System-Level Programming

12 Program Structure and Modules

J. Kleinöder, D. Lohmann, V. Sieh, P. Wägemann

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Erlangen-Nürnberg

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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

System-level software is still designed with the functional decomposition in mind.
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System-level software is still designed with the **functional decomposition** in mind.
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 $\mu$C via different bus systems
  - $I^2C$
  - RS232
Example Project: A Weather Station

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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

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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 I²C data transfer
      1.1.2 read data from the I²C-bus
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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
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.
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>
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</tr>
</thead>
<tbody>
<tr>
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<td>none, auto, static</td>
<td>definition → end of block</td>
<td>definition → end of block, program start → program end</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
}
```
Scope and lifespan should be chosen restrictively

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

- **Lifespan**
  - as short as possible!
  - save memory space
  - especially relevant for μController 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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**Rule:** Declaration of variables with minimal scope & lifespan
Solution: Modularisation

- Decomposition of related data & functions into dedicated, surrounding units → modules

```
RS232.c
RS232Init()
RS232Send()
I2CStart()
I2CRec()
GetTemp()
SendToPC()

I2C.c
weather.c
sendBuf[]
baud
init
curDev
lastTemp
lastWind
main()
```

```c
// RS232.c
RS232Init()
RS232Send()
I2CStart()
I2CRec()
GetTemp()
SendToPC()

// I2C.c

// weather.c
```
What is a Module?

\[
\text{module} := (\langle \text{set of functions} \rangle, \\
\quad \langle \text{set of data} \rangle, \\
\quad \langle \text{interface} \rangle)
\]

(\rightarrow \text{“class” in Java})

Modules are larger programming components

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

**module** := (\(<set\ of\ functions\>,
\,<set\ of\ data\>,
\,<interface\>)

(\(\mapsto\) “class” in Java)

Modules are larger programming components

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- hide information of implementation: **black-box** principle
- access only by means of the module’s interface

**Module \(\mapsto\) 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 (by using conventions).

- **module interface** => .h-file (contains declarations)
- **module implementation** => .c-file (contains definitions)
- **module usage** => #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)

- Declaration of provided functions
- Inclusion of the own interface ensures that the contract is adhered to
In C, the modules are not part of the language itself, instead it is handled solely **idiomatically** (by using **conventions**)

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

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

#include <RS232.h>
static uint16_t baud = 2400;
static char sendBuf[16];
...
void Init(uint16_t br) {
    ...
    baud = br;
}
void Send(char ch) {
    sendBuf[...] = ch;
    ...
}
```

**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.
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 are usually part of the header file, which module developers make available
- interface of the module
  - exported functions of the module
  - exported global variables of the module
  - module-specific constants, types, and macros
  - usage by including
- 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.

(→ “interface” in Java)

(→ “import” in Java)

(→ “implements” in Java)
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

Usage of the module by including the specific .h file
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Usage of the module by including the specific .h file
This is similar for libraries
Summary

- Principle of separation of concerns $\leadsto$ modularization
  - 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 is realized 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
    $\leadsto$ **Linking is not type safe!**
  - type safety has to be ensured during compilation
    $\leadsto$ with the help of a common header file