

Exercises in System Level Programming (SLP) – Summer Term 2025

Exercise 3

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Systemsoftware

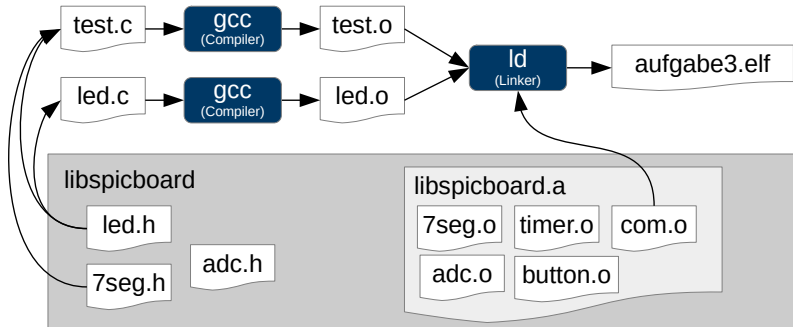


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Presentation Assignment 1

Modules

Overview: From the Source Code to a Program



1. Preprocessor
2. Compiler
3. Linker
4. Programmer/Flasher



- Header files contain the interface of a module
 - Function declarations
 - Preprocessor macros
 - Type definitions
- Header files can be included multiple times
 - `led.h` includes `avr/io.h`
 - `button.h` includes `avr/io.h`
 - ↪ Functions from `avr/io.h` declared multiple times
- Prevent Multiple inclusions/cycles ↪ **include-guards**
 - Definition and checking of a preprocessor macro
 - Convention: Macro has the same name as .h-file, '.' replaced by '_'
 - e.g. for `button.h` ↪ `BUTTON_H`
 - File is only included if the macro has not already been defined
- **Attention:** Flat name space ↪ always use unique names



- Creating a .h-file (convention: same name as .c-file)

```
01 #ifndef COM_H
02 #define COM_H
03 /* Include fixed-width data types (used in the header) */
04 #include <stdint.h>
05
06 /* Data Types */
07 typedef enum {
08     ERROR_NO_STOP_BIT, ERROR_PARITY,
09     ERROR_BUFFER_FULL, ERROR_INVALID_POINTER
10 } COM_ERROR_STATUS;
11
12 /* Functions */
13 void sb_com_sendByte(uint8_t data);
14 [...]
15 #endif //COM_H
```



- Internal variables and auxiliary functions not part of the interface
 - C has a flat name space
 - Unexpected accesses can lead to wrong behaviour
- ⇒ Encapsulation: Visibility & life span should be restricted



Visibility and Life Span	not static	static
Locale variable	visibility block life span block	visibility block life span program
Global variable	visibility program life span program	visibility module life span program
Function	visibility program	visibility module

- Local variables that are **not** declared as static:
 - ~> auto variable (automatically allocated & freed)
- Global variables and functions declared as static, if no export is necessary



```
01 static uint8_t state; // global static
02 uint8_t event_counter; // global
03
04 static void f(uint8_t a) {
05     static uint8_t call_counter = 0; // local static
06     uint8_t num_leds; // local (auto)
07     /* ... */
08 }
09
10 void main(void) {
11     /* ... */
12 }
```

- Visibility & life span should be chosen as **restricted** as possible
 - If possible: **static** for global variables and functions



- Modules have to perform an initialization
 - For example: Configuring ports
 - **Java:** Possible with class constructors
 - **C:** No such concepts
- *Workaround:* Modules have to initialize themselves upon the first function call
 - Remember completion of initialization
 - Prevent multiple initialization
- Creating an `initDone`-variable
 - Call of the `init` function in each function
 - `initDone`-variable initially set to 0
 - After initialization it is set to 1



- `initDone` is initially set to 0
 - Is set to 1 after initialization
- ~> Initialization only performed once

```
01 static void init(void) {  
02     static uint8_t initDone = 0;  
03     if (initDone == 0) {  
04         initDone = 1;  
05         ...  
06     }  
07 }  
08  
09 void mod_func(void) {  
10     init();  
11     ...  
12 }
```

In- & Output via Pins

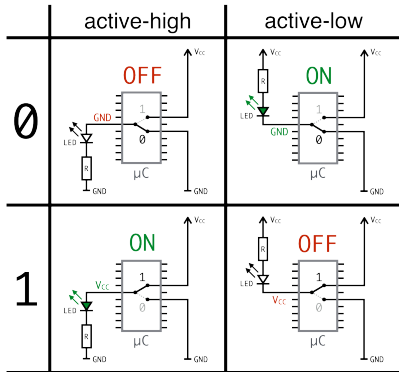


- Microcontroller interact with their environment
 - Besides some predefined protocols: Arbitrary (digital) signals
 - Many pins can be configured as an input or an output
- ~> General Purpose Input/Output (GPIO)

Output dependent on wiring:

active-high: high-level (logically 1; V_{cc} at Pin) → LED is on

active-low: low-level (logically 0; GND at Pin) → LED is on



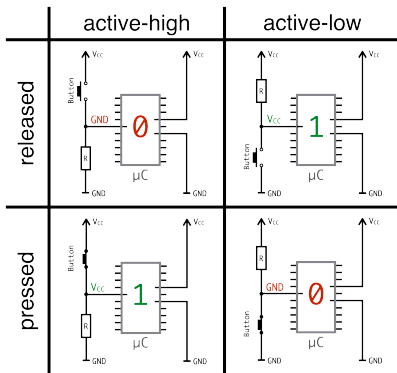
Input: Active-high & Active-low



Input dependent on wiring:

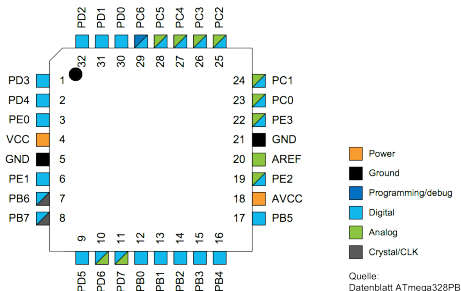
active-high: Button pressed $\rightarrow$ high-level (logically 1; V_{CC} at Pin)

active-low: Button pressed $\rightarrow$ low-level (logically 0; GND at Pin)



Inputs are of high impedance, a well defined level has to be present

$\leadsto$ Use pull-down or (internal) pull-up resistors



- Eight pins are combined to an I/O port for the AVR
- Each I/O port of the AVR is controlled by three 8-bit registers
 - DDRx** Data Direction Register
 - PORTx** Port Output Register
 - PINx** Port Input Register
- Every pin of a port has exactly one bit in each of the three register



DDRx: Data Direction Register configures pin i as an in- or output

- Bit $i = 1 \rightarrow$ Pin i used as an output
- Bit $i = 0 \rightarrow$ Pin i used as an input

Example:

```
01 DDRC |= (1 << PC3); // PC3 as output (Pin 3 at Port C)
02 DDRD &= ~(1 << PD2); // PD2 as input (Pin 2 at Port D)
```



PORTx: Port Output Register depends on DDRx register

- If **output**: Sets level to high or low at pin i
 - Bit $i = 1 \rightarrow$ high-level at pin i
 - Bit $i = 0 \rightarrow$ low-level at pin i
- If **input**: Sets the state of the internal pull-up resistor at pin i
 - Bit $i = 1 \rightarrow$ activates pull-up resistor for pin i
 - Bit $i = 0 \rightarrow$ deactivates pull-up resistor for pin i

Example:

```
01 PORTC |= (1 << PC3); // Pulls PC3 to high (LED off)
02 PORTC &= ~(1 << PC3); // Pulls PC3 to low (LED on)
03
04 PORTD |= (1 << PD2); // Activates internal pull up for PD2
05 PORTD &= ~(1 << PD2); // Deactivates internal pull up for PD2
```



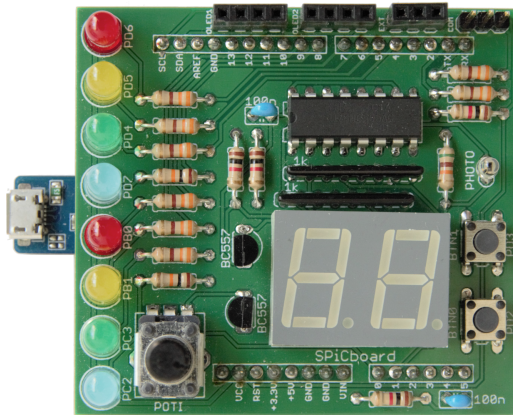
PINx: Port Input Register (read only) current value of pin *i*

- If **input**: poll what level is set from outside
- If **output**: poll whether high or low is put out

Example:

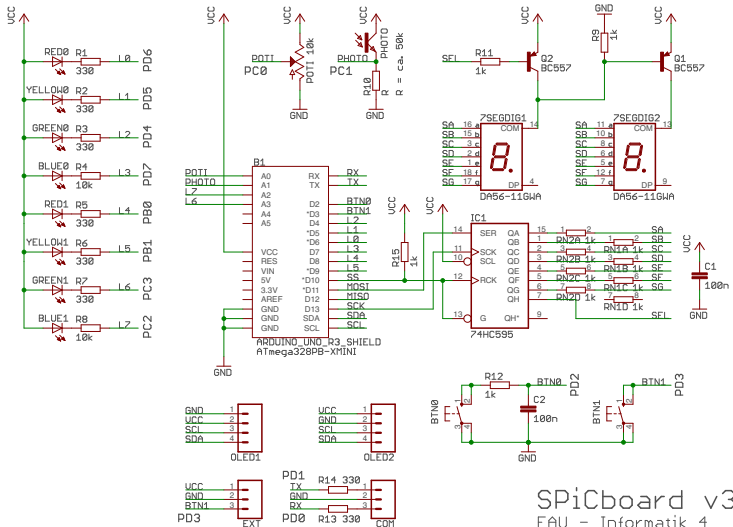
```
01 if((PIND & (1 << PD2)) == 0) { // Testing whether Pin PD2 is low
02     // low-level --> button is pressed
03     [...]
04 }
05
06 if((PIND & (1 << PD2)) != 0) { // Testing whether Pin PD2 is high
07     // high-level --> button is not pressed
08     [...]
09 }
```

Task: LED Module



- LED 0 (REDO) $\Rightarrow$ PD6 $\Rightarrow$ Port D, Pin 6 $\Rightarrow$ Bit 6 at PORTD and DDRD
- ...
- LED 7 (BLUE1) $\Rightarrow$ PC2 $\Rightarrow$ Port C, Pin 2 $\Rightarrow$ Bit 2 at PORTC and DDRC

SPiCboard Block Circuit Diagram





- Implement the LED module of the libspicboard
 - Same behaviour as the original
 - Description:
https://sys.cs.fau.de/lehre/ss25/spic/uebung/spicboard/libapi/extern/group__LED.html
- Including `led.h`
 - Definition of LED-IDs
 - Declaration of function signatures

```
01 typedef enum {  
02     RED0      = 0, /**< Upper red led    **/  
03     ...  
04     BLUE1     = 7  /**< Lower blue led   **/  
05 } LED;  
06  
07 int8_t sb_led_on(LED led);  
08 ...  
09 int8_t sb_led_off(LED led);
```



■ Testen des Moduls

- Eigenes Modul mit einem Testprogramm (`test-led.c`) linken
- Andere Teile der Bibliothek können für den Test benutzt werden

■ LEDs des SPiCboards

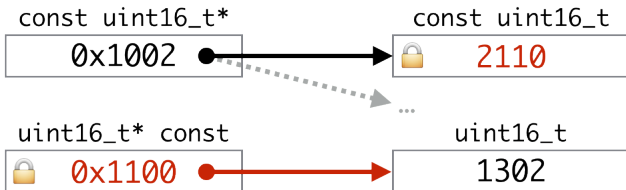
- Anschlüsse und Namen der einzelnen LEDs können dem Übersichtsbildchen entnommen werden
- Alle LEDs sind **active-low**, d.h. leuchten wenn ein low-Pegel auf dem Pin angelegt wird
- PD6 = Port D, Pin 6



- Testing of the module
 - Link your own module with a test program (`test-led.c`)
 - Other parts of the library can be used for testing
- LEDs of the SPiCboard
 - Connections and names of the single LEDs can be extracted from the overview pictures
 - All LEDs are **active-low**
i.e. they are switched on if a low-level is applied
 - PD6 = Port D, Pin 6



- `const uint8_t*`
 - Pointer to a **constant** `uint8_t`-value
 - **Value** cannot be modified via the pointer
- `uint8_t* const`
 - **Constant pointer** to an (arbitrary) `uint8_t`-value
 - **Pointer** is not allowed to point at a different memory address





- Address-of operator: &
- Indirection operator: *
- Definitions for ports and pins (in avr/io.h)

```
01 #define PORTD (* (volatile uint8_t *) 0x2B)
02 ...
03 #define PD0    0
04 ...
```

- Macro replaces `PORTD` by `(* (volatile uint8_t *) 0x2B)`
 1. Takes the integer `0x2B` (address of `PORTD`)
 2. Casts it into a `(volatile uint8_t *)` pointer
 3. Dereferences pointer `*` ($\Rightarrow$ `PORTD` is accessing the register contents)
 4. Brackets `(...)` enforce correct order of operations
(Attention, macro!)



■ Port array:

```
01 static volatile uint8_t * const ports[8] = { &PORTD,  
02                                     ...,  
03                                     &PORTC };
```

- Reverses the dereferencing of the address operator

⇒ Elements of `ports` are addresses in the form of `uint8_t` pointers

■ Pin array:

```
01 static uint8_t const pins[8] = { PD6, ..., PC2 };
```

■ Access:

```
01 * (ports[0]) &= ~(1 << pins[0]);
```



- Create project as usual
 - Initial source file: `test-led.c`
 - Then add second source file `led.c`
- When compiling, functions from your own module are used
- Additional parts of the library are included if required
- Code can be temporarily deactivated for testing the original functions:

```
01 #if 0
02     ....
03 #endif
```

- ⇒ Does the compiler see this “comment”?
- ⇒ How can we comment in the code again?



```
01 void main(void){
02     ...
03     // 1.) Testing with valid LED-ID
04     int8_t result = sb_led_on(RED0);
05     if(result != 0){
06         // Test failed
07         // Output e.g. with 7-Segment display
08     }
09     // wait some seconds
10
11     // 2.) Testing with invalid LED-ID
12     ...
13 }
```

- Pay close attention to the interface description (incl. return values)
- Testing of **all possible return values**
- Give an error if the returned value is different from the specification

Hands-on: Statistics Module

Screencast: <https://www.video.uni-erlangen.de/clip/id/16328>



- Statistics module and test program
- Functionality of the module (interface):

```
01 // Interface
02 uint8_t avgArray(uint16_t *a, size_t s, uint16_t *avg);
03 uint8_t minArray(uint16_t *a, size_t s, uint16_t *min);
04 uint8_t maxArray(uint16_t *a, size_t s, uint16_t *max);
05
06 // Internal auxiliary functions
07 uint16_t getMin(uint16_t a, uint16_t b);
08 uint16_t getMax(uint16_t a, uint16_t b);
```

- Return value:
 - 0: OK
 - 1: Error
- How to proceed:
 - Header file with module interface (and include guards)
 - Implementation of the module (consider visibility)
 - Testing of the module in the main program (incl. errors)