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Project Report

Introduction

The topic of our project is a Sudoku puzzle solver. The importance of the project is that it uses in-depth search which allows the program to go back to a previous block if there is an error until the correct answer is in the block. This helps out, since there could be a quite large amount of combinations for the solution and our program enumerate all these combination in a very neat way. The Sudoku puzzle solver uses the UART which is required to input the data for it to solve the puzzle.

Background

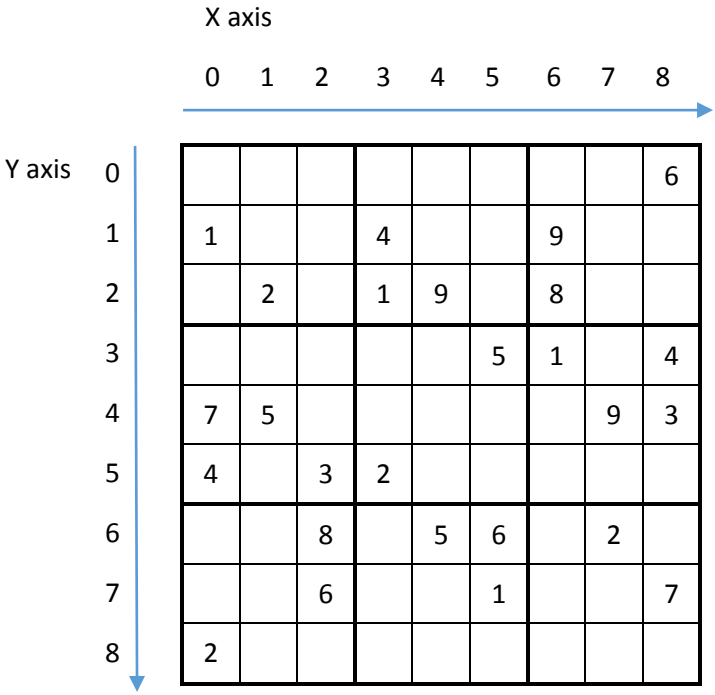
Sudoku is a logic-based, combinatorial number-placement puzzle. The objective of the puzzle is to fill a 9x9 grid with digits so that each column, row, and of the nine 3x3 sub-squared contains the digits from 1 to 9. The research required to be completed before attempting the project is learn how to solve a Sudoku puzzle. The rule to Sudoku is that only one number can be used in each row, column, and 3x3 sub-grid. The difficulty of the Sudoku varies depending on the amount of data given. The smaller the number given in the beginning, the harder it is to solve it. The materials used to complete the project was java, ARM assembly, and websudoku.com. Java was used to insured that the algorithm would work correctly without any errors before using ARM. Afterwards, the code was convert from Java to ARM assembly in order to make use of UART. Lastly, we use websudoku.com to test the answer given by our program.

Method

To solve an “evil” level Sudoku puzzle may be very hard for human, but it is relatively easy for computers. Since the number of ways to fill out a Sudoku puzzle is limited. For every box in the puzzle, there are nine possible numbers can be filled in. Further, the puzzle contains 81 such boxes. So, if each digit in grid is indepent, then the total number of ways to fill out a puzzle is 9^81. However, the digits in a Sudoku puzzle must satisfy column rule, row rule, and sub-grid rule. Since the available digit for a given box restricted by the state of the grid, the actual number of combination will be much smaller than in the case if the digits are independent. Therefore, we believe it is possible for a computing device to enumerate every possible combination to test the solution in a short time.

Our approach to solve a Sudoku puzzle is the brute force method, in which every possible way to filled out a puzzle is tested until a solution is found. For given “evil” level puzzle

as show below, we first index each of the box for indicating them. We choose horizontal axis X and vertical axis Y and index them from 0 to 8 as shown in the picture.



We chose to use depth-first search (DFS) to traverse all of the unknown boxes in order of top to bottom and left to right. In each unknown box we try every possible digit for that particular grid state and go to next unknown box to do the same. If all digits from 1 to 9 are tested for an unknown box and putting any of them in the box will violate the rule, we know that the current combination will not work. So we have to backtrack to the previous unknown box to try next possible number for the same state in which we gave a previous try. If we successfully fill a number in the last box, then we found the solution for this Sudoku puzzle. The reason we chose DFS is that it is intuitive for this problem and it can be easily implemented by recursive calls.

For example, we know that for a puzzle to be valid, each column (X axis), each row (Y axis), and each of the nine 3x3 sub-grids that compose the grid must contains all of the digits from 1 to 9. We choose the first unknown box in the order form top to bottom and from left to right. The first unknown box in the above picture is the box at position (0, 0), at the original state the first digit we can try is 3, since 1 and 2 is already in the same sub-grids. After we put 3 in the box(0, 0), the state of the grid changed and we go to next unknown box, which is box(1, 0). The first number we can try is 4, since 3 is just added in the same sub-grids by our first attempt. In the same way we fill out other unknown box in the order. Most probably we will encounter a dead end soon and we need to backtrack. When backtracking, we have to reset unknown to the tried out box where we go to backtrack. In this way, the previous state for the

previous unknown box we have tried is brought back, so we can try the next digit for the new current unknown box.

We use an array to represent a Sudoku puzzle, a digit 0 in a box denotes that the box is unknown. We wrote a testing java program to prove our method. Since the program in high-level programming language is easy to debug. So, we can catch other errors that not caused by the algorithm. After the method is proved working, we started to implement it in ARM assembly.

The following is the java code for algorithm check, it is already written without using the features that assembly does not provide, such as 2D array and division.

```
import java.io.File;
import java.util.Scanner;

public class Final {

    public static void main(String[] args) throws Exception {
        Scanner fileScanner = new Scanner(new File("Sudoku.txt"));
        int[] sudoku = new int[81];
        String line = fileScanner.nextLine();
        int x = 0;
        // getting Sudoku puzzle from the a file and
        // store the puzzle in sudoku array
        // 0 in a box means the box is unknown
        for (int i = 0; i < 81; i++) {
            sudoku[i] = Character.getNumericValue(line.charAt(x));
            x++;
            if (x == 9 && fileScanner.hasNextLine()) {
                line = fileScanner.nextLine();
                x = 0;
            }
        }
        // call solve funtion to find the solution
        // passing work positon 0, to start the searching
        // when solution is found, true is returned and
        // the answer is printed out, otherwise print "No solution"
        if (solve(sudoku, 0)) {
            printSudoku(sudoku);
        } else {
            System.out.println("No solution");
        }
        fileScanner.close();

    }
    // recursive call to find a solution for a puzzle stored in sudoku array
    // the current working index is i
    // return true is solution is found
    private static boolean solve(int[] sudoku, int i) {
        // base case for recursion
        // if the working position 81 is being call
        // we have been successfully fill all the box from index 0 to 80
        // then we found the solution
        if (i >= 81) {
            return true;
```

```
        } else {
            // get the next working postion
            int newI = i + 1;
            // at the current positon, the value for the box is already give
            // skip this position, recursive call to work on the next working
position
            if (sudoku[i] != 0) {
                return solve(sudoku, newI);
            } else {
                // the current positon is unknown
                // get the corresponding X and Y coordinate
                int cellY = getY(i);
                int cellX = getX(i, cellY);
                // loop to try all digits from 1 to 9
                for (int checkNum = 1; checkNum < 10; checkNum++) {
                    // if the digits does not violate the rule
                    if (checkSquare(sudoku, cellX, cellY, checkNum) &&
checkRow(sudoku, cellY, checkNum)
                            && checkCol(sudoku, cellX, checkNum)) {
                        // fill the tried number in the sudoku array
                        sudoku[i] = checkNum;
                        // recursive call to working on next position
                        if (solve(sudoku, newI)) {
                            return true;
                        }
                    }
                }
                // after the loop there is noway to find a digit without
violating the rule
                // undo the changes to the current positon by resetting 0 to
current position
                sudoku[i] = 0;
                // no solution can be found, goting the back to previous call
to try next digit
                return false;
            }
        }
    }
    // get X coordinate
    private static int getX(int i, int y) {
        return (i - y * 9);
    }
    // get Y coordinate
    private static int getY(int i) {
        if (i <= 8) {
            return 0;
        } else if (i <= 17) {
            return 1;
        } else if (i <= 26) {
            return 2;
        } else if (i <= 35) {
            return 3;
        } else if (i <= 44) {
            return 4;
        } else if (i <= 53) {
            return 5;
        } else if (i <= 62) {
```

```
            return 6;
        } else if (i <= 71) {
            return 7;
        } else {
            return 8;
        }
    }
    // is digit toCheck valid at (reqX, reqY) in its sub-grid
    private static boolean checkSquare(int[] sudoku, int reqX, int reqY, int
toCheck) {
        // colX and rowY are the coordinate of the top-left corner in the
sub-grid
        int rowY;
        int colX;
        if (reqX < 3) {
            colX = 0;
        } else if (reqX < 6) {
            colX = 3;
        } else {
            colX = 6;
        }
        if (reqY < 3) {
            rowY = 0;
        } else if (reqY < 6) {
            rowY = 3;
        } else {
            rowY = 6;
        }
        // the 1D index of the top-left corner in the sub-grid
        int i = colX + rowY * 9;
        int k = 0;
        // the loop traverse all elements in the sub-grid
        for (int j = 0; j < 9; j++) {
            k++;
            if (sudoku[i] == toCheck) {
                return false;
            }
            if (k == 3) {
                k = 0;
                i = i + 7;
            } else {
                i = i + 1;
            }
        }
        return true;
    }
    // is digit toCheck valid in rowY
    private static boolean checkRow(int[] sudoku, int rowY, int toCheck) {
        // the index of the left most element in rowY
        int i = rowY * 9;
        // the loop traverse all elements in rowY
        for (int x = 0; x < 9; x++) {
            if (toCheck == sudoku[i]) {
                return false;
            }
            i++;
        }
```

```
            return true;
        }
        // is digit toCheck valid in colX
        private static boolean checkCol(int[] sudoku, int colX, int toCheck) {
            // the loop traverse all elements in colX
            for (int y = 0; y < 9; y++) {
                if (toCheck == sudoku[colX]) {
                    return false;
                }
                colX = colX + 9;
            }
            return true;
        }

        private static void printSudoku(int sudoku[]) {
            int x = 0;
            for (int i = 0; i < 81; i++) {
                System.out.print(sudoku[i]);
                x++;
                if (x == 9) {
                    System.out.println();
                    x = 0;
                }
            }
        }
}
```

Implementation

The first difficulty we encountered is that there is no 2D array in ARM assembly. So, we have to use 1D array to express the grid. Still we index the grid from 0 in the order of top to bottom and left to right. Since 2D coordinate is still need to determine the column, the row, and the 3x3 sub-grid a box belong to. We added GetX and GetY function to calculate the 2D coordinate from 1D array. The math in this conversion is relatively easy, Y = 1D_index / 9 (integer division) and X = 1D_index % 9. However, the division and mod is expensive operation, so we calculate Y by using condition test. If index <= 8, then Y = 0, else if index <=17, then Y = 1, and so on. Then X will be calculated from Y, X = 1D_index – Y * 9.

The second difficulty we encountered is that the code becomes extremely hard to read and maintain. The label name started to conflict with each other and the parameter passing becomes unknown. To overcome this, aside from using the ARM application procedure call standard, we use uppercase initial to indicate a subroutine label and lowercase initial to indicate a branch label. Further, we put the lowercase acronym of the subroutine name in the beginning of the branch label to distinguish branches in one subroutine from those in other subroutines. We also comment every subroutine by proving the purpose and parameter passing the subroutine.

The third difficulty we encountered is the hardness to debug assembly code. Although we wrote the code very carefully, a few bugs still made some trouble for us to pin them down.

One of the bug is in the loop from ASCII 0 to ASCII 9. We wrote the loop form 0x30 to 0x40, a mistake missed up decimal and hexadecimal. The correct loop should be form 0x30 to 0x3A.

In the next section we will go through the main routine and some of the subroutines. Since the report for basic UART routines, such as initialization, display a string, and save user input to table, are already written in the previous lab report, we will not include them in this project report. We will only show the new written code here.

```
            entry
start

            ldr sp, = stackstart    ; set up stack pointer
            bl UARTConfig           ; initialize/configure UART1
            ldr r1, = string1       ; starting address of CharData1
            bl Display              ; display CharData1

            ldr r4, = ramstart      ; r4 stores the address of the sudoku
question
            mov r1, r4
            bl SaveInput
            ldr r1, = opa ;debug for input length
            str r2, [r1] ;debug for input length

            cmp r2, #81             ; section for checking sudoku question
validity
            blne WrongLength
            mov r1, r4
            bl CheckInput

            mov r1, r4
            mov r2, #0
            bl Solve
            cmp r0, #1
            blne NoSolution
            mov r2, r4
            bl DisplaySol



done        b done
```

The above code is the main routine. It sets up stack pointer, initialize UART, and display prompt for user input. Then it saves user input as a 0 terminated string stored in address r4. It also verify the user input by checking the length of the input string and making sure each character in the string is in the range form ‘0’ to ‘9’. If a wrong input is found, the program output the error and terminate. Otherwise it calls ‘Solve’ subroutine to find the solution. If the solution is found, it calls ‘DisplaySol’ to output the solution. Otherwise, it calls ‘NoSolution’ to output “No solution!”.

```
Display1    ; display the string stored at address r1, output a space in
every 3 character
            ; parameter r1, the address of the string to be displayed
            push {lr}
            mov r2, #-1
dp1start    add r2, r2, #1
            cmp r2, #3
            bne skipspace
            mov r2, #0
            mov r0, #0x20       ; output a space
            bl Transmit
skipspace   ldrb r0, [r1], #1   ; load character, increment address
            cmp r0, #0      ; null terminated?
            blne Transmit       ; send character to UART
            bne dp1start        ; continue if not a '0'
            pop {pc}
```

The above code is used to output the Sudoku solution. It is a little different from the normal Display subroutine that is used to display strings. It insert a space in every 3 output character, so that the solution of the Sudoku can be easily read.

```
SaveInput   ; save the input string at address r1 and return the length of
the string in r2
            ; parameter r1, the address of the saved input string
            ; return r2, the length of the string
            push {lr}
            mov r2, #0
sistart     bl Receive
            bl Transmit
            cmp r0, #13
            addne r2, r2, #1
            strbne r0, [r1], #1
            bne sistart
            mov r0, #0
            strb r0, [r1]
            pop {pc}
```

This code is used to store the input Sudoku problem to a string in memory. It is also a little different from the normal user input save subroutine. In addition to save the string, it also returns the length of the input string. So the main routine use this length to check if the input is valid.

```
CheckInput  ; check the input string at address r1
            push {lr}
ciloop      ldrb r2, [r1], #1
            cmp r2, #0
            beq cidone
            cmp r2, #0x30
            bllt WrongData
            cmp r2, #0x39
            blgt WrongData
```

```
            b ciloop
cidone      pop {pc}
```

The ‘CheckInput’ subroutine tests each element in the string to make sure that they are in range from ‘0’ to ‘9’.

```
Solve
            ; recersive call to solve the sudoku puzzle
            ; parameter r1, the address of the sudoku table
            ; parameter r2, the current working index of the table
            ; return r0 = 1, found a solution
            ; return r0 = 0, no solution
            push {r4-r9, lr}
            mov r4, r1      ; the address of the sudoku table
            mov r5, r2      ; the current wokring index
            cmp r5, #81
            beq strue
            add r6, r5, #1  ; the next wokring index
            ldrb r7, [r4, r5]   ; the digit at current index
            cmp r7, #0x30
            beq sguess
            mov r1, r4          ; preparing call Solve on next index
            mov r2, r6
            bl Solve
            b sdone
sguess      mov r1, r5          ; preparing call GetY
            bl GetY
            mov r7, r0          ; the current Y index
            mov r1, r5          ; preparing call GetX
            mov r2, r7
            bl GetX
            mov r8, r0          ; the current X index
            ; check loop
            mov r9, #0x31       ; guess number
sloop       mov r0, r4          ; preparing call CheckSquare
            mov r1, r8
            mov r2, r7
            mov r3, r9
            bl CheckSquare
            cmp r0, #0
            beq sloopupdate
            mov r1, r4          ; preparing call CheckRow
            mov r2, r7
            mov r3, r9
            bl CheckRow
            cmp r0, #0
            beq sloopupdate
            mov r1, r4          ; preparing call CheckCol
            mov r2, r8
            mov r3, r9
            bl CheckCol
            cmp r0, #0
            beq sloopupdate
            strb r9, [r4, r5]
```

```
            mov r1, r4          ; preparing call Solve on next Index
            mov r2, r6
            bl Solve
            cmp r0, #1
            beq strue
sloopupdate add r9, r9, #1
            cmp r9, #0x3A
            blt sloop
            ;after loop
            mov r1, #0x30
            strb r1, [r4, r5]
            mov r0, #0
            b sdone
strue       mov r0, #1
sdone       pop {r4-r9, pc}
```

The 'Solve' subroutine is the central part of the algorithm. It recursively calls itself until a solution is found or every possible combination is tried without finding a solution. The code is in parallel with our java test code.

```
GetY        ; find Y index of the current index
            ; parameter r1, the current index to be translated
            ; return r0, the corresponding Y index
            push {lr}
            cmp r1, #8
            bgt getytest2
            mov r0, #0          ; i <= 8
            b getydone
getytest2   cmp r1, #17
            bgt getytest3
            mov r0, #1          ; i <= 17
            b getydone
getytest3   cmp r1, #26
            bgt getytest4
            mov r0, #2          ; i <= 26
            b getydone
getytest4   cmp r1, #35
            bgt getytest5
            mov r0, #3          ; i <= 35
            b getydone
getytest5   cmp r1, #44
            bgt getytest6
            mov r0, #4          ; i <= 44
            b getydone
getytest6   cmp r1, #53
            bgt getytest7
            mov r0, #5          ; i <= 53
            b getydone
getytest7   cmp r1, #62
            bgt getytest8
            mov r0, #6          ; i <= 62
            b getydone
getytest8   cmp r1, #71
            movle r0, #7        ; i <= 71
```

```
            ble getydone
            mov r0, #8          ; else
getydone    pop {pc}


GetX        ; find X index of the current index
            ; parameter r1, the current index to be translated
            ; parameter r2, the current Y index
            ; return r0, the corresponding X index
            push {lr}
            add r2, r2, r2, lsl #3  ; Y * 9
            sub r0, r1, r2      ; i - Y * 9
            pop {pc}
```

The ‘GetY’ and ‘GetX’ subroutine is used to get Y and X coordinate, respectively. They are in parallel with java test code.

```
CheckSquare ; check if the current guess number satisfies the little square
            ; parameter r0, the address of the sudoku table
            ; parameter r1, the X index
            ; parameter r2, the Y index
            ; parameter r3, the current guess number
            ; return r0 = 0, not satisfied
            ; return r0 = 1, satisfied
            push {r4-r7, lr}
            cmp r1, #2
            bgt csxtest1
            mov r4, #0      ; X index of the top-left corner of the little
square when real X <= 2
            b csytest
csxtest1    cmp r1, #5
            movle r4, #3    ; real X <= 5
            movgt r4, #6    ; real X else
csytest     cmp r2, #2
            bgt csytest1
            mov r5, #0      ; Y index of the top-left corner of the little
square when real Y <= 2
            b cscalindex
csytest1    cmp r2, #5
            movle r5, #3    ; real Y <= 5
            movgt r5, #6
cscalindex  add r5, r5, r5, lsl #3  ; Y * 9
            add r6, r4, r5  ; X + Y * 9 index of the top-left corner in
sudoku table
            mov r1, #0      ; index k
            mov r2, #0      ; index j
csloop      add r1, r1, #1
            ldrb r7, [r0, r6]
            cmp r7, r3
            beq csfalse
            cmp r1, #3
            moveq r1, #0
            addeq r6, r6, #7
            addne r6, r6, #1
            add r2, r2, #1
```

```
            cmp r2, #9
            blt csloop
            mov r0, #1
            b csdone
csfalse     mov r0, #0
csdone      pop {r4-r7, pc}

CheckRow    ; check if the current guess number satisfies the row
            ; parameter r1, the address of the sudoku table
            ; parameter r2, the Y index
            ; parameter r3, the current guess number
            ; return r0 = 0, not satisfied
            ; return r0 = 1, satisfied
            push {r4-r5, lr}
            lsl r4, r2, #3
            add r4, r4, r2      ; check index
            mov r0, #0
crloop      ldrb r5, [r1, r4]
            cmp r5, r3
            beq crfalse
            add r4, r4, #1
            add r0, r0, #1
            cmp r0, #9
            blt crloop
            mov r0, #1
            b crdone
crfalse     mov r0, #0
crdone      pop {r4-r5, pc}


CheckCol    ; check if the current guess number satisfies the column
            ; parameter r1, the address of the sudoku table
            ; parameter r2, the X index
            ; parameter r3, the current guess number
            ; return r0 = 0, not satisfied
            ; return r0 = 1, satisfied
            push {r4, lr}
            mov r0, #0
ccloop      ldrb r4, [r1, r2]
            cmp r4, r3
            beq ccfalse
            add r2, r2, #9
            add r0, r0, #1
            cmp r0, #9
            blt ccloop
            mov r0, #1
            b ccdone
ccfalse     mov r0, #0
ccdone      pop {r4, pc}
```

The ‘CheckSquare’, ‘CheckRow’, and ‘CheckCol’ are used to test if a digit is valid in given position according to sub-grid rule, row rule, and column rule, respectively. They are also parallel with the java test code.

Testing and Demo

We tested each new subroutine added to the program to make sure there are bug free. Then we do integrate test to make sure the subroutine is correctly called and the correct value is returned. In this way, if a bug shows up, most probably it is in the newly added code. The final code is tested on many problems from websudoku.com, and the program passed every test.

For the problem in figure under method section, input the puzzle in order of top to bottom and left to right using 0 indicate unknown box as shown below.

```
Enter Question : 000000006100400900020190800000005104750000093403200000008056020006001007200000000
```

Press enter, the program gives the solution showed in the same order.

```
Solution : 934 582 716 185 467 932 627 193 845 892 375 164 751 648 293 463 219 578 318 756 429 546 921 387 279 834 651
```

Fill the solution to the original question:

9	3	4	5	8	2	7	1	6
1	8	5	4	6	7	9	3	2
6	2	7	1	9	3	8	4	5
8	9	2	3	7	5	1	6	4
7	5	1	6	4	8	2	9	3
4	6	3	2	1	9	5	7	8
3	1	8	7	5	6	4	2	9
5	4	6	9	2	1	3	8	7
2	7	9	8	3	4	6	5	1

Conclusion

The assembly language has same power as any high-level imperative programming language. In fact many code written by high-level programming language will be compile to assembly code first. After implementing the algorithm for solving a Sudoku puzzle in ARM assembly, we are proficient in using subroutines. We also gained many experience in writing long assembly code. In the future, we will be able to implement even more complex algorithm in assembly.