ARM Assembly: Stack Frames and Frame Pointers Demo

CPE 221

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March 16, 2025

C++ Implementation

ARM Assembly Implementation

Stack Frame Analysis During Program Execution

Introduction

- ARM Assembly program with 4 nested function calls
- Assume base address of SP as $0x2000$
- Each function has its own stack frame
- Visualizing stack and frame pointers during execution

Stack Organization in ARM

- Stack grows downward in memory
- SP (Stack Pointer) - Points to the current top of stack
- FP (R11) - Frame Pointer, maintains reference to current frame
- Each function:
  - Saves previous FP and LR (Link Register)
  - Sets up new frame with local variables
  - Restores previous frame on exit

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C++ Implementation - Main Function

```cpp
#include <iostream>

// Function prototypes
int firstFunction(int a);
int secondFunction(int b);
int thirdFunction(int c);
int fourthFunction(int d);

int main() {
    int inputValue = 8;
    std::cout << "Starting with value: " << inputValue << std::endl;
    std::cout << "------------------------" << std::endl;

    int finalResult = firstFunction(inputValue);

    std::cout << "------------------------" << std::endl;
    std::cout << "Final result: " << finalResult << std::endl;

    return 0;
}
```

C++ Implementation - First Function

```cpp
// First function (outermost)
int firstFunction(int a) {
    // Four local variables
    int localVar1 = a + 15;
    int localVar2 = a * 3;
    int localVar3 = a << 3;  // Bit shift left by 3 (multiply by 8)
    int localVar4 = 100;

    // Call the second function
    int nestedResult = secondFunction(localVar2 + a);

    // Final calculation
    int result = localVar1 * localVar4 + nestedResult - localVar3;

    std::cout << "First function: " << a << " -> " << result << std::endl;
    return result;
}
```

C++ Implementation - Second Function

```cpp
// Second function
int secondFunction(int b) {
    // Four local variables
    int localVar1 = b << 1;  // Bit shifting (multiplication by 2)
    int localVar2 = b + b;
    int localVar3 = b * b;
    int localVar4 = 12;

    // Call the third function
    int nestedResult = thirdFunction(localVar1 - localVar4);

    // Some bitwise operations for variety
    int result = nestedResult & localVar3 | localVar2;

    std::cout << "Second function: " << b << " -> " << result << std::endl;
    return result;
}
```

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C++ Implementation - Third Function

```cpp
// Third function
int thirdFunction(int c) {
    // Four local variables
    int localVar1 = c * 3;
    int localVar2 = c - 5;
    int localVar3 = c + 7;
    int localVar4 = 7;

    // Call the fourth function
    int nestedResult = fourthFunction(localVar1 + localVar2);

    // More math operations
    int result = nestedResult + (localVar3 * localVar4);

    std::cout << "Third function: " << c << " -> " << result << std::endl;
    return result;
}
```

C++ Implementation - Fourth Function

```cpp
// Fourth function (innermost)
int fourthFunction(int d) {
    // Four local variables
    int localVar1 = d * 2;
    int localVar2 = d + 10;
    int localVar3 = d * d;
    int localVar4 = 5;

    // Some interesting math: Compute a polynomial expression
    int result = localVar1 * localVar3 + localVar2 * localVar4;

    std::cout << "Fourth function: " << d << " -> " << result << std::endl;
    return result;
}
```

ARM Assembly - Program Entry

```
@ ARMv7 Assembly implementation of the nested function calls program
@ Using SP for stack pointer and FP (R11) for frame pointer

.text
.global _START

_START:
    LDR SP, =0x2000        // Initialize stack pointer
    MOV R0, #8             // inputValue = 8
    SUB SP, SP, #8         // Allocate space for inputValue + finalResult
    STR R0, [SP, #4]       // Store inputValue at 0x1FFC
    BL FIRSTFUNCTION       // Call FIRSTFUNCTION
    STR R0, [SP]           // Store finalResult at 0x1FF8
DONE:  B DONE              // Infinite loop
```

ARM Assembly - First Function

```
FIRSTFUNCTION:
    PUSH {FP, LR}           // Save FP and LR
    MOV FP, SP              // FP = current SP
    SUB SP, SP, #24         // Allocate 24 bytes for locals

    // CORRECTED: Load inputValue from [FP, #12] instead of [FP, #8]
    LDR R0, [FP, #12]       // Load inputValue from 0x1FFC
    ADD R1, R0, #15         // localVar1 = a + 15
    STR R1, [FP, #-24]      // Store localVar1 at [FP-24]


    // localVar2 = a * 3
    MOV R1, #3              // Load 3 into R1
    MUL R1, R0, R1          // localVar2 = a * 3
    STR R1, [FP, #-20]      // Store localVar2 at [FP-20]

    // localVar3 = a << 3
    LSL R1, R0, #3          // localVar3 = a << 3
    STR R1, [FP, #-16]      // Store localVar3 at [FP-16]

    // localVar4 = 100
    MOV R1, #100            // localVar4 = 100
    STR R1, [FP, #-12]      // Store localVar4 at [FP-12]

    // Call SECONDFUNCTION(localVar2 + a)
    LDR R1, [FP, #-20]      // Load localVar2
    ADD R0, R1, R0          // R0 = localVar2 + a
    BL SECONDFUNCTION       // Call SECONDFUNCTION
    STR R0, [FP, #-8]       // Store nestedResult at [FP-8]
```

ARM Assembly - First Function (continued)

```
// Calculate final result
    LDR R1, [FP, #-24]     // Load localVar1
    LDR R2, [FP, #-12]     // Load localVar4
    MUL R3, R1, R2         // R3 = localVar1 * localVar4
    LDR R1, [FP, #-8]      // Load nestedResult
    ADD R3, R3, R1         // R3 += nestedResult
    LDR R1, [FP, #-16]     // Load localVar3
    SUB R0, R3, R1         // R0 = R3 - localVar3
    STR R0, [FP, #-4]      // Store result at [FP-4]
    LDR R0, [FP, #-4]      // Load result into R0

    MOV SP, FP             // Epilogue: Restore SP
    POP {FP, PC}           // Restore FP and return
```

ARM Assembly - Second Function

```
SECONDFUNCTION:
    PUSH {FP, LR}          // Prologue: Save FP and LR
    MOV FP, SP             // Set FP to current SP
    SUB SP, SP, #24        // Allocate 24 bytes for locals

    // localVar1 = b << 1
    LSL R1, R0, #1         // localVar1 = b << 1
    STR R1, [FP, #-24]     // Store localVar1 at [FP-24]

    // localVar2 = b + b
    ADD R1, R0, R0         // localVar2 = b + b
    STR R1, [FP, #-20]     // Store localVar2 at [FP-20]

    // localVar3 = b * b
    MUL R1, R0, R0         // localVar3 = b * b
    STR R1, [FP, #-16]     // Store localVar3 at [FP-16]

    // localVar4 = 12
    MOV R1, #12            // localVar4 = 12
    STR R1, [FP, #-12]     // Store localVar4 at [FP-12]
```

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ARM Assembly - Second Function (continued)

```
// Call THIRDFUNCTION(localVar1 - localVar4)
    LDR R1, [FP, #-24]     // Load localVar1
    LDR R2, [FP, #-12]     // Load localVar4
    SUB R0, R1, R2         // R0 = localVar1 - localVar4
    BL THIRDFUNCTION       // Call THIRDFUNCTION
    STR R0, [FP, #-8]      // Store nestedResult at [FP-8]

    // Calculate result
    LDR R1, [FP, #-8]      // Load nestedResult
    LDR R2, [FP, #-16]     // Load localVar3
    AND R3, R1, R2         // R3 = nestedResult & localVar3
    LDR R1, [FP, #-20]     // Load localVar2
    ORR R0, R3, R1         // R0 = R3 | localVar2
    STR R0, [FP, #-4]      // Store result at [FP-4]
    LDR R0, [FP, #-4]      // Load result into R0

    MOV SP, FP             // Epilogue: Restore SP
    POP {FP, PC}           // Restore FP and return
```

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ARM Assembly - Third Function

```
THIRDFUNCTION:
    PUSH {FP, LR}          // Prologue: Save FP and LR
    MOV FP, SP             // Set FP to current SP
    SUB SP, SP, #24        // Allocate 24 bytes for locals

    // localVar1 = c * 3
    MOV R1, #3             // Load 3 into R1
    MUL R1, R0, R1         // localVar1 = c * 3
    STR R1, [FP, #-24]     // Store localVar1 at [FP-24]

    // localVar2 = c - 5
    SUB R1, R0, #5         // localVar2 = c - 5
    STR R1, [FP, #-20]     // Store localVar2 at [FP-20]

    // localVar3 = c + 7
    ADD R1, R0, #7         // localVar3 = c + 7
    STR R1, [FP, #-16]     // Store localVar3 at [FP-16]

    // localVar4 = 7
    MOV R1, #7             // localVar4 = 7
    STR R1, [FP, #-12]     // Store localVar4 at [FP-12]
```

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ARM Assembly - Third Function (continued)

```
// Call FOURTHFUNCTION(localVar1 + localVar2)
    LDR R1, [FP, #-24]     // Load localVar1
    LDR R2, [FP, #-20]     // Load localVar2
    ADD R0, R1, R2         // R0 = localVar1 + localVar2
    BL FOURTHFUNCTION      // Call FOURTHFUNCTION
    STR R0, [FP, #-8]      // Store nestedResult at [FP-8]

    // Calculate result
    LDR R1, [FP, #-16]     // Load localVar3
    LDR R2, [FP, #-12]     // Load localVar4
    MUL R3, R1, R2         // R3 = localVar3 * localVar4
    LDR R1, [FP, #-8]      // Load nestedResult
    ADD R0, R1, R3         // R0 = nestedResult + R3
    STR R0, [FP, #-4]      // Store result at [FP-4]
    LDR R0, [FP, #-4]      // Load result into R0

    MOV SP, FP             // Epilogue: Restore SP
    POP {FP, PC}           // Restore FP and return
```

ARM Assembly - Fourth Function

```
FOURTHFUNCTION:
    PUSH {FP, LR}          // Prologue: Save FP and LR
    MOV FP, SP             // Set FP to current SP
    SUB SP, SP, #24        // Allocate 24 bytes for locals

    // localVar1 = d * 2
    LSL R1, R0, #1         // localVar1 = d * 2
    STR R1, [FP, #-24]     // Store localVar1 at [FP-24]

    // localVar2 = d + 10
    ADD R1, R0, #10        // localVar2 = d + 10
    STR R1, [FP, #-20]     // Store localVar2 at [FP-20]

    // localVar3 = d * d
    MUL R1, R0, R0         // localVar3 = d * d
    STR R1, [FP, #-16]     // Store localVar3 at [FP-16]

    // localVar4 = 5
    MOV R1, #5             // localVar4 = 5
    STR R1, [FP, #-12]     // Store localVar4 at [FP-12]
```

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ARM Assembly - Fourth Function (continued)

```
// Calculate result
    LDR R1, [FP, #-24]     // Load localVar1
    LDR R2, [FP, #-16]     // Load localVar3
    MUL R3, R1, R2         // R3 = localVar1 * localVar3
    LDR R1, [FP, #-20]     // Load localVar2
    LDR R2, [FP, #-12]     // Load localVar4
    MUL R2, R1, R2         // R2 = localVar2 * localVar4
    ADD R0, R3, R2         // R0 = R3 + R2
    STR R0, [FP, #-8]      // Store result at [FP-8]
    LDR R0, [FP, #-8]      // Load result into R0

    MOV SP, FP             // Epilogue: Restore SP
    POP {FP, PC}           // Restore FP and return
```

Program Initialization

Address	**Content**	**Description**
0x2000	SP_init	Initial stack pointer
0x1FFC	8	inputValue (R0)
0x1FF8	(empty)	Reserved for finalResult

- SP initialized to 0x2000
- SP adjusted to 0x1FF8 (SP - 8 bytes)
- R0 = 8 (inputValue) stored at [SP, #-4]
- Now ready to call firstFunction with R0 = 8

FIRSTFUNCTION Stack Frame

Address	Content	Description
0x1FF4	LR	Return address
0x1FF0	Old FP	Previous frame pointer
0x1FEC	result	Final calculation
0x1FE8	nestedResult	From SECONDFUNCTION
0x1FE4	100	localVar4
0x1FE0	64	localVar3 a<<3
0x1FDC	24	a*3 localVar2
0x1FD8	23	a+15 localVar1

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SECONDFUNCTION Stack Frame

Address	Content	Description
0x1FD4	LR	Return to FIRSTFUNCTION
0x1FD0	Old FP	Previous frame pointer
0x1FCC		Final result
0x1FC8		nestedResult
0x1FC4		localVar4
0x1FC0		localVar3 (b * b)
0x1FBC		localVar2 (b + b)
0x1FB8		localVar1 (b <<1)

- Bitwise AND/OR operations
- Receives parameter from FIRSTFUNCTION

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THIRDFUNCTION Stack Frame

Address	Content	Description
0x1FB4	LR	Return to SECONDFUNCTION
0x1FB0	Old FP	Previous frame pointer
0x1FAC		Final result
0x1FA8		nestedResult
0x1FA4		localVar4
0x1FA0		localVar3 (c + 7)
0x1F9C		localVar2 (c - 5)
0x1F98		localVar1 (c * 3)

- Calls FOURTHFUNCTION

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FOURTHFUNCTION Stack Frame

Address	Content	Description
0x1F94	LR	Return to THIRDFUNCTION
0x1F90	Old FP	Previous frame pointer
0x1F8C		Final result
0x1F88		localVar4
0x1F84		localVar3 (d * d)
0x1F80		localVar2 (d + 10)
0x1F7C		localVar1 (d * 2)

- Innermost function

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Final _START Stack State

Address	Content	Description
0x2000	(SP init)	Original stack top
0x1FFC	8	Preserved inputValue
0x1FF8	2300	Final result
0x1FF4	...	Cleaned stack space

- SP returns to 0x1FF8 after functions unwind
- 8-byte allocation remains with final result
- All temporary stack frames cleaned

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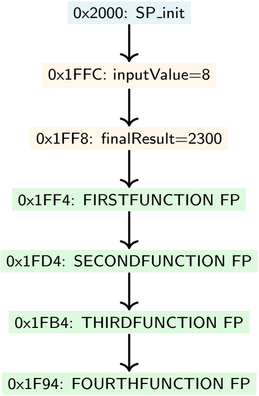
Complete Stack Growth Diagram



0x2000: SP_init

0x1FFC: inputValue=8

0x1FF8: finalResult=2300

0x1FF4: FIRSTFUNCTION FP

0x1FD4: SECONDFUNCTION FP

0x1FB4: THIRDFUNCTION FP

0x1F94: FOURTHFUNCTION FP

- Total stack depth: 0x2000 - 0x1F94 = 108 bytes
- Each function frame uses 28 bytes (7×4)
- Stack unwinds completely except for final result