Algorithms and Programming IV
Determinism

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Objectives of Today‘s Lecture

• Defining the Requirements on Programming
• Specifying the Meaning of Correctness
• Identifying the sequential Processing as Foundation of Determinism
• Exploring existing Models to support Programming
Concepts of Non-Sequential and Distributed Programming

DETERMINISM
Programming Paradigms

- **imperative**
  - assembler language, Cobol, BASIC, Fortran

- **structured**
  - JavaScript, Visual Basic, C, Scratch

- **procedural/modular**
  - JavaScript, Visual Basic, Visual J, C

- **object-oriented**
  - Java, C++, C#

- **declarative**
  - Prolog, Datalog, SQL

- **functional**
  - Lisp, XSLT, Opal, Haskell

Technology Review
Requirements for Programs

- A program should do what it is expected to do!
  - Functional requirements, such as
    - Scope of functions
    - Correctness

- A program should comply with certain requirements about its behavior.
  - Non-functional requirements, such as
    - Performance
    - Usability
    - Security
    - ...
Functional Characteristics

• **Scope of Service**
  - Requirements elicitation, design, project management, quality assurance
    - \(\Rightarrow\) LV (lecture course) Software Engineering

• **Correctness**
  - Hoare logic (calculus), Simulation via pen and paper (Handsimulation) and Testing
    - select input values
    - apply algorithm
    - execute program
    - compare results

\(\Rightarrow\) Problem: it works with existing program only
Foundations of Building Correct Programs

1. Amount of operations changing the current state of the system in a known way
   - We have an idea (model) of the change of state of the system by the operation in a specific context (previous state of the system).
   - The operations are identified explicitly by a command (of the current programming language).
   - So, we do have a model of the execution (change of state of the system) of the commands.

2. Selection and order (sequence) of the operations (represented by the commands) based on the algorithm to be implemented
   - By connecting the operations together we build a model of the execution of the program.
   - The sequence of the commands represents this model of program execution.
Ordered Execution of a Set of Commands

- Sequential processing of the commands using numerical ordering

- Example BASIC

```
10 REM This is a test program
20 PRINT "Hello World!"
30 INPUT "Please enter your name"; A$
40 PRINT "Hello, "; A$
```

How about other (imperative) programming languages?
Sequential Processing

• Example C

```c
// first C-program

int main (void) {
    int a = 0;
    int b = 0;
    
    a = 2;
    b = 3;
    
    a = a * b;
    
    return a;
}
```

• How is sequential processing ensured?
Programming

• With selection and the sequential order of the operations the state of the system and the state change can be anticipated in our minds.
  – That’s called Programming model!
  – Building a (correct) programming model is called Programming.
  – It’s the same approach as to check correctness of the program.
  – So, building a correct execution model of the program ensures the implementation of a correct program.
    – … but is only the first step – Testing, testing, testing is also needed.

• But…

  … how is it ensured that the sequence of commands will be executed as expected?
  … where does the knowledge about the change of system’s state by the commands comes from?
From Program to Process

source code → compiler → assembler code → assembler (and linker) → executable machine code → operating system → process
From Program to Machine Program

```c
int main (void)
{
    int a = 0;
    int b = 0;
    a = 2;
    b = 3;
    a = a * b;
    return a;
}
```

00000000 <main>:

```asm
0:   e52db004        push    {fp}; (str fp, [sp, #-4]!)
4:   e28db000        add     fp, sp, #0
8:   e24dd00c        sub     sp, sp, #12
c:   e3a03000        mov r3, #0
10:  e50b3008        str     r3, [fp, #-8]
14:  e3a03000        mov r3, #0
18:  e50b300c        str     r3, [fp, #-12]
1c:  e3a03002        mov r3, #2
20:  e50b3008        str     r3, [fp, #-8]
24:  e3a03003        mov r3, #3
28:  e50b300c        str     r3, [fp, #-12]
2c:  e51b3008        ldr     r3, [fp, #-8]
30:  e51b200c        ldr     r2, [fp, #-12]
34:  e0030392        mul r3, r2, r3
38:  e50b3008        str     r3, [fp, #-8]
3c:  e51b3008        ldr     r3, [fp, #-8]
40:  e1a00003        mov     r0, r3
44:  e24bd000        sub     sp, fp, #0
48:  e49db004        pop     {fp}; (ldr fp, [sp], #4)
4c:  e12fff1e        bx     lr
```

ALP IV: Concepts of Non-Sequential and Distributed Programming Summer Term 2024
From Program to Machine Program

// first program in C

int main (void)
{
    int a = 0;
    int b = 0;

    a = 2;
    b = 3;

    a = a * b;

    return a;
}
The automatic incrementation of the Instruction Pointer ensures the sequential execution of the instructions.
Execution of the Program

- All of the following components have work correctly to ensure that the commands will be executed as expected and in the determined sequence:
  - Compiler or Interpreter
    - Translates the commands to machine instructions
  - Linker
    - Builds a memory image with machine instructions and initial data
  - Operating system
    - Sets up the process out of the linked image
    - Sets up the execution environment
  - Hardware
    - Executes the machine instruction in an defined environment (by the OS)
    - Increments the Instruction Pointer automatically
Machine Model

- The representation of the technical workflow
  - von Neumann architecture
Relations between the Models

• If there is a way to transform all of the models from programming model to execution model based on the machine model, then the correct execution of the algorithm implemented by the programming model can be assured.

• The transformation allows us to make statements about the behavior of the system controlled by the execution of our program.

• Based on these statements we can (mentally) anticipate the program execution and write our program.
Determinism

• The (mental) anticipation of the program execution holds for all of the runs of our program.

• Definition: A **deterministic algorithm** is an algorithm which, given a specific input, will always produce the same specific output and will always fulfill changes to the state of the system in the same way (and order).

  – Using all of the models we can decide if an algorithm is deterministic.
  – If every step of transferring one model to another is performed correctly a deterministic algorithm is correctly implemented and the program will be executed correctly.
  – This program can be called a deterministic program.
Sequential Processing

• One foundation for deterministic execution of the programs is the sequential processing of operations, commands and instructions.

• Can it be assumed to have a sequential processing?
Sequential Processing and Programming Paradigms

- **imperative**
  - assembler language, Cobol, BASIC, Fortran

- **structured**
  - JavaScript, Visual Basic, C, Scratch

- **procedural/modular**
  - JavaScript, Visual Basic, Visual J, C

- **object-oriented**
  - Java, C++, C#

- **declarative**
  - Prolog, Datalog, SQL

- **functional**
  - Lisp, XSLT, Opal, Haskell

Technology Review
Sequential Processing in further Programming Models – Loops

```c
// Program in C with // while loop

int main (void)
{
    int a = 0;
    int b = 0;

    b = 3;

    while (b > 0)
    {
        a += 2;
        b--;
    }

    return a;
}
```

```
00000000 <main>:
0:   ...    mov  r3, #0
  c:  e3a03000  str  r3, [fp, #-8]
  10:  e50b3008  mov  r3, #0
  14:  e3a03000  str  r3, [fp, #-12]
  18:  e50b300c  mov  r3, #3
  1c:  e3a03003  str  r3, [fp, #-12]
  20:  e50b300c  b  40 <main+0x40>
  24:  ea000005  ldr  r3, [fp, #-8]
  28:  e51b3008  add  r3, r3, #2
  2c:  e2833002  str  r3, [fp, #-12]
  30:  e50b3008  ldr  r3, [fp, #-12]
  34:  e51b300c  sub  r3, r3, #1
  38:  e2433001  str  r3, [fp, #-12]
  3c:  e51b300c  ldr  r3, [fp, #-12]
  40:  e50b300c  cmp  r3, #0
  44:  e3530000  bgt  28 <main+0x28>
  48:  cafffff6  ldr  r3, [fp, #-8]
  4c:  e51b3008  mov  r0, r3
  50:  e1a00003
  54:  ...
```
Sequential Processing in further Programming Models – Loops

// Program in C with
// while loop

int main (void)
{
    int a = 0;
    int b = 0;

    b = 3;

    while (b > 0)
    {
        a += 2;
        b--;
    }

    return a;
}

Sequential processing of commands and instructions is provided even with loops and jumps or conditional execution.
Sequential Processing in further Programming Models – Functions

// Program in C with function

```c
int foo (int a, int b)
{
    return a * b;
}

int main (void)
{
    int a = 0;
    int b = 0;
    a = 2;
    b = 3;

    a = foo (a, b);

    return a;
}
```
Sequential Processing in further Programming Models – Functions

00000000 <foo>:
0: e52db004 push {fp}
4: e28d000 add fp, sp, #0
8: e24dd00c sub sp, sp, #12
c: e50b0008 str r0, [fp, #-8]
10: e50b100c str r1, [fp, #-12]
14: e51b3008 ldr r3, [fp, #-8]
18: e51b200c ldr r2, [fp, #-12]
1c: e0030392 mul r3, r2, r3
20: e1a00003 mov r0, r3
24: e24bd000 sub sp, fp, #0
28: e49db004 pop {fp}
2c: e12fff1e bx lr

00000030 <main>:
30: e92d4800 push {fp, lr}
34: e28d0004 add fp, sp, #4
38: e24dd008 sub sp, sp, #8
3c: e3a03000 mov r3, #0
40: e50b3008 str r3, [fp, #-8]
44: e3a03000 mov r3, #0
48: e50b300c str r3, [fp, #-12]
4c: e3a03002 mov r3, #2
50: e50b3008 str r0, [fp, #-8]
54: e50b3008 str r1, [fp, #-12]
58: e51b300c ldr r0, [fp, #0]
5c: e51b0008 ldr r1, [fp, #0]
60: e51b100c ldr r2, [fp, #0]
64: ebfffffe bl 0 <foo>
68: e50b0008 str r0, [fp, #-8]
6c: e51b3008 ldr r3, [fp, #-8]
70: e1a00003 mov r0, r3
74: e24bd004 sub sp, fp, #4
78: e8bd4800 pop {fp, lr}
7c: e12fff1e bx lr
Sequential Processing in further Programming Models – Functions

00000000 <foo>:
0:   e52db004  push   {fp}
4:   e28db000  add    fp, sp, #0
8:   e24dd00c  sub    fp, sp, #12
12:  e50b0008  str     r0, [fp, #8]
16:  e51b000c  str     r1, [fp, #12]
20:  e51b200c  ldr     r3, [fp, #12]
24:  e030392   mul     r3, r2, r2
28:  e1a00003  mov     r0, r3
32:  e24bd000  sub     sp, fp, #0
36:  e49db004  pop     {fp}
40:  e12fff1e  bx      lr

00000030 <main>:
30:  e92d4800  push    {fp, lr}
34:  e28db004  add    fp, sp, #4
38:  e24dd008  sub    sp, sp, #8
3c:  e3a03000  mov     r3, #0
40:  e50b3008  str     r3, [fp, #8]
44:  e3a03000  mov     r3, #0
48:  e50b300c  str     r3, [fp, #12]
50:  e50b300c  str     r3, [fp, #12]
54:  e50b300c  str     r3, [fp, #12]
56:  e1a00003  mov     r0, r3
58:  e50b000c  ldr     r0, [fp, #8]
60:  e51b100c  ldr     r1, [fp, #12]
62:  e50b0008  ldr     r0, [fp, #8]
64:  e51b3008  ldr     r3, [fp, #12]
66:  e1a00003  mov     r0, r3
68:  e50b0008  ldr     r0, [fp, #8]
70:  e51b0008  ldr     r3, [fp, #12]
72:  e51b3008  ldr     r3, [fp, #12]
74:  e24bd004  sub     sp, fp, #4
76:  e8bd4800  pop     {fp, lr}
78:  e12fff1e  bx      lr
Sequential Processing in further Programming Models – Functions

// Program in C with function

```c
int foo (int a, int b)
{
    return a * b;
}

int main (void)
{
    int a = 0;
    int b = 0;
    a = 2;
    b = 3;

    a = foo (a, b);

    return a;
}
```

Disassembly of section .text.startup:

```
00000000 <main>:
  0:   e3a00006        mov     r0, #6
  4:   e12fff1e        bx      lr

00000000 <foo>:
  0:   e0000091        mul     r0, r1, r0
  4:   e12fff1e        bx      lr
```
Sequential Processing in further Programming Models – Functions

// Program in C with function

```c
int foo (int a, int b) {
    return a * b;
}
```

```c
int main (void)
{
    int a = 0;
    int b = 0;
    a = 2;
    b = 3;
    a = foo (a, b);
    return a;
}
```

Sequential processing of commands and instructions is provided even with function calls.

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Sequential Processing in Object Oriented Programming Models – Classes/Objects

// simple program in Java
public class Rectangle {
    private int x, y;
    private int width, height;

    public Rectangle() {
        x = y = 0;
        width = 10;
        height = 10;
    }
    // methods ...
}

public class SimpleProgram {
    public static void main ( String[] args ) {
        Rectangle r = new Rectangle ();
    }
}

Methods in classes or objects correspond to functions.
Functional and Logical Languages

- In functional and logical (declarative) languages, the runtime environment takes care of the translation into (sequential) machine code.
Non-Deterministic Algorithms

• In real world applications external events often prevent the deterministic execution of a program.
  – user input
  – response of (external) devices
  – timers

• So, the strict definition of determinism is not applicable for most of the programs.

What does this mean for programming and correctness of our program?
Non-Deterministic Algorithms and Programs

• Programs can (and should) be split into reasonable pieces (modules).
• These modules should provide a deterministic behavior by their own,
  − using distinct interfaces,
  − by encapsulating internal data
  − (see Lecture on “Software Engineering”)
• Knowledge about every single step in the executing of a program is often not needed as long as the results are correct (and the same applies for every other run with the same input).
Determined Algorithms and Programs

- Definition: A **determined algorithm** is an algorithm which, given a specific input, produces always the same specific output.

  - Thus, all deterministic algorithms are determined algorithms, but not all determined algorithms are deterministic.
  - Of course, this definition holds for programs too.
  - (It’s not always usual to distinct determined algorithms from deterministic algorithms – but we do.)

  - With a more general assumption of input data the definition can be applied to many even broader ranges of applications.
Programs with Stochastic Variables

// Test for random variable
#include <stdlib.h>
#include <time.h>
#include <stdio.h>

int main (void)
{
    int random_nr = 0;
    srand ((unsigned) time (NULL));
    random_nr = rand ();
    if (random_nr < RAND_MAX / 2)
        printf ("The random number is in the lower half! \n");
    else
        printf ("The random number is in the upper half! \n");
    return 0;
}

Does this program provides deterministic execution?
// Test for random variable
#include <stdlib.h>
#include <time.h>
#include <stdio.h>

int main (void)
{
    int random_nr = 0;
    srand ((unsigned) time (NULL));
    random_nr = rand ();
    if (random_nr < RAND_MAX / 2)
        printf ("The random number is in the lower half! \n");
    else
        printf("The random number is in the upper half! \n");
    return 0;
}

With the same start parameters (input data), each program run provides the same results and the same final state with respect to the distribution(s) of the random variables!

With these preconditions we do have a determined program.
Programs using ML Algorithms

• Artificial Intelligence
  – Yes, but…
  – The amount of input data is the amount of all data ever processed as input data!

Concepts of Non-Sequential and Distributed Programming

SUMMARY AND TAKE AWAYS
Correctness and Determined Program Execution

• With correct transformation of all of the models from programming model to execution model based on machine model the correct and determined (sometimes even deterministic) execution of the program can be assured.
  − The program given a specific input, will always produce the same specific output.
  − The sequential execution of the commands and instructions are one foundation of the reliable change of the system’s state.
  − We can make reasonable assumptions about the program behavior at the process of programming.
  − Afterwards the program can be tested and checked with respect to the machine model.

• Models help us to abstract from real world and provide reasonable assumptions about the system and the state changes of the system.
Requirements for Programs

• A program should do what it is expected to do!
  − Functional requirements, such as
    − Scope of functions
    − Correctness

• A program should comply with certain requirements about its behavior.
  − Non-functional requirements, such as
    − Performance
    − Usability
    − Security
    − ...
Concepts of Non-Sequential and Distributed Programming

NEXT LECTURE
Algorithms and Programming IV
Concurrency

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