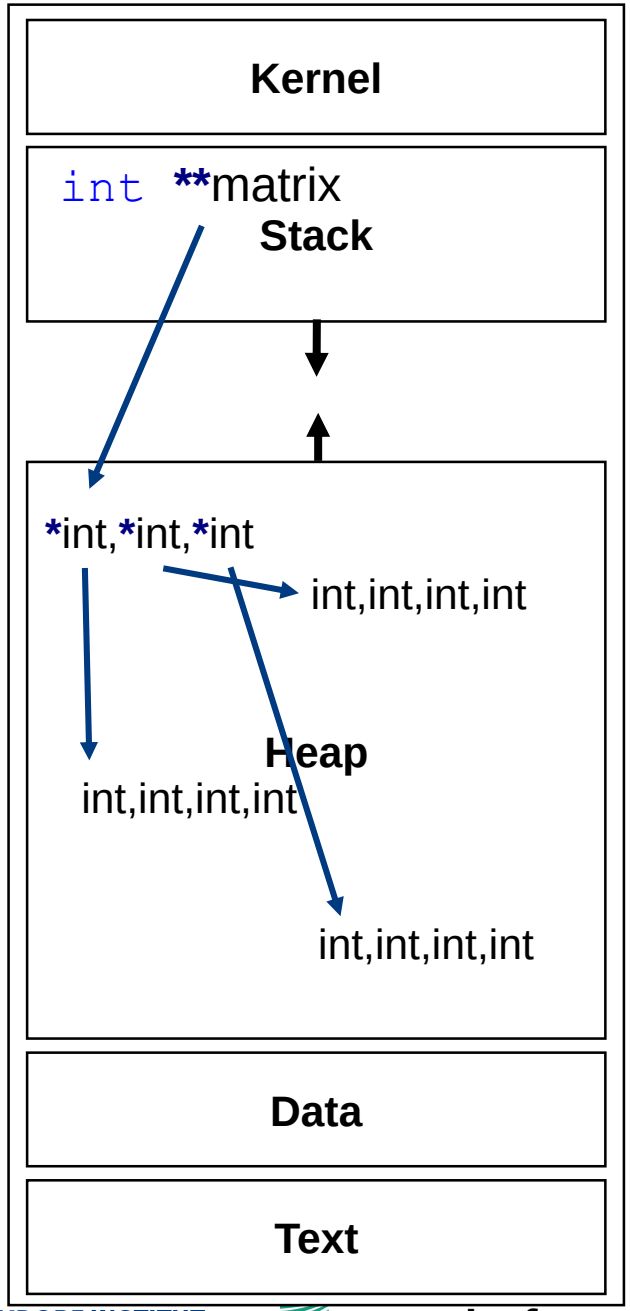
```
int main() {
  int *array = new int[10];
  for (int i = 0; i < 10; ++i) {
    array[i] = 13;
// this is pointer arithmetic, same meaning as ´array[i]´
    *(array+i) += 2;
  }
  // do useful things with array
  delete[] array; // we have to use the array delete
  return 0;
}
```

- Problem with dynamic arrays
  - Programmers have to store size information themselves
    - High risk for index out-of-bounds
      - Undefined behavior or segmentation fault



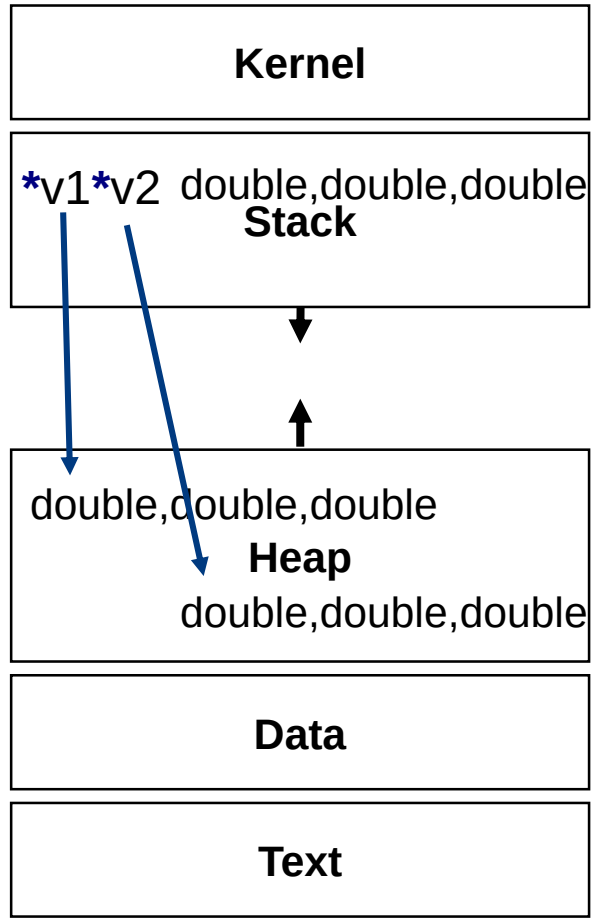
Dynamically allocated 2D arrays (matrices)

```
int main() {
  int rows = 3;
  int cols = 4;
  int **matrix = new int*[rows];
  for (int row = 0; row < rows; ++row)
    matrix[row] = new int[cols];
  for (int row = 0; row < rows; ++row)
    for (int column = 0; column < cols; ++column)
      matrix[row][column] = 42;
  // do useful stuff with matrix
  for (int row = 0; row < rows; ++row)
    delete[] matrix[row];
  delete[] matrix;
  matrix = nullptr;
  return 0;
}
```



Allocate a user-defined type

```
struct Vertex {
  Vertex() : x(0), y(0), z(0) { }
  Vertex(double x, double y, double z) : x(x), y(y), z(z) { }
  double x, y, z;
  friend std::ostream& operator<< (std::ostream& os, const Vertex& v) {
    return os << v.x << " " << v.y << " " << v.z;
  }
};
int main() {
  Vertex *v1 = new Vertex;
  Vertex *v2 = new Vertex(1, 2, 3);
  Vertex v3(3, 2, 1);
  v2->x = 42; // -> shorthand for(*v2).x (dereference and access data)
  std::cout << *v2 << '\n';
  delete v1; v1 = nullptr;
  delete v2; v2 = nullptr;
  return 0; }
```



Copy & move using dynamic memory

Copy constructor & copy assign gone wrong

```
#include <iostream>
struct DynInt {
  DynInt(int i) : i_ptr(new int(i)) {}
  ~DynInt() { delete i_ptr; }     // we have to clean up
  DynInt(const DynInt &di) = default;
  DynInt& operator= (const DynInt &di) = default;
  friend std::ostream& operator<< (std::ostream& os, const DynInt &di) {
    return os << *di.i_ptr;
  }
  int *i_ptr;
};
int main() {
  DynInt di1(42);
  // ups! we copy the pointer i_ptr, but not what it points-to!
  DynInt di2 = di1;
  *di2.i_ptr = 100;
  std::cout << di1 << '\n';
  std::cout << di2 << '\n';
  // we call dtor for di1 and di2 ➔ we call dtor twice for the same heap object
  return 0;
}
```

Copy constructor & copy assign gone wrong

```
philipp@pdschbrt:~/ownCloud/cppp/tmp$ clang++ -std=c++17 -Wall -Wextra dyn-int.cpp -o dyn-int
philipp@pdschbrt:~/ownCloud/cppp/tmp$ ./dyn-int
100
100
*** Error in `./dyn-int': double free or corruption (fasttop): 0x0000000001b9dc20 ***
======= Backtrace: =========
/lib/x86_64-linux-gnu/libc.so.6(+0x777f5)[0x7fcc39bee7f5]
/lib/x86_64-linux-gnu/libc.so.6(+0x8038a)[0x7fcc39bf738a]
/lib/x86_64-linux-gnu/libc.so.6(cfree+0x4c)[0x7fcc39bfb58c]
./dyn-int[0x400aad]
./dyn-int[0x4009e3]
/lib/x86_64-linux-gnu/libc.so.6(__libc_start_main+0xf0)[0x7fcc39b97840]
./dyn-int[0x400889]
======= Memory map: ========
00400000-00401000 r-xp 00000000 08:02 29923143                           /home/philipp/ownCloud/cppp/tmp/dyn-int
00600000-00601000 r--p 00000000 08:02 29923143                           /home/philipp/ownCloud/cppp/tmp/dyn-int
00601000-00602000 rw-p 00001000 08:02 29923143                           /home/philipp/ownCloud/cppp/tmp/dyn-int
01b8c000-01bbe000 rw-p 00000000 00:00 0                                  [heap]
7fcc34000000-7fcc34021000 rw-p 00000000 00:00 0
7fcc34021000-7fcc38000000 ---p 00000000 00:00 0
7fcc39b77000-7fcc39d37000 r-xp 00000000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
7fcc39d37000-7fcc39f37000 ---p 001c0000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
7fcc39f37000-7fcc39f3b000 r--p 001c0000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
```

Copy constructor & copy assign: How to fix it?

```
#include <iostream>
struct DynInt {
  DynInt(int i) : i_ptr(new int(i)) {}
  ~DynInt() { delete i_ptr; }
  DynInt(const DynInt &di) : i_ptr(new int(*di.i_ptr)) {} // create a deep copy!
  DynInt &operator=(const DynInt &di) {
    if (this != &di) { *i_ptr = *di.i_ptr; }
    return *this;
  }
  friend std::ostream &operator<<(std::ostream &os, const DynInt &di) {
    return os << *di.i_ptr;
  }
  int *i_ptr;
};
int main() {
  DynInt di1(42);
  DynInt di2 = di1; // call copy constructor
  *di2.i_ptr = 100;
  std::cout << di1 << '\n';
  std::cout << di2 << '\n';
  return 0;
}
```

Move constructor & move assign gone wrong

```
#include <iostream>
struct DynInt {
  DynInt(int i) : i_ptr(new int(i)) {}
  ~DynInt() { delete i_ptr; }
  DynInt(const DynInt &di) : i_ptr(new int(*di.i_ptr)) {} // create a deep copy!
  DynInt &operator=(const DynInt &di) {
    if (this != &di) { *i_ptr = *di.i_ptr; }
    return *this;
  }
  DynInt(DynInt &&di) = default;
  DynInt& operator= (DynInt &&di) = default;
  friend std::ostream &operator<<(std::ostream &os, const DynInt &di) {
    return os << *di.i_ptr;
  }
  int *i_ptr;
};
int main() {
  DynInt di1(42);
  DynInt di2 = std::move(di1); // call move constructor
  *di2.i_ptr = 100;
  std::cout << di2 << '\n';
  return 0;
}
```

Move constructor & move assign gone wrong

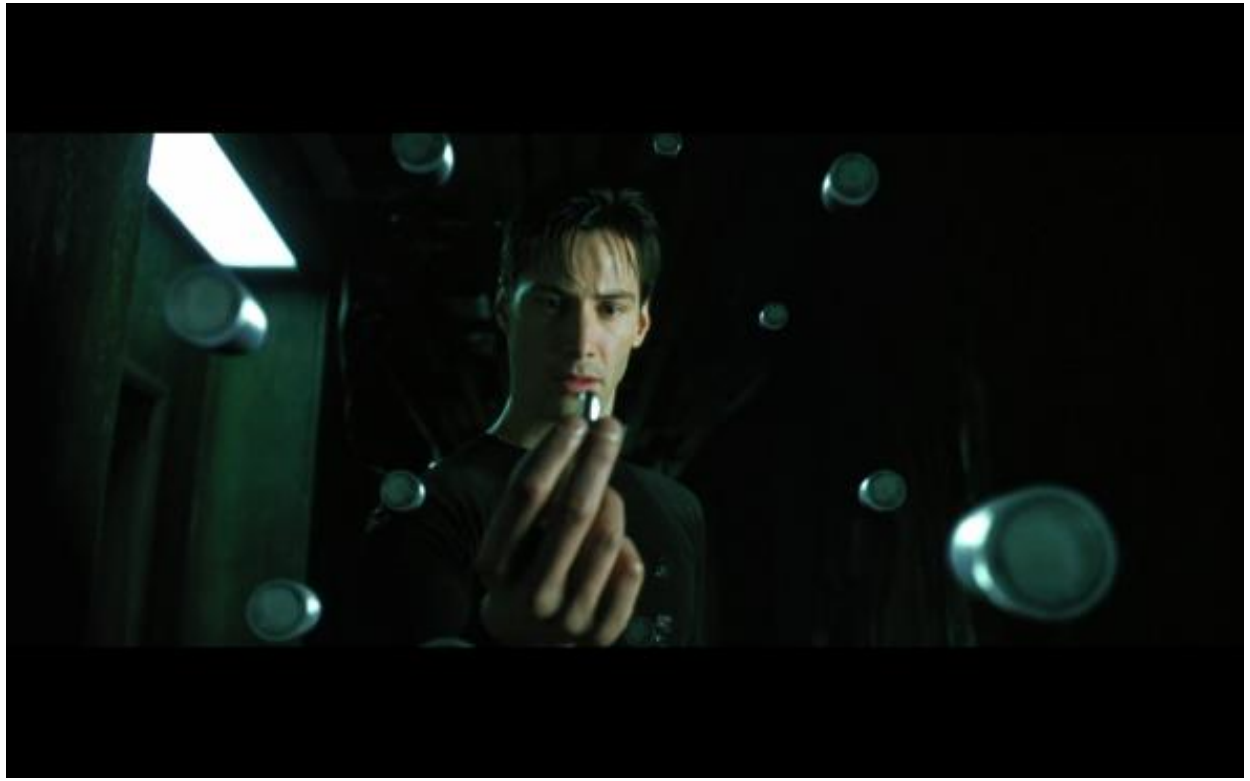
```
philipp@pdschbrt:~/ownCloud/cppp/tmp$ clang++ -std=c++17 -Wall -Wextra dyn-int.cpp -o dyn-int
philipp@pdschbrt:~/ownCloud/cppp/tmp$ ./dyn-int
100
*** Error in `./dyn-int': double free or corruption (fasttop): 0x00000000010c5c20 ***
======= Backtrace: =========
/lib/x86_64-linux-gnu/libc.so.6(+0x777f5)[0x7efc1c0757f5]
/lib/x86_64-linux-gnu/libc.so.6(+0x8038a)[0x7efc1c07e38a]
/lib/x86_64-linux-gnu/libc.so.6(cfree+0x4c)[0x7efc1c08258c]
./dyn-int[0x400a9d]
./dyn-int[0x4009c1]
/lib/x86_64-linux-gnu/libc.so.6(__libc_start_main+0xf0)[0x7efc1c01e840]
./dyn-int[0x400889]
======= Memory map: ========
00400000-00401000 r-xp 00000000 08:02 29923143                           /home/philipp/ownCloud/cppp/tmp/dyn-int
00600000-00601000 r--p 00000000 08:02 29923143                           /home/philipp/ownCloud/cppp/tmp/dyn-int
00601000-00602000 rw-p 00001000 08:02 29923143                           /home/philipp/ownCloud/cppp/tmp/dyn-int
010b4000-010e6000 rw-p 00000000 00:00 0                                  [heap]
7efc14000000-7efc14021000 rw-p 00000000 00:00 0
7efc14021000-7efc18000000 ---p 00000000 00:00 0
7efc1bffe000-7efc1c1be000 r-xp 00000000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
7efc1c1be000-7efc1c3be000 ---p 001c0000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
7efc1c3be000-7efc1c3c2000 r--p 001c0000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
7efc1c3c2000-7efc1c3c4000 rw-p 001c4000 08:02 21627152                   /lib/x86_64-linux-gnu/libc-2.23.so
```

Move constructor & move assign: How to fix it?

```
#include <iostream>
struct DynInt {
  DynInt(int i) : i_ptr(new int(i)) {}
  ~DynInt() { delete i_ptr; }
  DynInt(const DynInt &di) : i_ptr(new int(*di.i_ptr)) {}
  DynInt &operator=(const DynInt &di) {
    if (this != &di) { *i_ptr = *di.i_ptr; }
    return *this;
  }
  DynInt(DynInt &&di) : i_ptr(di.i_ptr) { di.i_ptr = nullptr; }
  DynInt &operator= (DynInt &&di) {
    if (this != &di) {
      delete i_ptr;
      i_ptr = di.i_ptr;
      di.i_ptr = nullptr;
    }
    return *this;
  }
  friend std::ostream &operator<<(std::ostream &os, const DynInt &di) {
    return os << *di.i_ptr;
  }
  int *i_ptr;
};
int main() {
  DynInt di1(42);
  DynInt di2 = std::move(di1); // call move constructor
  *di2.i_ptr = 100;
  std::cout << di2 << '\n';
  return 0; }
```

Relax now

- You know how to handle special member functions in context of dynamic memory allocation
  - It will not get anymore complicated than that



A note on special member functions using built-in and STL types

- STL types provide many useful constructors
- STL types know how they have to be …
  - destructed
  - copied
  - copied assigned
  - moved
  - move assigned

- If your are dealing with types containing only primitive (built-in) or STL data members **=** `default` is fine
- If you are dealing with dynamic memory yourself, you now know how to deal with special member functions such as copy, move, and the assignment operators

Notes on dynamic memory allocation

```cpp
#include <iostream>
#include <utility>
using namespace std;
int main() {
  int outer_scope;
  {
    int inner_scope = 42;
    outer_scope = std::move(inner_scope);
  }
  std::cout << outer_scope << '\n';
  return 0;
}
```

- Raw `new` and `delete` need to be used rarely
  - “Too” error prone
  - Usually no need for raw `new` and `delete`
  - There are exceptions of course
- If you need to allocate an object
  - Just do so using stack memory
    - and return by value (RVO and `std::move()` take care of performance)
    - `std::move()` the variable between scopes, if you want it to live longer then its scope
  - If the object is too large to be stored on the stack, **then** use dynamic memory allocation

Notes on dynamic memory allocation

- If you need to allocate a fixed-size array of objects
  - Just do so using stack memory
    - `int data[10];`
    - `std::array<int,10> more_data; // use: #include <array>`
      - Safe wrapper for fixed-size stack allocated arrays
      - Carries size information
- If you need to dynamically allocate an array of objects
  - Use `std::vector`
    - It was created for this purpose
    - Safe wrapper for dynamically allocated arrays
    - Carries size information

Notes on dynamic memory allocation

- If you need raw `new` and `delete` nevertheless
  - Try to use smart pointers rather than raw pointers
    - Smart pointers take care of deallocation → `delete`
    - Smart pointers do the clean-up themselves
      - You cannot leak anymore
      - “The poor man’s garbage collector”
      - Implement reference counting
    - We will see smart pointers in one of the next lectures

Recap

- Operator overloading
- A program’s memory layout
- Dynamic memory allocation
- Dynamic memory allocation for arrays
- Dynamic memory allocation for objects
- Valgrind and Clang’s Sanitizers
- Copy constructor
- Move constructor
- Notes on dynamic memory allocation

Thank you for your attention
Questions?