12 Program Structure and Modules

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Software Design

- Software design: general considerations about structure of a program before the actual programming/implementation starts
  - Goal: Partitioning of the problem in manageable sub-problems

- There exists a multitude of different approaches for software design
  - Object-oriented approach
    - decomposition into classes and objects
    - designed for Java or C++
  - Top-down design/functional decomposition
    - state of the art until the mid 80s
    - decomposition into functions and function calls
    - design constraints for FORTRAN, COBOL, Pascal, or C
Software Design

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System-level software is still designed with the **functional decomposition** in mind.
Example Project: A Weather Station

Typical embedded system

- multiple sensors
  - air speed
  - air pressure
  - temperature

- multiple actuators
  (here: output devices)
  - LCD-screen
  - PC via RS232
  - PC via USB

- Sensors and actuators are connected to the µC via different bus systems
  - I²C
  - RS232

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  the µC via different bus systems
  - I\textsuperscript{2}C
  - RS232

What does functional decomposition of the software look like?
Functional Decomposition: Example

Functional decomposition of the weather station (extract):
1. read sensor data
2. process data (e.g., smoothing)
3. output data
4. wait and eventually re-start again with step 1
Functional Decomposition: Example

Functional decomposition of the weather station (extract):

1. read sensor data
   1.1 read the temperature sensor
   1.2 read the pressure sensor
   1.3 read the air speed sensor
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Functional Decomposition: Example

Functional decomposition of the weather station (extract):

1. read sensor data
   1.1 read the temperature sensor
      1.1.1 initialize \( I^2C \) data transfer
      1.1.2 read data from the \( I^2C \)-bus
   1.2 read the pressure sensor
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   3.1 sending data via RS232
   3.2 refresh the LCD

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   1.3 read the air speed sensor

2. process data (e.g., smoothing)

3. output data
   3.1 sending data via RS232
      3.1.1 choose baud rate and parity (once)
      3.1.2 write data
   3.2 refresh the LCD

4. wait and eventually re-start again with step 1
Functional Decomposition: Problems

- The obtained decomposition does only account for the structure of the *activities*; however, not for the structure of the *data*
- Risk: Functions “wildly” work on a vast amount of unstructured data → inadequate separation of concerns

![Diagram showing data and activities connections]

**Data**
- `sendBuf[]`
- `init`
- `lastTemp`
- `lastWind`
- `baud`
- `curDev`

**Activities**
- `RS232Init()`
- `I2CStart()`
- `GetTemp()`
- `RS232Send()`
- `I2CRec()`
- `SendToPC()`
- `main()`
Functional Decomposition: Problems

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- Risk: Functions “wildly” work on a vast amount of unstructured data; inadequate separation of concerns.

Principle of separation of concerns

Parts that have **nothing in common** with each other should be placed **separately**!

*Separation of concerns* is a fundamental principle in computer science (likewise in each other engineering discipline).
Access to Data (Variables)

Variables have

- Scope
  - “Who can access the variable?”
- Lifespan
  - “How long is the memory accessible?”

These get set by position (pos) and storage class (sc)

<table>
<thead>
<tr>
<th>pos</th>
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</tr>
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<tbody>
<tr>
<td>local</td>
<td>none,</td>
<td>definition → end of block</td>
<td>definition → end of block</td>
</tr>
<tr>
<td></td>
<td>auto</td>
<td>definition → end of block</td>
<td>program start → program end</td>
</tr>
<tr>
<td></td>
<td>static</td>
<td></td>
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```c
int a = 0; // a: global
static int b = 47; // b: local to module

void f(void) {
    auto int a = b; // a: local to function (auto optional)
    // destroyed at end of block
    static int c = 11; // c: local to function, not destroyed
}
```
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Scope and lifespan should be chosen **restrictively**

- **Scope**
  - as **restricted as possible**!
    - prevent unwanted access from other modules (debug)
    - hide information of the implementation (black-box principle)

- **Lifespan**
  - as **short as possible**!
    - save memory space
    - especially relevant for $\mu$Controller platforms

Consequence: Avoid global variables!

Global variables are visible everywhere

Global variables require memory for the entire program execution

**Rule:** Declaration of variables with **minimal scope & lifespan**
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Solution: Modularisation

Decomposition of related data & functions into dedicated, surrounding units \(\leadsto\) modules

- RS232.c
  - RS232Init()
  - RS232Send()
- I2C.c
  - I2CStart()
  - I2CRec()
- weather.c
  - GetTemp()
  - SendToPC()

Variables:
- sendBuf[]
- init
data:
- baud
- curDev
- lastTemp
- lastWind

Functions:
- main()
**What is a Module?**

**module**: $(\langle \text{set of functions} \rangle, \langle \text{set of data} \rangle, \langle \text{interface} \rangle)$

$(\mapsto \text{"class" in Java})$

Modules are larger programming components

- problem oriented aggregation of functions and data
  - separation of concerns
- enable easy reuse of components
- enable simple exchange of components
- hide information of implementation: **black-box** principle
  - access only by means of the module’s interface
What is a Module?

**module** := (set of functions), (↦→ “class” in Java), (set of data), (interface)

Modules are larger programming components

- problem oriented aggregation of functions and data
- separation of concerns
- enable easy reuse of components
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- hide information of implementation: **black-box** principle

Module ↔ Abstraction

- The interface of a module **abstracts**
  - from the actual implementation of the functions
  - from the internal representation and use of data
In C, the modules are not part of the language itself, instead it is handled solely idiomatically (with help of conventions)

- module interface \(\rightarrow\) .h-file (contains declarations \(\hookrightarrow\) 9–9)
- module implementation \(\rightarrow\) .c-file (contains definitions \(\hookrightarrow\) 9–4)
- module usage \(\rightarrow\) #include <module.h>

```c
extern void Init(uint16_t br);
extern void Send(char ch);
...
```

RS232.h: Interface / Contract (public)
Declaration of provided functions (and data)
In C, the modules are not part of the language itself, instead it is handled solely *idiomatically* (with help of *conventions*).

- **module interface** → .h-file (contains declarations)
- **module implementation** → .c-file (contains definitions)
- **module usage** → `#include <module.h>`

**RS232.h:** Interface / Contract (public)
Declaration of provided functions (and data)

**RS232.c:** Implementation (not public)
Definition of provided functions (and data)

Possible module-internal helper functions and variables (*static*)

Inclusion of the own interface ensures that the contract is adhered to
C module exports a set of defined symbols

- all functions and global variables (→ “public” in Java)
- export can be prevented with static (→ “private” in Java)
  (→ restriction of scope → 12–5)

Export takes place during compilation (.c file → .o file)

source file (foo.c)

```c
uint16_t a;
// public
static uint16_t b;
// private

void f(void) // public
{ ... }
static void g(int) // private
{ ... }
```

object file (foo.o)

Symbols a and f are exported.
Symbols b and g are declared as static and, therefore, they are not exported.
C module imports a set of not-defined symbols
- functions and global variables that are used but not defined in the module itself
- during compilation, they are marked as unresolved

source file (bar.c)
```c
extern uint16_t a; // declare
extern void f(void); // declare

void main(void) { // public
    a = 0x4711; // use
    f(); // use
}
```

object file (bar.o)

Symbol `main` is exported.
Symbols `a` and `f` are unresolved.
The actual resolution is performed by the linker

foo.c
Compiler
bar.c

foo.o
Compiler

foo.o
Compiler

main
Linker

bar

Linking is not type safe!
Information about types is not anymore present in the object files
Resolution by the linker takes place exclusively via names of symbols (identifier);
type safety has to be ensured during compilation; uniform declaration with the help of a common header file.
The actual resolution is performed by the linker.

Linking is **not type safe!**

- Information about types is not anymore present in the object files.
- Resolution by the linker takes place **exclusively** via **names of symbols** (identifier).

→ **type safety has to be ensured during** compilation.

→ uniform declaration with the help of a common header file.
Elements from other modules have to be declared
- functions with the `extern` declaration
  ```c
  extern void f(void);
  ```
- global variables with `extern`
  ```c
  extern uint16_t a;
  ```

Declarations take place usually in a header file, which is made available by the module developers
- interface of the module
  - exported functions of the module
  - exported global variables of the module
  - module specific constants, types and macros
  - usage by inclusion
- is included by the module itself to ensure a match of declaration and definition

The keyword `extern` differentiates between a declaration and definition of a variable.
module interface: foo.h

// foo.h
#ifndef _FOO_H
#define _FOO_H

// declarations
extern uint16_t a;
extern void f(void);
#endif // _FOO_H

module implementation foo.c

// foo.c
#include <foo.h>

// definitions
uint16_t a;
void f(void) {
    ...
}

module usage bar.c

// bar.c
extern uint16_t a;
extern void f(void);
#include <foo.h>

void main(void) {
    a = 0x4711;
    f();
}
Each module consists of a header and one or more implementation file(s).
- .h-file defines the interface
- .c-file implements the interface, includes the .h-file to ensure a match of declaration and definition

Use of the module by including the specific .h-file
Each module consists of a header and one or more implementation file(s):
- `.h`-file defines the interface
- `.c`-file implements the interface, includes the `.h`-file to ensure a match of declaration and definition

Use of the module by including the specific `.h`-file

This is similar for libraries
Summary

- Principle of separation of concerns \(\sim\) modularisation
  - reuse and exchange of well defined components
  - hiding of implementation details

- In C, the concept of modules is not part of the language, therefore, it has to be made possible **idiomatically** by conventions
  - module interface \(\mapsto\) .h-file (contains declarations)
  - module implementation \(\mapsto\) .c-file (contains definitions)
  - use of module \(\mapsto\) #include <module.h>
  - **private** symbols \(\mapsto\) define as static

- The actual combination is done by the linker
  - resolution exclusively by symbol names
    - **Linking is not type safe!**
  - type safety has to be ensured during compilation
    - with the help of a common header file