C++ PROGRAMMING

Lecture 2

Secure Software Engineering Group

Philipp Dominik Schubert

CONTENTS


HEINZ NIXDORF INSTITUT
UNIVERSITÄT PADERBORN
Fraunhofer
IEM

Notion of a function

- “A function declaration introduces the function name and its type. A function definition associates the function name and type with the function body.” [en.cppreference.com]
- Example: a function that computes the maximum of two integer values
  - Declaration

```
int max(int, int);
int max(int a, int b);      // or with formal parameter names
```

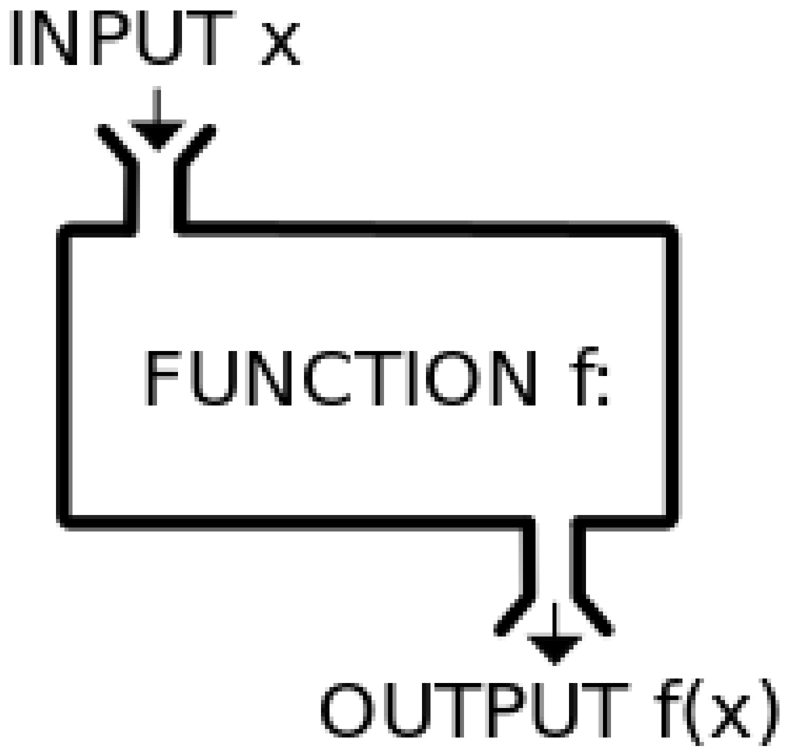
  - Definition

```
int max(int a, int b) {
  if (a >= b) { return a; }
  return b;                   // observe, that we do not need ‘else’ here
}
```

  - Some languages allow function definition only (e.g. Java)
  - We will learn why function declarations are useful in the next lecture

What is a function?

- A function is a little machine
  - Gets some input
  - Manipulates input
  - Returns output
  - Think of it as a functional unit!
- Similar to a mathematical function



Mathematical functions and C++

- Task
  - Declare a function f that is able to sum two numbers $x, y \in \mathbb{N}$
  - Define this function f to actually sum two numbers $x, y \in \mathbb{N}$

- Declaration in mathematics
  - $f: \mathbb{N} \times \mathbb{N} \to \mathbb{N}$
- Definition in mathematics
  - $f(x, y) \longmapsto x + y$

- Declaration in C++
  - `unsigned f(unsigned, unsigned);`
- Definition in C++
  - `unsigned f(unsigned x, unsigned y) { return x + y; }`

- Note `unsigned` is a shorthand for `unsigned int`

Functions in C++

- Note
  - A function may not return
  - A function may receive no parameters

```
void f() {}            // void is a "special" type → no type
void g(int a);
void h(void);
int returnOne() { return 1; }
```

- Functions should have a “meaningful” name (unlike mathematical functions)
  - General rule: name things according to their purpose, same holds for variables!
- Function’s in- and output can be …
  - Built-in types
  - User-defined types (today and next time)

Functions in C++

- Lets define a function
- Why you should use meaningful names:

```
int function(int x, int y) {
        int result = x;
        for (int i = 2; i <= y; ++i) {
                result *= x;
        }
        return result;
}
```

- What is the value of `result` after the function call?
  - `int result = function(2, 4);`
  - 16
- What does the function do?
  - Implements the power function
- What would be a better declaration?
  - `int pow(int base, int exponent);`
- Note this function “only works” for integers!
  - Don’t try `int result = pow(2.5, 4.8);`
    - Significant figures get cut off (type casting)

Use of functions

- Use a function to
  - perform a logical task
    - that has to be performed multiple times

      → don't repeat yourself
  - build an abstraction / generalization
  - structure your source code

- The task described by a function can be reused!
  - Faster development
  - Less error prone
  - Improved readability
  - **Use libraries:** a collection of useful functions

```
int pow(int base, int exponent) {
  int result = base;
  for (int i = 2; i <= exponent; ++i) {
    result *= base;
  }
  return result;
}
```

Use of functions

- Let's consider the factorial function!
- Sequential

```
int factorial(int n) {
  int f = n;
  while (n-- > 1) {
    f *= n;
  }
  return f;
}
```

- What is that?

```
int factorial(int n) {
  if (n > 1) { return n * factorial(n-1) };
  return 1;
}
```

- Computes the factorial function using recursion!

Conditional assignments and the ternary operator

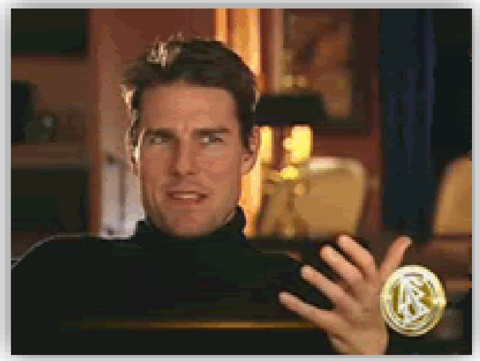
- If an assignment depends on a condition you can use a shortcut

```
int i = ... // some value
int variable;
if (i > 10) {
    variable = 100;
} else {
    variable = 0;
}
int variable = (i > 10) ? 100 : 0; // shorthand which does the same
```

- Note there are many of these short forms
  - `c++;`
  - `d += 10;`
  - `unsigned // shorthand for unsigned int`
  - You will get used to it

Recursion

- With functions one can make use of recursion!
- “**Recursion** occurs when a thing is defined in terms of itself or of its type. Recursion is used in a variety of disciplines ranging from linguistics to logic. The most common application of recursion is in mathematics and computer science, where a function being defined is applied within its own definition.” [en.wikipedia.com]
- Another recursive definition of recursion: “Recursion, see recursion!”



- A recursive function uses itself to solve a task
- A function exhibits recursive behavior if
  1. it defines one (or more) base case(s) that do not use recursion
  2. a set of rules that reduce all other cases towards the base case

[Figure taken from http://giphy.com/]

Factorial function revisited

```
int factorial(int n) {
  if (n > 1){ return n * factorial(n-1);}
  return 1;
}
```

- What happens if `factorial` gets called?

  ```
  int result = factorial(5);
  ```

  - Let's see what happens:

    factorial(5)

    if (5 > 1) return 5 * factorial(4);

    factorial(4)

    if (4 > 1) return 4 * factorial(3);

    factorial(3)

    if (3 > 1) return 3 * factorial(2);

    factorial(2)

    if (2 > 1) return 2 * factorial(1);

    factorial(1)

    if (1 > 1) NO!

    return 1;

    We have reached the base case!

    The call to `factorial(5)` can now evaluate

    5 * 4 * 3 * 2 * 1 = 120

- If you are still not convinced have a look at:
  - What on Earth is Recursion? – Computerphile
- Recursion often allows for elegant solutions
- Requires some time to get used to

Functions

- You can now divide your computations into logical pieces (functions)
- The OS calls the `main` function for you
- In `main` you can call whatever you like

```
int main() {
    int i = factorial(5);
    int j = factorial(6);
    return 0;
}
```

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

A note on functions

- With `constexpr` we effectively have to versions:
  - a `constexpr` version
  - a non-`constexpr`-version

```
// can be evaluated at compile time
constexpr int i = factorial(8);
```

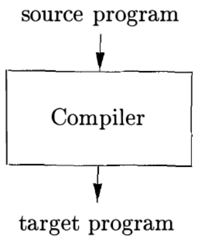


Figure 1.1: A compiler

```
int x = ... // non-constant x
// can only be evaluated at run time
int j = factorial(x);
```

Figure 1.2: Running the target program

- Actual parameters passed to a function are copied by default!
  - Inside a function you work on copies by default!

```
int increment(int x) { return ++x; }
int x = 10;
int y = increment(x); // y is now 11
// x is still 10
```

- Remember `constexpr`

```
// C++11 allows one return statement
constexpr int addNumbers(int a, int b) {
  return a + b;
}
// C++14 allows more than one statement
constexpr int factorial(int n) {
  int result = 1;
  while (n-- > 0) {
    result *= n;
  }
  return result;
}
```


HEINZ NIXDORF INSTITUT UNIVERSITÄT PADERBORN
Fraunhofer IEM

A note on functions

- Function calls come with some costs in terms of performance
  - Safe registers' contents, put function arguments on the stack, increment stack pointer, …, restore registers, perform jump back
    - But usually that is not why your code is slow!
- If high performance really matters, compiler can inline small functions
  - A function call is replaced by copying the functions body to the call site
  - Use the keyword `inline` to give the compiler some hints

```
inline int add(int a, int b) { return a + b; }
// a call to add()
int c = add(10, 20);
// may be replaced with
int c = 10 + 20;
```

  - Inlining is only necessary in rare cases (sometimes you make it worse)
    - Compiler inlines on its own if compiler optimizations are turned on (-Ox flag, where x is 1,2 or 3)

Local and global variables

- Local variables are only accessible within a certain function / scope (e.g. `main`)
- A variable is local if it is defined inside a function
- Example

```
int main() {
    int i = 42;
    int j = 13;
    std::cout << i << '\n';
    std::cout << j << '\n';
    return 0;
}
```

- So far we only used local variables

- Global variables are accessible across functions (and modules)
- A variable is global if it is not defined within a function
- Example

```
int i = 10;
double d = 1.234;
void printGobals() {
    std::cout << i << '\n';
    std::cout << d << '\n';
}
double addGlobals() {
    return i + d;
}
```

A note on global variables

- Try to avoid global variables as much as possible
  - You rarely need them
  - They break local reasoning
    - It becomes pretty hard to understand the code
  - It is hard to parallelize code that heavily makes use of globals

User-defined types / non-built-in data types

- Two very important user-defined types
  - `std::string`
  - `std::vector<typename T>`
  - Implemented in the standard template library (STL)
  - Vector is perhaps the most used non-built-in data type

- You can define your own data types
  - Use `class` or `struct` keyword
  - Next lecture!

std::string

- Why should you use `std::string` in C++?
- C has no built-in string datatype
  - In C a string is stored in an array of characters

```
char str[] = "Hello, World!";
std::cout << str << '\n';
int i = 0;
while (str[i] != '\0') {
  std::cout << str[i] << '\n';
  ++i;
}
char *ptr2str = "Hello, World!";
char data[10] = "Hi!";
```

  - Such character arrays are (hopefully) terminated with `'\0'`
    - Which you can't see directly

- Remember built-in arrays are dangerous
  - What if you forget the size of that array?
  - What if you lose `'\0'` or have multiple `'\0'` in your character array through incorrect string processing?
  - You risk reads and writes outside your array
    - Undefined behavior / buffer overflows
    - Please watch this video
      - Buffer overflow attack
  - C++ has no built-in strings either
  - But it offers a safe wrapper: `std::string`

`std::string`

- Use the `#include <string>` header file
- `std::string` allows you to store strings
- `std::string` offers a lot of useful functionalities as well
  - Functionalities are offered as member functions (member functions: next lecture)
- `std::string` can grow and shrink dynamically (dynamic memory allocation: next lectures)
- `std::string` knows its size as well, unlike simple built-in arrays!
- `std::string` automatically adds the terminal character `'\0'`
- No buffer overflows!
- For the complete list of functionalities see
  - http://en.cppreference.com/w/cpp/string/basic_string

std::string

- The design is so good, it can be used like an ordinary built-in type (C++ is powerful)
- Example

```
// create a string from string literal
std::string str = "Hello World!";
// copy str to other
std::string other = str;
// get str's size
std::cout << str.size() << '\n';
// replace a single character
str[4] = 'O';
```

```
// append some more characters
str += "some more characters";
// extract a substring
std::string hello = str.substr(0,5);
std::string yetanother = "Hello";
// check for equality
std::cout << (hello == yetanother)
          << '\n';
```

`std::vector<typename T>`

- Again built-in arrays are dangerous for several reasons
- `std::vector<typename T>` is a safe wrapper for built-in arrays (similar to `std::string`)
- `std::vector<typename T>` can store multiple elements of the same type in sequence
- It is mutable and can grow and shrink dynamically (dynamic memory allocation: next lectures)
- Ok fine, but what is this `<typename T>`?
  - This is called a template parameter
  - Templates and template metaprogramming? (in the next lectures)
  - What are templates used for?
    - Allow for writing code that is independent of the type! (Cannot be done in the C language)
    - A vector can store any type!

```
vector<int> ivec = {1, 2, 3};
vector<double> dvec;
vector<std::string> svec = { "Hello", "World", "!" };
```

std::vector<typename T>

- How to initialize (or construct) a vector?
- Example

```
std::vector<int> ivec;                    // call to default constructor
std::vector<int> ivec(10);                // call to constructor
std::vector<int> ivec(10, 42);            // another constructor
std::vector<int> ivec{1, 2, 3, 4, 5};     // yet another constructor
std::vector<int> ivec = {1, 2, 3, 4, 5};  // even more
```

- A vector can be constructed using one of its constructors
- All user-defined data types have constructors
  - A constructor’s job is to construct a variable / an object
    - Acquires resources and initializes correctly
  - Constructors are special member functions (next lecture)

`std::vector<typename T>`

- `std::vector` is designed such that it can be used like a built-in type
- Example

```
std::vector<int> ivec = {1, 2, 3};
std::cout << "size: " << ivec.size() << '\n';
ivec.push_back(42);
ivec.push_back(120);
std::cout << "size: " << ivec.size() << '\n';
for (int i : ivec) {
  std::cout << i << ' ';
}
std::cout << '\n';
```

- Note: we are using members functions (next lecture)
  - Members can be data (variables) or functions → data members / function members
  - Members can be accessed with the `.` (point) operator

Type aliasing

- Introduce type aliases
  - using the `typedef` or `using` keyword
  - Prefer `using` (modern version)
  - as types get more complicated
  - to stride towards more flexible programs
- `typedef double real_t;`
- `using ivec = vector<int>;`
- Dealing with types `decltype(*)` (this is a C++11 feature)
  - `*` can be a variable / expression / function

```
const int i = 13;
decltype(i) x = 10;
```

  - `x` has now `i`’s declared type (which is `const int`)

- A “real world example”

```
// oh dear
std::vector<std::pair<std::string,int>> v;
// better use an alias for that
using vpsi_t =
std::vector<std::pair<std::string,int>>;

// you can declare variables of that type
vpsi_t x; // easier to read and write
```

What are containers?

- `std::vector<typename T>` is a container
- A container can store a bunch of data
- Containers are generic
  - Use one or more template parameters
  - Can hold values of any type
- Use different containers for different purposes
- Choose the right container depending on your problem
- Note that you can nest containers!
  - `std::vector<std::vector<double>> matrix = { {1, 2}, {4, 5} };`

STL containers?

- Sequence containers
  - `array   // fixed size array`
  - `vector // flexible size array`
  - `deque   // double-ended queue`
  - `forward_list // singly linked list`
  - `list   // doubly linked list`
- Associative containers
  - `set    // unique element set`
  - `map    // unique element associative storage`
  - `multiset // non-unique element set`
  - `multimap // non-unique element associative storage`
- Unordered associative containers
  - `unordered_set // hash set`
  - `unordered_map // hash map`
  - `unordered_multiset // …`
  - `unordered_multimap // …`
- Container adaptors
  - `stack // stack adaptor`
  - `queue // queue adaptor`
  - `priority_queue // priority queue adaptor`
- STL containers …
  - are quite useful
  - are implemented very efficiently
  - are accessible by including their header file

When to use what?

- Sequence containers

```
// fixed size array
std::array<int, 4> a = {1, 2, 3, 4};
std::cout << a.size() << '\n';
for (int i : a) {
  std::cout << i << ' ';
}
// flexible size array
std::vector<int> b = {1, 2, 3, 4};
std::cout << b.size() << '\n';
for (int i : b) {
  std::cout << i << ' ';
}
b.push_back(5);
b.push_back(6);
```

- Rarely used:
  - `forward_list  // singly linked list`
  - `list          // doubly linked list`

- Associative containers

```
// unique element set
std::set<int> c = {1, 2, 3};
c.insert(5);
c.insert(6);
if (c.count(5)) {
  std::cout << "set contains '5'.\n";
}
// unique element associative storage
std::map<int, std::string> d;
d.insert(std::make_pair(1, "A"));
d.insert(std::make_pair(2, "B"));
d[3] = "C";
std::cout << d[2] << '\n';
```

- You may wish to use their unordered counterparts

Containers in action

- Use STL vector to represent mathematical vectors $\in \mathbb{R}^n$
- `std::vector<typename T>          // use #include <vector>`
- Task: create two vectors to represent vectors from maths and write a function that calculates the scalar product!
  - $\mathrm{x}, \mathrm{y} \in \mathbb{R}^3$
  - The scalar product $< \cdot , \cdot >$ is defined as
    - $< a, b > = \sum_{i=0}^{n} a_i \cdot b_i$
  - Solution in C++

```
std::vector<double> x{1, 2, 3};   // call the initializer_list constructor
std::vector<double> y{4, 5, 6};   // call the initializer_list constructor
```

    - We now have two vectors x and y filled with some floating-point numbers

Containers in action

- $< a, b > = \sum_{i=0}^{n} a_i \cdot b_i$
- A function that computes the scalar product

```
double scalar_product(std::vector<double> x, std::vector<double> y) {
  double scalar_prod = 0; // create a variable holding the result
  if (x.size() != y.size()) { /* handle that error */ } // check dimensions
  for (size_t i = 0; i < x.size(); ++i) { // iterate over vectors’ entries
    scalar_prod += x[i] * y[i]; // multiply the entries and sum up to result
  }
  return scalar_prod; // return the result
}
```

- More on error handling later on

Containers in action

- Data

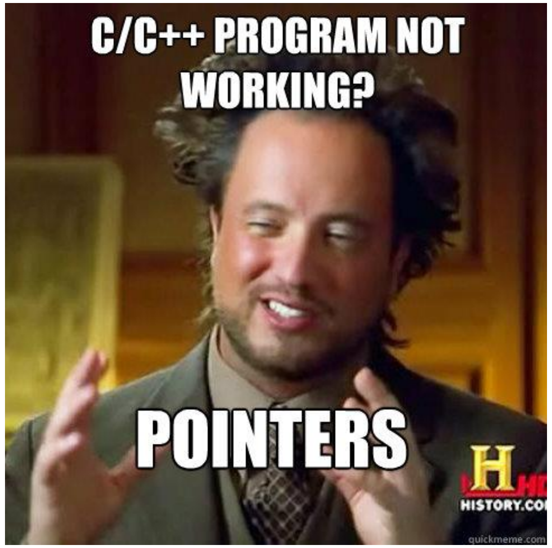
```
std::vector<double> x{1, 2, 3};
std::vector<double> y{4, 5, 6};
```

- Function to manipulate data (computes scalar product)

```
double scalar_product(std::vector<double> x, std::vector<double> y) {
  double scalar_prod = 0; // create a variable holding the result
  if (x.size() != y.size()) { /* handle that error */ } // check dimensions
  for (size_t i = 0; i < x.size(); ++i) { // iterate over vectors' entries
    scalar_prod += x[i] * y[i]; // multiply the entries and sum up to result
  }
  return scalar_prod; // return the result
}
```

- `double s =scalar_product(x, y);`
  - `s` is 32

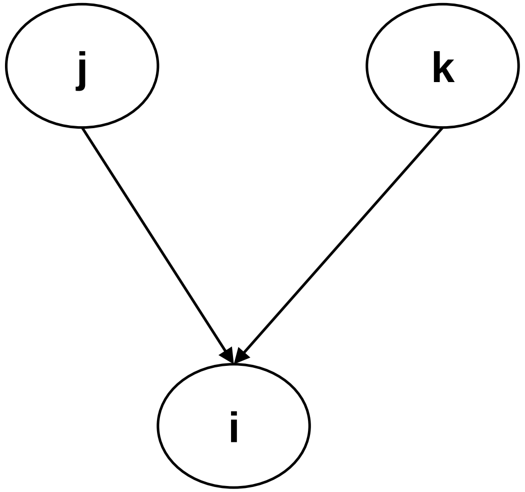
More on types: pointer, reference, and value types



- **Take a deep breath!**

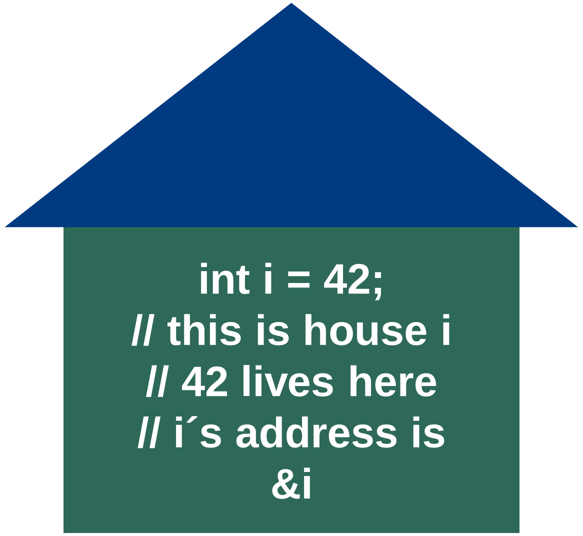
- What makes C++ so powerful?
  - Full control over resources (e.g. memory) !

- Three “kinds / versions” of types exist in C++
  - “Normal”/value integer type `int i = 42;`
  - Pointer to an integer type `int *j = &i;`
  - Reference to an integer type `int &k = i;`
  - Makes C++ very powerful
  - Pointers and references are types that store addresses
    - Think of them as “pointers” (points-to graphs)



[Figure taken from http://www.quickmeme.com/meme/3ovgn9]
HEINZ NIXDORF INSTITUT UNIVERSITÄT PADERBORN
Fraunhofer IEM

More on types: pointers



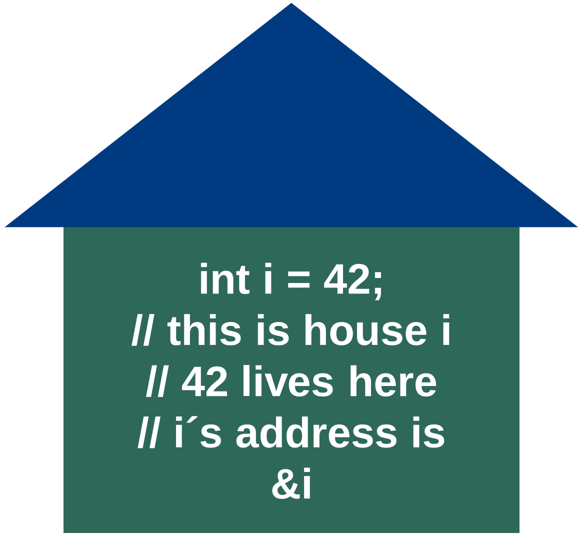
- Pointers, references, addresses?
- Every variable has a memory address
  - Think of houses (= variables)
    - People live in houses (= values)
    - Every house has a house number (= address)

```
int *i_ptr;       // i_ptr can store an address to an int
double *d_ptr;    // d_ptr can store an address to a double
float *f_ptr = nullptr;   // f_ptr is initialized with a null-pointer: f_ptr points to nothing!

int i = 42;       // integer initialized with 42
int *j = &i;      // j holds the address of i (or points to i), & is the address of operator here
int *k;           // uninitialized pointer to an integer
k = &i;           // let k point to i
int **l = &j;     // l holds the address of j
```

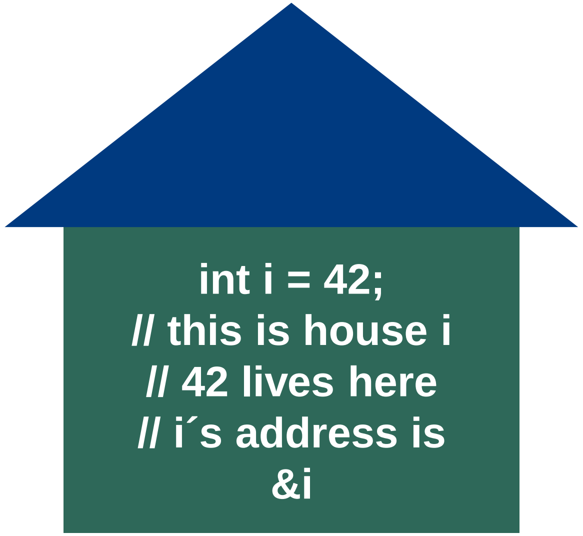
More on types: pointers

- Pointers, references, addresses?
- Every variable has a memory address
  - A mail man can deliver letters and parcels
    - You can also find a person using his address




```
int i = 42;
int *j = &i;  // get i’s address, this is called referencing (we create a pointer / reference)
*j = 100;     // modify i’s value through its address, this is called dereferencing
int k = *j;   // obtain i’s value through its address, this is called dereferencing
```

More on types: pointers



- Pointers, references, addresses?
- Every variable has a memory address

```
int i = 42;
int *j = &i;  // get i´s address, this is called referencing (we create a pointer / reference)
int k = *j;   // obtain i´s value through its address, this is called dereferencing

std::cout << &i << '\n';
std::cout << i << '\n';

std::cout << &j << '\n';
std::cout << j << '\n';

std::cout << &k << '\n';
std::cout << k << '\n';
```

Variable´s name	Address	Content
i	0x7fffab7c4770	42
j	0x7fffab7c4778	0x7fffab7c4770
k	0x7fffab7c4774	42
…	…	….

More on types: pointers

- Important
  - A pointer might be null
  - `int *i = nullptr;`
  - Meaning: the address does not exist / there is no address / `i` points to nothing
  - Don't dereference a `nullptr`!
  - A pointer can be checked for `nullptr`

    ```
    if (i == nullptr) { cout << "i holds the null pointer\n"; }
    ```
  - Or if you wish to pretend to be cool

    ```
    if (!i) { cout << "i holds the null pointer\n"; }
    ```

More on types: pointers

- Things to remember
  - Declare a pointer type using `*`
  - Take an address of a variable with `&`
  - Dereference a pointer with `*`
  - A pointer variable may hold the null pointer `nullptr`
  - A pointer may dangle

```
int *p;
int q = *p; // please don't
```

- We will discuss techniques and tools to debug memory issues later on

HEINZ NIXDORF INSTITUT
UNIVERSITÄT PADERBORN
Fraunhofer
IEM

More on types: references

- Example

```
int i = 42;
int &j = i;
```

  - Declare a reference type by using `&`
  - “You can use `j` as if it was `i`”
- **References behave much like pointers, but**
  - Pointers can be re-assigned, references can not
  - Pointers can be null and are allowed to dangle
    - References always refer to a valid object
  - Pointer’s address can be taken, references addresses cannot be taken
  - Pointers allow for pointer arithmetic, references don’t (next lecture(s))
  - References are internally implemented as pointers
  - In general: references are much safer to use

References vs pointers

- When to use what and why do I need references **and** pointers?
  - References
    - Use references in functions’ parameter lists
    - See next slides
  - Pointers
    - Use pointers to implement algorithms and data structures (e.g. linked lists)
    - Use pointers for dynamic memory allocation
    - Next lecture(s)

Functions: parameter passing (and returning)

- How to pass and return huge amounts of data to and from a function?
- Consider a function that implements a matrix multiplication

```
matrix matrixMult(matrix a, matrix b);
```

  - Problem
    - If `matrixMult()` is called, actual parameters are **copied**!
    - Matrices can be huge, millions of elements → copying may be very expensive
      - Processor is only copying data, rather than computing useful results
    - Can we avoid copying large data into functions?
    - **Pass data by reference, rather than by value!**

```
matrix matrixMult(matrix& a, matrix& b);
```

      - Matrices are not copied, we just pass a reference to a matrix (which is an address)
      - Matrix references can be used as if they were the matrices within the function's body

Functions: parameter passing (and returning)

```
matrix matrixMult(matrix& a, matrix& b);
```

- Problem
  - Caution: If we modify the references `a` and `b` within the function we are changing the actual matrices
  - How can we avoid accidental changes made to the matrices `a` and `b`?
    - Use `const` references to avoid modifications

      ```
      matrix matrixMult(const matrix& a, const matrix& b);
      ```

      - Changes made to `const` references result in compiler errors
- How to return results if data to be returned is very large?
  - Return by reference?

    ```
    matrix& matrixMult(const matrix& a, const matrix& b);
    ```

    - No! Return by value, compilers use return value optimization (RVO)!
    - Use: `matrix matrixMult(const matrix& a, const matrix& b);`

Functions: parameter passing (and returning)

- If your data is small (e.g. built-in types such as `int`)
  - Pass and return by value (copy data)

- If you do not know the size upfront (e.g. in case of containers) or deal with huge data
  - Pass by reference (data itself stays where it is, no unnecessary copying)
  - Use `const` if you do not wish to modify the data within the function
  - Return by value (since all modern compilers support RVO)

Recap

- Functions
- Recursion
- Conditional assignments
- `constexpr` functions
- `inline` functions
- Local and global variables
- `std::string` and `std::vector<typename T>`
- STL containers
- Containers in action: scalar product
- Values, pointers, references
- Parameter passing

Thank you for your attention
Questions?