Concurrency in Arduino

Development of a programming language

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Semester Project

STUDENT REPORT
AALBORG UNIVERSITY

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Preface

Here is the preface. You should put your signatures at the end of the preface.

Aalborg University, April 11, 2022

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Chapter 1

Introduction

This report details the design, definition and implementation of a programming language, as per AAU's fourth semester module description [1].

1.1 Initial problem

The problem analysis begins from the project proposal: "A Concurrent Programming Language for Arduino" [2].

What is the best way to cite powerpoint slides from Moodle?

The proposal outlines how microcontrollers like the Arduino, is used in Cyber-Physical System (CPS)

Based on the project proposal, a set of issues have been extracted.

Arduino What it is, who uses it, and the challenges of the standard Arduino programming model in regards to concurrency/RTS.

Approaches Operating systems, scheduling, and differences between the options.

Scanner/Parser Generation of code. Or should this be after design? Otherwise, discussion of strengths and weaknesses.

Compilation Transpilation and compilation.

HOWEVER, the content should be considered from the perspective of a programming language, rather than the perspective of computation.

Chapter 2

Problem analysis

2.1 Arduino

Arduino is an open-source platform that enables users to easily and simply create small projects. Including projects such as an LED lighting up when a button is pushed, or building a thermostat to display the current ambient temperature. It is classified as a microcontroller board, which is a small computer that enables users to read some input and turn it into an output, and between this apply some logic. Arduino can be split into two categories, the physical and software:

The physical part of the Arduino is the board. There exist many types of boards that have different components and specs, but the most common board is the Arduino UNO. The Arduino UNO SET provides a USB cable to connect to a user's PC, a power input, some digital and analog pins, the microcontroller itself, the ATmega328, and various other components [3].

The software that Arduino makes use of is its IDE, which enables users to write code, also called sketches, which can be uploaded on the board and then be run. The code for Arduino is, in some ways, a simplified version of C++, which has integrated methods specifically made for Arduino.

The board is made to be inexpensive and simple to use, so it is possible for people with little to no experience working with electronics to pick up and start making projects. As in the past, it was necessary to have in-depth knowledge about microcontrollers and the like, to be able to create such projects. The Arduino IDE is also cross-platform, enabling users of Linux, Windows, and Mac OS to run the Arduino software [4].

2.1.1 Arduino Language

The Arduino language is a smaller version of C++. It holds most of the known semantics made from C++, but with some differences, which will be covered in this section [4]. A program in Arduino is called a sketch, Arduino sketch normally follows a basic structure, that consists of implementing the procedures "setup()" and "loop". "setup()" is called once at the beginning of the execution of the program;

it is meant to initialize the data structure and pins [5]. After the setup procedure, the loop() function beings. The loop() function is a loop that runs while the Arduino is on, and implements the Arduino behavior [6].

2.1.2 Who uses it

Arduino is used by a wide range of people, such as students, hobbyists, programmers, and professionals [4]. Many different groups of people use the Arduino for different purposes. Some are focused on the learning aspects of the Arduino, others are more interested in easily designing concepts for a product. Students can use the board to learn the basics of electronics, hobbyists use it to build projects, and professionals use it to design product concepts [7].

For this report, the focus is on hobbyists who use the Arduino to create projects and want to learn the basics of electronics. The main concern regarding this group of users is that they spend a limited amount of time working with Arduino, as the time they spend with it will be in their leisure time. Moreover, hobbyists might have limited coding proficiency or be complete beginners. We characterize the users we want to focus on as hobbyists who want to do as much as they can with their limited time and limited coding proficiency.

A little more detail on what we define as our target audience - hobbyists.

Write into definition of our target audience

2.1.3 What do hobbyists use the Arduino for

Hobbyists use Arduino for many different things, a Google search will show a vast amount of project ideas to people showing off their projects and maybe guiding people through to make their version. Such as this list of 10 uses for the Arduino [8]. The list includes projects that range from a simple thermostat to display the current temperature, to an automatic gardening device to water plants.

This shows just some of the projects that hobbyists could be interested in making, but for some projects, it might be useful for hobbyists to use concurrency.

2.2 Concurrency

Concurrency is the ability for tasks to be scheduled in a way that makes things work at the correct time. For example, if one task is running it will be paused if a more pertinent task appears, The system will then start that task. The scheduler is usually what takes care of these choices and prioritization [9].

I don't agree entirely on this definition, see page 60.

Concurrency is used for things like coordinating the execution of processes to maximize throughput. Concurrency is not to be confused with parallelism, which requires multiple cores because you have to do several things at the same time. Concurrency, on the other hand, does not need to be at the same time, just in the right order at the correct times, so it is possible to do with a single core. Since the Arduino has only a single core, this project deals with concurrency without parallelism.

It is possible to achieve concurrency on Arduino, but not without scheduling of some kind. Scheduling is to schedule different tasks to run on the same CPU, fooling users to think that they all run at the same time, while in fact it is running different tasks very fast and switching between them. This scheduling is not built into Arduino so the project will have to decide on how to achieve it. Part of the problem is choosing how to do this, while also keeping the end-user in mind. A hobbyist typically tries to achieve concurrency through the standard functions in Arduino, but many of these functions are not ideal for concurrency.

Several tutorials on how to implement different techniques to achieve some sort of concurrency in Arduino exist. These techniques include Milis() and Interrupt(). Milis() uses the milis function to tell the time, while not pausing to achieve the ability to wait and not do unnecessary tasks at all times. The interrupt() function, on the other hand, cancels the process if something happens, and this can be used to change between different tasks.

Maybe include references or examples?

2.2.1 Concurrency for hobbyist

Try to polish your argument

Concurrency is not achieved effortlessly with Arduino, as an additional layer of programming complexity is necessary. This is, of course, a problem for the hobbyist who is not the most experienced programmer, since it makes the problem of getting the Arduino to do what they want even harder. It also increases the time the hobbyist spends implementing a solution that seems relatively intuitive. To help the hobbyist achieve correct and functional concurrency easily and simply, this is what the project will try to do..

Early conclusion and problem statement. Perhaps too early? If not, it is a bit superficial

2.3 What is the problem

The problem we will try to solve in this project is an extension for hobbyists working on Arduino, concurrency and real-time systems . The problem is based on hobbyists having trouble implementing concurrency simply and effectively without getting into the nitty-gritty details, that a hobbyist does not want to deal with. It is also based on many tutorials, which have implementations containing bad practices.

Giovanni: ??

Real-time systems has never been mentioned

This has led us to the problem we want to try and solve, hobbyists have a hard time using concurrency easily on Arduino. We will try to solve this by creating a programming language for hobbyists to easily and correctly implement concurrency on their Arduino devices. Therefore our problem statement is:

How can you create a programming language that would allow a hobby-level user of Arduino to use concurrency easily and correctly concerning the best Arduino concurrency practices?

2.4 Language evaluation criteria

There is no common consensus on objectively evaluating a language. The measurement of compilation speed, execution speed, and file size speak to the efficiency of the *implementation* of the language, not the *design* of the language. Popularity could be measured, but would vary greatly with time, and contain several skews from bias, as well as popularity not necessarily meaning it is better, which would have to be considered as well.

As such, a set of prioritized language evaluation criteria has been determined based on the criteria presented in [10]. An objective evaluation of the language based on these criteria is not practically possible [10], however, the criteria may work well when making decisions during language design, implementation, and evaluation. The most relevant concerns in regard to the choice of relevant criteria are presented in this section.

The primary concern is with the users of the programming language; writers of Arduino programs, in this case, the Arduino hobbyist, as described earlier. The programming of an Arduino project may be secondary to hobbyists, who prioritize the hardware aspects of their project.

The secondary concern is the concurrency issue that follows from the primary concern - making an Arduino behave concurrently is not a trivial programming task. There are several variations on the theme of simulating concurrency, but each with different issues, and none solve the issue in a general way [11].

The tertiary and last concern follows from the secondary issue - determining how to use concurrency to solve the problem in an Arduino. Concurrency problems can be subtle and complex, so understanding that you are even dealing with a concurrency issue may not be immediately apparent, and thus a simple solution may be hard to spot.

2.4.1 Priority of criteria characteristics

Concepts of programming languages lists four criteria: readability, writability, reliability, and cost. These criteria are each affected by several characteristics, with varying influence and importance [10].

Description or subsections?

Readability

Writability

Reliability

Cost

Readability

Writability

Reliability

Cost

Maybe briefly mention the criteria in full. Not detailed or copied, but mentions.

With these considerations in mind, we have prioritized and selected the characteristics for each criterion as we expect them to matter in this context.

The primary concern deals primarily with a subset of considerations related to the cost criterion. Specifically, the cost associated with learning and understanding the programming language is important. This suggests that general simplicity, in the form of few but expressive language constructs as well as clear, consistent combination and application of the constructs is important.

Expressivity and syntax design are also important characteristics, as seen from the secondary and tertiary concerns. The language should express new constructs that are not available in the Arduino language in a concise manner. An aim of the syntax could be to describe concurrent programs simply.

The number of data types is probably a somewhat important characteristic. As long as the expressivity of the language is not greatly affected, the number of data types is reduced compared to the Arduino language is likely to have a positive effect on overall simplicity and writability. On the other hand, good support for abstraction, that is, user-defined types, may enable advanced users to have the freedom of many primitive types, without significantly impacting the overall simplicity of the language.

What does it mean to reduce data types. Perhaps explain it as generalizing data types with an example.

Abstraction should be explained properly as from the perspective of the type system.

It is important to consider the language paradigm as well, as this has a large effect on the type checking mechanisms commonly used, not to mention the syntax design. It is a determinant factor in the description of mutability versus immutability, state versus statelessness, aliasing, and pointer management.

By default, Arduino does not use exceptions and exception handling as per the C++ language. The common solution for Arduino code writers is to write code that handles the possible exceptions that may occur without the language construct. For the sake of footprint, this will also be the preferred solution for this project.

It is worth noting that the Arduino programming language has already addressed several of the above concerns when compared to C++ for the platform. Examples of this can be seen in the introduction of new constants and a reduction in some language capabilities, such as exceptions and try-catch blocks from C++. The Arduino IDE is another point to consider in favor of cost concerns for the Arduino platform.

2.5 Concurrency on an Arduino

In this section, some of the more relevant ways of achieving concurrency on an Arduino will be explored. Emphasis will be put on the immediate advantages and disadvantages related to each of the different ways of concurrency, and how well

Characteristics	Very important	Important	Somewhat important	Not important
Simplicity		X		
Orthogonality		X		
Data types			X	
Syntax design		X		
Support for abstraction			X	
Expressivity		X		
Type checking		X		
Exception handling				X
Restricted aliasing	X			

Table 2.1: Summary of priorities. Characteristics not mentioned are of low or no priority.

they might fit as a solution to the problem. The first discussion will be about the prospect of using programming libraries to achieve concurrency on an Arduino. The second discussion is going to be about an alternative solution, namely implementing an operating system (OS) to handle the concurrency.

2.5.1 Achieving Concurrency with Programming Libraries

Introduce the different programming languages

Protothreads, Eventually, ARTe (and maybe TaskManagerIO)

Protothreads

Protothreads is a library for the C language, which has been packaged to a library for Arduino. The point of this library is to give programmers a simpler way to write programs for an event-driven system in memory-constrained environments such as an Arduino UNO.

> Protothreads provides a blocking context on top of an event-driven system, without the overhead of per-thread stacks. The purpose of protothreads is to implement sequential flow of control without complex state machines or full multi-threading. [12]

Protothreads are lightweight, stackless threads that provide a mechanism for concurrent programming, which is designed for memory-constrained systems, such as a smaller embedded system or wireless sensor nodes. Protothreads can be used with or without any underlying operating system to provide blocking for event handlers' [13]. It uses a cooperative concurrency form, which means it is up to the user to synchronize the program to run concurrently. This means that the program is event-driven and before the program can continue to another task, it needs to "complete" the current task before moving on to the next one. When working with Protothreading, it is nice to know what the overhead is on two bytes. This means that there is no hidden memory cost during the execution of the program.

When using local variables inside a Protothread, the local variables are not preserved and therefore can not be allocated onto the memory, therefore the programmer would have to use global variables instead, if they want to store something inside a variable.

Lastly, it is important that the code inside a Protothread needs to be "fast", meaning that the programmer can not use any blocking function such as the delay() function because this would block the other functions to run. [13]

In relation to what protothreads are, there has been taken an example of a simple and small program to show what Protothreading can be used to which can be seen at Figure [14].

Insert figure reference

```
#include "protothreads.h"

const int buttonPin = 12;     // the number of the pushbutton pin
const int ledPin =  8;      // the number of the LED pin
int buttonState = 0;         // variable for reading the pushbutton status
pt ptBlink;
int blinkThread(struct pt* pt) {
  PT_BEGIN(pt);
  for(;;) {
    digitalWrite(ledPin, HIGH);   // turn the LED on (HIGH is the voltage level)
    PT_SLEEP(pt, 500);
    digitalWrite(ledPin, LOW);    // turn the LED off by making the voltage LOW
    PT_SLEEP(pt, 500);
  }
  PT_END(pt);
}

pt ptButton;
int buttonThread(struct pt* pt) {
  PT_BEGIN(pt);
  for(;;) {
    int sensorValue = digitalRead(buttonPin);
    Serial.println(sensorValue);
    PT_SLEEP(pt, 1);
    PT_YIELD(pt);
  }
  PT_END(pt);
}

void setup() {
  PT_INIT(&ptBlink);
  PT_INIT(&ptButton);
  Serial.begin(9600);
  pinMode(ledPin, OUTPUT);
  pinMode(buttonPin, INPUT);
}

void loop() {
  PT_SCHEDULE(blinkThread(&ptBlink));
  PT_SCHEDULE(buttonThread(&ptButton));
}
```

Listing 2.1: A small program on how a Protothreads can be implemented

Explain what the advantages and disadvantages of protothreads is relative to the our problem

Eventually C++ Library

Eventually is an Arduino Event-based Programming Library. Where the goal is to make a more event-oriented environment for the Arduino programming language.

To give a better understanding of how the Eventually C++ library is working, in this section there has been taken an example from a GitHub page [15] where there can be seen, a code example on how to use the Eventually library. Since it is a C++ library it would work on any Arduino board, which includes the one the group has acquired.

ARTe

Arduino Real-Time extension (ARTe) is being developed by Real-Time System Laboratory. We tried to create an example similar to the former examples, however, it was simply not possible. While the scope of this project only focuses on the most popular Arduino UNO, and they still remain to support other devices than the Arduino DUO boards, no more time will be allocated to this option. However, once they release official support for the Arduino UNO, it is a viable option to look into. As for now, it is simply not ready for us to work with.

2.5.2 Achieving Concurrency with an Operating System

Introduce the different operative systems

(Erika OS), FreeRTOS, Simba OS, TaskManagerIO

Is writing about the OS Erika relevant?

FreeRTOS

Free Real-Time Operating System (abbreviated to FreeRTOS) is an operating system specifically designed for microcontrollers and microcomputers, such as the Arduino. It has been developed in partnership with the leading chip companies in the world, over more than 18 years, and with a special emphasis on reliability, accessibility and ease of use [16]. This leads itself well to our project, while we are targeting hobbyists. FreeRTOS utilises preemptive scheduling [17], which means that it implements a scheduler to be responsible for deciding which tasks to do in which order.

2.5.3 Summary

2.6 Problem statement

unfinished section. We want only one problem statement, and preferably some references to previous choices

The problem statement goes here. Temporary problem statement (Probably a full language, rather than an extension):

```
#include <Eventually.h>
#define LIGHT_PIN 8
#define BUTTON_PIN 12

bool pinState = true;
EvtManager mgr;
bool blinker() {
  mgr.resetContext();
  mgr.addListener(new EvtTimeListener(1000, true, (EvtAction)blink_pin));
  mgr.addListener(new EvtPinListener(BUTTON_PIN, (EvtAction)digital_read));
}

void blink_pin() {
  if (pinState == true) {
     digitalWrite(LIGHT_PIN, HIGH);
  }
  else {
    digitalWrite(LIGHT_PIN, LOW);
  }
  pinState = !pinState;
}

void digital_read() {
    int sensorVal = digitalRead(BUTTON_PIN);
    Serial.println(sensorVal);
    delay(1);
}

void setup() {
  Serial.begin(9600);
  pinMode(LIGHT_PIN, OUTPUT);
  pinMode(BUTTON_PIN, INPUT);
  blinker();
}

USE_EVENTUALLY_LOOP(mgr)
```

Listing 2.2: A small program on how Eventually can be implemented

```
#include <Arduino_FreeRTOS.h>

void TaskBlink( void *pvParameters );
void TaskAnalogRead( void *pvParameters );

void setup() {
  Serial.begin(9600);
  while (!Serial) {;}
  xTaskCreate(TaskBlink, "Blink", 128, NULL, 2, NULL);
  xTaskCreate(TaskAnalogRead, "AnalogRead", 128, NULL, 1, NULL);
}

void loop(){}

void TaskBlink(void *pvParameters){ // This is a task.
  (void) pvParameters;
  pinMode(LED_BUILTIN, OUTPUT);
  for (;;) { // A Task shall never return or exit.
    digitalWrite(LED_BUILTIN, HIGH);
    vTaskDelay( 1000 / portTICK_PERIOD_MS );
    digitalWrite(LED_BUILTIN, LOW);
    vTaskDelay( 1000 / portTICK_PERIOD_MS );
  }
}

void TaskAnalogRead(void *pvParameters){ // This is a task.
  (void) pvParameters;
  for (;;) {
    int sensorValue = digitalRead(12);
    Serial.println(sensorValue);
    vTaskDelay(1);
  }
}
```

Listing 2.3: A small example of a possible implementation of Free RTOS.

To create an extension on the Arduino programming language to support concurrency in real-time systems. The language should aid hobbyists in writing idiomatic Arduino programs.

2.6.1 Second attempt

To create a programming language for Arduino, which leverages some concurrency mechanism, to make it simpler or easier for hobbyists to write idiomatic Arduino programs with concurrency.

To create a programming language for Arduino, which leverages some concurrency mechanism, to make it simpler or easier for hobbyists to write idiomatic Arduino programs with concurrency.

Chapter 3

Language design

3.1 Parser generator

Instead of writing code by hand, several tools automatically generate code for scanning and parsing based on a grammar. Therefore, a discussion of *JavaCC*, *ANTLR4*, and *CUP* precedes the formal language description. The tools mentioned are only a few of those available and have been chosen because the group has experience with them through coursework. The main reason a parser generator has been chosen is because of the gains in productivity that it makes possible. It also makes it possible to create a functioning compiler yet still have language design as a larger focus.

the way you put it sounds like: "we don't feel like writing code, then we use a parser generator". Maybe there are some deeper reasons why it's best to employ a parser generator in contrast to implementing your own ad hoc parser

Perhaps mention that the biggest advantage of auto-generating a scanner and parser is productivity?

Each tool is evaluated using a reduced fragment of the Bims grammar from table 3.1 [18]. For each tool, the grammar was adapted, and the tool was run with the rewritten grammar as input. The process of rewriting, inputting, and running the tool was compared, and a tool was selected.

$$\begin{aligned} n &\in \textbf{Num} - \text{Numerals} \\ x &\in \textbf{Var} - \text{Variables} \\ a &\in \textbf{Aexp} - \text{Arithmetic expressions} \\ b &\in \textbf{Bexp} - \text{Boolean expressions} \\ S &\in \textbf{Stm} - \text{Statements} \end{aligned}$$

$$\begin{aligned} S &\rightarrow x := a \mid \text{skip} \mid S_1; S_2 \\ b &\rightarrow a_1 = a_2 \mid a_1 < a_2 \mid \neg b_1 \mid b_1 \wedge b_2 \mid (b_1) \\ a &\rightarrow n \mid a_1 + a_2 \mid a_1 * a_2 \mid a_1 - a_2 \mid (a_1) \end{aligned}$$

Table 3.1: Sample Bims syntax [18]

3.1.1 JavaCC

JavaCC stands for Java Compiler Compiler and is an open-source parser generator and lexical analyzer developed by Oracle, written in the Java language. It is one of the most popular parser generators for Java[19], and it is very well documented.

JavaCC takes as input a Context-Free Grammar (CFG) in Extended Backus-Naur Form (EBNF) to generate a scanner and a parser based on the input. The parser generated is a Left-to-right, Leftmost derivation with 1 token lookahead (LL(1)) parser by default. However, the parser can be extended to *k* lookahead for parts of the grammar if necessary [19].

Setting up JavaCC was easy as it is well documented, and requires Java to be installed. Having set this up, we were able to begin writing our grammar. After setting up, it became clear that writing grammars in JavaCC were simple but less intuitive. In JavaCC, the grammar has to be written as code, whereas the syntax of other tools resembles the way it is seen in books, as shown in Table 3.1. An example of this can be seen in listing 3.1

```
PARSER_BEGIN(Example)

public class Example {
  public static void main(String args[]) throws ParseException {
    Example parser = new Example(System.in);
    parser.Input();
  }
}

PARSER_END(Example)

void Input() : {}
{
  MatchedBraces() ("\n"|"\r")* <EOF>
}

void MatchedBraces() : {}
{
  "{" [ MatchedBraces() ] "}"
}
```

Listing 3.1: An example of the JavaCC syntax

Rewriting Bims

Because the generated parser is LL(1), the input grammar must be non-left-recursive. Bims, however, is left-recursive and has to be rewritten. This can be seen in Table 3.2.

Grammar in table is incomplete

this part has left recursion (see comment for details).

$$
\begin{aligned}
S &\rightarrow x := aS' \mid \text{skip } S' \mid \text{while } S' \\
S' &\rightarrow ;SS' \mid \epsilon \\
b &\rightarrow a_1 = a_2 \mid a_1 < a_2 \mid \neg b_1 \mid b_1 \wedge b_2 \mid (b_1) \\
a &\rightarrow n \mid a_1 + a_2 \mid a_1 * a_2 \mid a_1 - a_2 \mid (a_1)
\end{aligned}
$$

Table 3.2: Rewrite of Bims without left recursion

3.1.2 ANTLR4

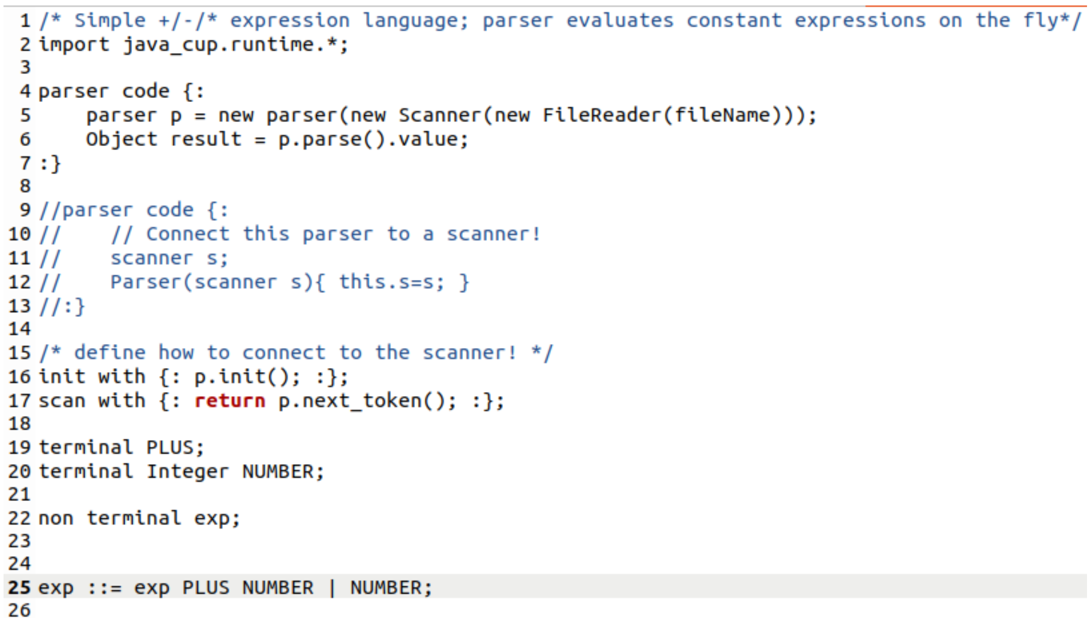
ANTLR (short for ANother Tool for Language Recognition) is a powerful parser generator that can be used to process, execute, or even translate structured text or binary files. It is widely used around the world by both Twitter and Oracle for parsing queries. [20]

One of the major advantages of ANTLR is their high level of support in almost any popular IDE, making it easy to work with regardless of the preferred development environment of the programmer. The ability to generate the lexer, parser and concrete syntax tree from a single grammar file is also very appealing. The grammar is very similar to that of EBNF and utilises a custom parsing technology called Adaptive LL(*) or ALL(*). This differs from the LL(*) used in ANTLR3, by analysing the grammar dynamically at runtime rather than statically, before the parser executes [21].

ANTLR is very easy to work with. One simply installs the plugin in their IDE of choice and read through the simple-to-understand documentation found on the official GitHub page of ANTLR [22]. Understanding the grammar rules and how to set it up in its respective grammar4 (.g4 file extension) is very manageable thanks to this. After the grammar file has been written it is possible to run the ANTLR tool on it, which then automatically generate a number of files for us, such as a parser, a lexer and a set of tokens. Then the generated code can be compiled against the ANTLR runtime. This also provides the developer with both a visual representation of the created parse tree or a tree in a LISP-like text form, along with a list of tokens found - all of these options are accessible through optional flags during compilation. The fourth major version of ANTLR introduces a lot of new capabilities compared to that of ANTLR3, which helps to reduce the learning curve by making the development of grammars and language applications easier - in part thanks to the powerful extensions and tools included in their plugins.

3.1.3 CUP

"CUP stands for Construction of Useful Parsers and is a Look-Ahead Left-to-right, Rightmost derivation (LALR) parser generator for Java" [23]. CUP implements a standard LALR(1) parser generation. Documentation for CUP recommends using the scanner generator JFlex, as a Lexical Analyzer Generator. Figure 3.1 is an example of how CUP was used.



```
/* Simple +/-/* expression language; parser evaluates constant expressions on the fly*/
import java_cup.runtime.*;

parser code {:
    parser p = new parser(new Scanner(new FileReader(fileName)));
    Object result = p.parse().value;
:}

//parser code {:
//    // Connect this parser to a scanner!
//    scanner s;
//    Parser(scanner s){ this.s=s; }
//:}

/* define how to connect to the scanner! */
init with {: p.init(); :};
scan with {: return p.next_token(); :};

terminal PLUS;
terminal Integer NUMBER;

non terminal exp;


exp ::= exp PLUS NUMBER | NUMBER;

```

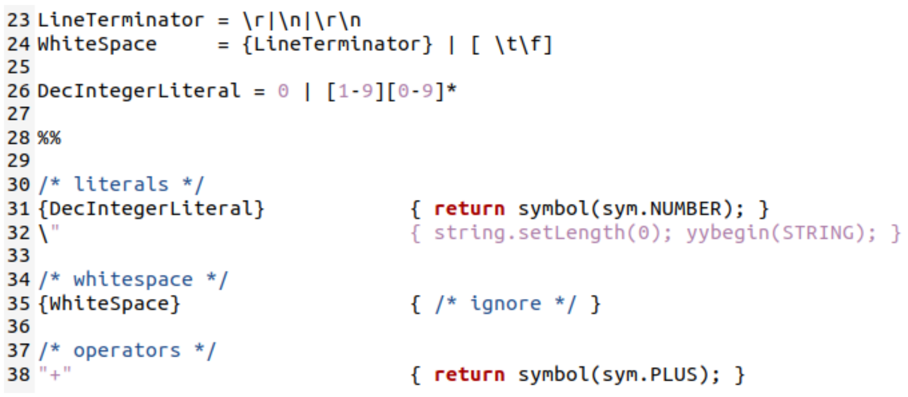
Figure 3.1: An example of CUP

In this we created a simple grammar that could add two integers together; this was done to try using CUP and to understand how everything worked.

JFlex

JFlex is an abbreviation for Java Flex. Flex is an abbreviation for Fast Lexical Analyzer Generator. As the name suggests, it is a tool for generating fast lexers. It makes adjustments to the size and speed of the generated lexer possible.

In figure 3.2 there is an example of how JFlex looked, in conjunction with our previously mentioned CUP file.



```
LineTerminator = \r|\n|\r\n
WhiteSpace     = {LineTerminator} | [ \t\f]

DecIntegerLiteral = 0 | [1-9][0-9]*

%%

/* literals */
{DecIntegerLiteral}            { return symbol(sym.NUMBER); }
\"                             { string.setLength(0); yybegin(STRING); }

/* whitespace */
{WhiteSpace}                   { /* ignore */ }

/* operators */
"+"                            { return symbol(sym.PLUS); }
```

Figure 3.2: An example of JFlex

3.1.4 Experiences with CUP

The general experience with CUP was good, except for connecting the parser and the lexical analyzer. At first, CUP was easy and workable, and setting up a simple grammar and creating the parser and symbol tree for it went well. But when there were specific issues it was difficult to find solutions, as CUP is not a very popular parser generator, which meant there was a minimal amount of information to be found.

3.1.5 Result

Incomplete argumentation. Comments welcome but not necessary

CUP will not be used in the project, as it proved difficult, combined with a lack of documentation, to connect the parser generator with the lexical analyzer generator, whereas other tools, such as JavaCC and ANTLR, automatically creates the lexical analyzer.

Based on our experiences with the different compiler compilers we have chosen to work with ANTLR. We chose ANTLR primarily because of how powerful it is and the great extensions it provides. These factors in particular could help us to efficiently develop our language and compiler. It does commit us to a LL parser which is not as expressive as an LR parser but we do not believe this will be a problem for our language since it will be relatively compact.

3.2 Language grammar

Which arithmetic and other operations should be available in the language?

3.3 Minted ANTLR test

```
grammar Expr;
prog:       (expr NEWLINE)* ;
expr:       expr ('*'|'/') expr
    |       expr ('+'|'-') expr
    |       INT
    |       '(' expr ')'
    ;
NEWLINE : [\r\n]+ ;
INT     : [0-9]+ ;
```

$$
\begin{aligned}
Start &\rightarrow \text{Setup Pipeline}\\
PLS &\rightarrow \text{PL PLS} \mid \epsilon\\
PL &\rightarrow Def\\
stmts &\rightarrow \text{stmt ;(newline) stmts} \mid \epsilon\\
stmt &\rightarrow \text{expr} \mid \text{ass} \mid \text{dcl}\\
dcl &\rightarrow \text{type funcID (Params)\{stmts\}}\\
ass &\rightarrow \text{type varID = expr}\\
params &\rightarrow \text{param, params} \mid \text{param}\\
param &\rightarrow \text{type varID}\\
expr &\rightarrow \text{for params in varID}
\end{aligned}
$$

Everything breaks when I add this in math mode below. So I am going to use comments.

$$\begin{aligned}
Start &\rightarrow \text{Setup}\\
Setup &\rightarrow \text{Setup \{ SetupDeclaration \}}\\
SetupDeclaration &\rightarrow \text{Declaration; SetupDeclaration}\\
&\mid \text{FunctionCall; SetupDeclaration}\\
&\mid \epsilon\\
Statements &\rightarrow \text{ExpressionStatement; Statements}\\
&\mid \text{ReturnStatement; Statements}\\
&\mid \text{IfStatement; Statements}\\
&\mid \text{ForLoop; Statements}\\
&\mid \text{WhileLoop; Statements}\\
&\mid \text{SwitchStatements; Statements}\\
&\mid \epsilon\\
ExpressionStatement &\rightarrow \text{Expression}\\
ReturnStatement &\rightarrow \text{'return' '('Expression')'}\\
IfStatement &\rightarrow \text{'if''(' LogicalExpression ')' '\{' Statements '\}' ElseStatement}\\
ElseStatement &\rightarrow \text{'else''(' LogicalExpression ')' '\{' Statements '\}'}\\
ForLoop &\rightarrow \text{'for' '(' VariableDeclaration 'in' Identifier ')' '\{' Statements '\}'}\\
WhileLoop &\rightarrow \text{'while' '(' LogicalExpression ')' '\{' Statements '\}'}\\
SwitchStatements &\rightarrow \text{'when' '(' Identifier ')' '\{' SwitchCase+ ElseStatement'\}'}\\
SwitchCase &\rightarrow \text{Expression '=>' '\{' Statements '\}'}\\
ExpressionList &\rightarrow \text{Expression (,Expression)*}\\
Expression &\rightarrow \text{ArithmeticExpression}\\
&\mid \text{RelationalExpresssion}\\
&\mid \text{LogicalExpression}\\
&\mid \text{ConditionalExpression}\\
ArithmeticExpression &\rightarrow \text{AtomArithmeticExpression}(* \mid /)\text{ArithmeticExpression}\\
&\mid \text{AtomArithmeticExpression}(+ \mid -)\text{ArithmeticExpression}\\
AtomArithmeticExpression &\rightarrow \text{NUMBER}\\
&\mid \text{'(' ArithmeticExpression ')'}\\
&\mid \text{IDENTIFIER}\\
RelationExpression &\rightarrow \text{AritmeticExpression}(<|>|==)\text{ArithmeticExpression}\\
LogicalExpression &\rightarrow \text{RelationalExpression}(or \mid and)\text{RelationalExpression}\\
&\mid not \text{ RelationalExpression}\\
Declaration &\rightarrow \text{FunctionDeclaration}\\
&\mid \text{VariableDeclaration}\\
FunctionDeclaration &\rightarrow \text{TypeOf IDENTIFIER '(' VariableDelcarationList ')' '\{' Statements '\}'}\\
TypeOf &\rightarrow \text{TYPE (TYPEOPERATOR)*}\\
VariableDeclarationList &\rightarrow \text{VariableDeclaration (,VariableDeclaration)*}\\
VariableDeclaration &\rightarrow \text{TypeOf IDENTIFIER '=' Expression}\\
FunctionCall &\rightarrow \text{IDENTIFIER '(' ExpressionList ')'}
\end{aligned}$$

NUMBER → ('-')?('0'..'9')+('.('0'..'9')+)?;
DIGIT → [0...9]*
ALPHA → 'a'...'z' | 'A'...'Z' | '_'
IDENTIFIER → ALPHA(DIGIT | ALPHA)*
TYPEOPERATOR → (' [ ] ');
TYPE → (num | text | bool);
WS → [\t \n \r]+ -> skip;
COMMENTS → '//' .*?'\n'-> skip;
LINECOMMENT → '/*' .*? '*/' -> skip;
KEYWORDS → return, while, it, for, in, when,
void?, Arduino{}, setup, true, false, else, define
OPERATORS → '+' | '-' | '*' | '/'
LOGICALOPERATION → 'and' | 'or' | 'not' | (xor)
RELATIONOPERATORS → '>' | '<' | '==' | '!=' | '<=' | '>='
BOOL → 'true' | 'false'

3.4 Parser generator v.2 arc

Parser grammar

start → setup tasks declarations
declarations → (declaration)* declarations
| ϵ
tasks → (task)* tasks
task → ′task′ IDENTIFIER ′(′ parameterlist ′)′ ′every ′ ′(′ expression ′)′ ′{′ statements ′}′
| ϵ
setup → ′setup′ ′{′ setupDeclaration ′}′
setupDeclarations → setupDeclaration (′;′ setupDeclarations)*)?
setupDeclaration → declaration | functionCall
| functionCall ′;′ setupDeclaration
| ϵ
statements → ′return′ expression statements
| ′if′ ′(′ expression ′)′ ′{′ statements ′}′
(′else′ ′{′statements′}′)? statements
| ′for′ ′(′ parameterDeclaration ′in′ IDENTIFIER ′)′
′{′ statements ′}′ statements
| ′while′ ′(′ expression ′)′ ′{′ statements ′}′ statements
| ′when′ ′(′ IDENTIFIER ′)′ ′{′ (expression ′=>′
′{′ statements ′}′)+ else ′}′ statements
| TYPE_TYPEOPERATOR IDENTIFIER ′=′
(′[′ (expression (′,′ expression)*)? ′]′ expression) ′;′ statements
| IDENTIFIER (′[′ NUMBER ′]′)? ′=′
(′[′ (expression (′,′ expression)*)? ′]′ | expression) ′;′
| ϵ
expression → (NUMBER | IDENTIFIER | BOOL)
| (functionCall | IDENTIFIER ′[′ NUMBER ′]′)
| ′(′ expression ′)′
| ′not′ expression
| expression (MULTI | DIVI) expression
| expression (PLUS | MINUS) expression
| expression RELATIONEQOPERATORS expression
| expression RELATIONOPERATORS expression
| expression ′and′ expression
| expression ′or′ expression;
functionCall → IDENTIFIER (′(′ expression (′,′ expression)* ′)′)?
declaration → TYPE_TYPEOPERATOR IDENTIFIER ′(′ (parameterDeclaration
(′,′ parameterDeclaration)*)? ′)′ ′{′ statements ′}′
| TYPE_TYPEOPERATOR IDENTIFIER ′=′
(′[′ (expression (′,′ expression)*)? ′]′ | expression) ′;′
| ′#′ ′pin′ IDENTIFIER ′(′NUMBER, (′OUTPUT′ | ′INPUT′)′)′

Lexical grammar

WS → [\t\n\r]+ -> skip
NUMBER → '-'? DIGIT+ ('.'DIGIT+)?
fragmentDIGIT → [0-9]
BOOL → 'true' | 'false'
TYPE_TYPEOPERATOR → TYPE (TYPEOPERATOR)*
fragmentTYPEOPERATOR → '[' ']'
fragmentTYPE → 'num'
| 'text'
| 'bool'
| 'char'
| 'time'
| 'pin'
COMMENTS → '//' .*? '\n' -> skip
LINECOMMENTS → '/*' .*? '*/' -> skip
RETURN → 'return'
WHILE → 'while'
IT → 'it'
FOR → 'for'
IN → 'in'
WHEN → 'when'
VOID → 'void'
ARDUINO → 'arduino'
SETUP → 'setup'
ELSE → 'else'
DEFINE → 'define'
EVERY → 'every'
TASK → 'task'
MULTI → '*'
DIVI → '/'
PLUS → '+'
MINUS → '-'
RELATIONEQOPERATIONS → '=='
| '!='
RELATIONOPERATORS → '<'
| '>'
| '<='
| '>='
AND → 'and'
OR → 'or'
NOT → 'not'
XOR → 'xor'
IDENTIFIER → ALPHA(DIGIT | ALPHA)*

3.5 Inspiration to our language

When designing a programming language it is a good idea to look at other programming languages for inspiration. We started out, by discussing the languages that we all had worked with in previouse semesters, which were C, JavaScript and C#. It was also important to check C++, as it was the language, our language was going to compile to. During the group discussion, we all tried to find things that other programming languages did well, what we each liked in a language and why we liked it. This was done to get an idea for what our programming language should include. When discussing the syntax of the languages we looked at, we agreed that many of these languages might not be very intuitive for a hobbyist. We therefore needed to do more research on how other languages did this. We started looking at more modern languages, to gather ideas from them, and see what we could do to make our language simpler for hobbyists, to learn and write. The languages Dart, Kotlin, Rust, Python and Zyg were all looked at, for inspiration. One thing we all looked for in the languages, was if they had a readable syntax and what made it readable.

By doing this, many ideas were taken from many different programming languages, some where modified to fit our needs or wants better, others were taken straight from one language and put into ours. Therefore you will see inspiration from many programming languages, when describing ours.

3.5.1 Types

The language is held simple, and therefore does not contain many different types, the main types in the language are num, text and bool. Num is for all numbers in the language, and using a name that is just short for number should make it recognizable for most people. The value of a type num, is a correct input as long it is a real number. This can be both integers and floats, it was decided to combine the two, to try and simplify the language for beginners and hobbyists. Bool is like the bool in other languages, as it can only be true or false. We saw no reason to change this, and therefore decided to keep it as many other languages. The type text is an array of characters made by using quotation marks, from the start to the end of the input. This is simillar to languages such as Python, C#, JavaScript and so on. The main difference is that we have decided to call our strings, text. This is much like with num, where we have made it more recognizable for beginners and hobbyists, who might not know what a string is, but should know what text is.

3.5.2 Control Structures

As mentioned, there has been taken inspiration from languages such as C, C#, Python, JavaScript and others. There are three main types of control structure, sequence, conditional and iteration. These are structures like if statements, for loop, while loops and so on. Since many languages use these common control structures in a similar way, we have decided to do the same. These will be described in the following sections:

If statement The conditional structure 'if' statement, has the terminal if, with a non-terminal expression, in parentheses, followed by non-terminal statements contained in brackets.After the if statement, there is the option to use an else statement, which follows the same structure, but without the expression. After this more statements can be made.

The non-terminal expression, can become many different variants, and how these expressions are evaluated, will be handled in type checking. If the value is true, the conditional structure will execute the statements contained in the brackets, if not, and an else condition is made after the brackets, a jump will occur to the else condition. The non-terminal statements in the brackets of the if and else conditional structures can, as an expression, become many different variants. The statements, are where function calls and additional control structures are made. Followed by additional statements, so that more statements can be made. This structure is the simmilar to languages that have been used as inpiration, languages such as C, JavaScript and others, create the conditional structure in the same way.

For loop

The iteration structire 'for' loop, has the terminal for, with a non-terminal paramaterDeclaration, a terminal 'in' and a non-terminal IDENTIFIER, in paratheses. After this, there are non-terminal statements in brackets, followed by additional statements. The paramaterDeclaration is for declaring a variable, that has to match the type of the IDENTIFIER, that is to be iterated through.

The iteration structure has especially taken inspiration from how Pythons for loop works. Where in Python the IDENTIFIER could be an array, and the paramaterDeclaration is something that is declared, and made a placeholder for the current object in the array. In Python the paramaterDeclaration does not have a given type, however in our language the type will be declared and must match with the type of the IDENTIFIER. The reason for using a Python-like syntax, is because it is simple and rather intuitive, compared to something such as C, where an iterator is declared and used to go through an array. In our case, aswell as in Python, the work is being done in the background, so the user does not have to warry about it.

While loop

What do we call a while loop? Iteration structure?

The control structure, 'while' loop, has the terminal while, with an expression in paratheses, followed by statements in bracket and additional statements after. The while loop is used to continually execute a block of code, until some condition is met. In this case, the condition is the expression, and as long as the expression evaluates to true, the block of code will be executed.

Inspiration for the syntax of the while loop, has been taken from many different languages, since many of the languages the group has used, use a simmilar syntax. Inspiration from languages such as JavaScript, C and C# can be seen, as the syntax matches, with a keyword 'while' with a condition in paratheses, followed by a block of code in brackets. Python is also very simmilar, the main difference is that python does not use paratheses or brackets, instead it uses colons and indents to seperate code.

Acronyms

CPS	Cyber-Physical System. 1

Bibliography

[1] *Design, definition and implementation of programming languages.* Aalborg University, 2022. URL: `https://moduler.aau.dk/course/2022-2023/DSNDATB410`.

[2] Moodle, 2022. URL: `https://www.moodle.aau.dk/pluginfile.php/2425806/mod_page/content/24/projects-giovanni.pdf`.

[3] *What Is an Arduino? - Learn.Sparkfun.Com.* URL: `https://learn.sparkfun.com/tutorials/what-is-an-arduino/all#introduction` (visited on 03/04/2022).

[4] *What Is Arduino?* URL: `https://www.arduino.cc/en/Guide/Introduction` (visited on 03/04/2022).

[5] Arduino. *setup*. `https://www.arduino.cc/reference/en/language/structure/sketch/setup/`. 2022.

[6] Arduino. *loop*. `https://www.arduino.cc/reference/en/language/structure/sketch/loop/`. 2022.

[7] *Is Arduino Used in Real Life Products?* The Robotics Back-End. Dec. 9, 2018. URL: `https://roboticsbackend.com/is-arduino-used-in-real-life-products/` (visited on 03/07/2022).

[8] *Top 10 Arduino Uses of 2021*. All3DP. Jan. 13, 2021. URL: `https://all3dp.com/2/best-arduino-uses/` (visited on 03/07/2022).

[9] Randal. Bryant and David O'Hallaron. *Computer Systems*. Pearson, 2016.

[10] Robert W. Sebesta. *Concepts of programming languages*. Pearson, 2016.

[11] Francesco Restuccia, Marco Pagani, Agostino Mascitti, Michael Barrow, Mauro Marinoni, Alessandro Biondi, Giorgio Buttazzo, and Ryan Kastner. "ARTe: Providing real-time multitasking to Arduino". In: *Journal of Systems and Software* 186 (2022), p. 111185. ISSN: 0164-1212. DOI: `https://doi.org/10.1016/j.jss.2021.111185`. URL: `https://www.sciencedirect.com/science/article/pii/S016412122100265X`.

[12] Ben Artin. *Protothreads for Arduino*. `https://gitlab.com/airbornemint/arduino-protothreads`. visited 24/03/2022. 2020.

[13] Adam Dunkel. `http://dunkels.com/adam/pt/index.html`. Accessed: 23/03/2022. 2022.

[14] *Arduino Protothreads [Tutorial]*. `https://roboticsbackend.com/arduino-protothreads-tutorial/`. visited 23/03/2022. The Robotics Back-End, 2019.

[15] Jonathan Bartlett. *Eventually*. Feb. 23, 2022. URL: https://github.com/johnnyb/Eventually (visited on 03/07/2022).

[16] *About FreeRTOS Kernel*. https://www.freertos.org/RTOS.html. visited 04/04/2022. FreeRTOS.

[17] *Scheduling Basics*. https://www.freertos.org/implementation/a00005.html. visited 04/04/2022. FreeRTOS.

[18] Hüttel Hans. *Transitions and trees: An introduction to structural operational sematics*. Cambridge University Press, 2011.

[19] JavaCC Community. *JavaCC Github page*. https://javacc.github.io/javacc/. Accessed: 21-03-2022. 2021.

[20] Parr Terence. *About ANTLR*. 2014. URL: https://www.antlr.org/about.html.

[21] Parr Terence. *The Definitive ANTLR4 Reference*. 2nd ed. Pragmatic Bookshelf, 2014.

[22] Terence Parr. *ANTLR Documentation*. visited 21/03/2022. URL: https://github.com/antlr/antlr4/blob/master/doc/index.md.

[23] C. Scott Ananian, Frank Flannery, Dan Wang, Andrew W. Appel, and Michael Petter. *Cup 0.11b*. http://www2.cs.tum.edu/projects/cup/index.php. 2022.

Appendix A

Reading instructions

These are the reading instructions for the next supervisor meeting.

A.1 Review priority

1. Read and answer all green notes
2. Read 3
3. Ignore sources that are not input properly yet, except if they are marked by a green note.