# ARM Assembly Programming

*Computer Organization and Assembly Languages*
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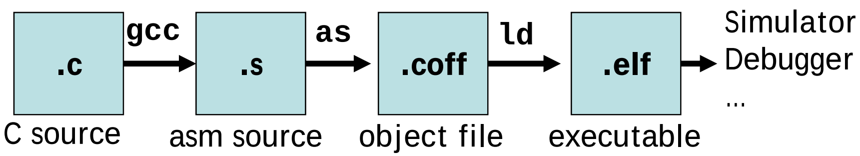
## GNU compiler and binutils

- HAM uses GNU compiler and binutils
  - gcc: GNU C compiler
  - as: GNU assembler
  - ld: GNU linker
  - gdb: GNU project debugger
  - insight: a (Tcl/Tk) graphic interface to gdb

## Pipeline

- COFF (common object file format)
- ELF (extended linker format)
- Segments in the object file
  - Text: code
  - Data: initialized global variables
  - BSS: uninitialized global variables




## GAS program format

```
        .file "test.s"
        .text
        .global main
        .type main, %function
main:
        MOV R0, #100
        ADD R0, R0, R0
        SWI #11
        .end
```

## GAS program format

```
        .file "test.s"
        .text
        .global main
        .type main, %function
main:
        MOV R0, #100
        ADD R0, R0, R0
        SWI #11
        .end
```

- export variable → .global main
- set the type of a symbol to be either a function or an object → %function
- call interrupt to end the program → SWI #11
- signals the end of the program → .end

## ARM assembly program

| label | operation | operand | comments |
|---|---|---|---|
| main: | | | |
| | LDR | R1, value | @ load value |
| | STR | R1, result | |
| | SWI | #11 | |
| value: | .word | 0x0000C123 | |
| result: | .word | 0 | |

## Control structures

- Program is to implement algorithms to solve problems. Program decomposition and flow of control are important concepts to express algorithms.
- Flow of control:
  - Sequence.
  - Decision: if-then-else, switch
  - Iteration: repeat-until, do-while, for
- Decomposition: split a problem into several smaller and manageable ones and solve them independently. (subroutines/functions/procedures)

## Decision

- If-then-else
- switch

## If statements

if C then T else E

```
        C
        BNE else
        T
        B    endif
else:   E
endif:
```

```
// find maximum
if (R0>R1) then R2:=R0
else R2:=R1
```

## If statements

if C then T else E

```
        C
        BNE else
        T
        B    endif
else:   E
endif:
```

```
// find maximum
if (R0>R1) then R2:=R0
else R2:=R1
```

```
        CMP R0, R1
        BLE else
        MOV R2, R0
        B   endif
else:   MOV R2, R1
endif:
```

## If statements

```
// find maximum
if (R0>R1) then R2:=R0
else R2:=R1
```

Two other options:

```
CMP   R0, R1
MOVGT R2, R0
MOVLE R2, R1

MOV   R2, R0
CMP   R0, R1
MOVLE R2, R1
```

```
        CMP R0, R1
        BLE else
        MOV R2, R0
        B   endif
else:   MOV R2, R1
endif:
```

## If statements

```
if (R1==1 || R1==5 || R1==12) R0=1;

TEQ   R1, #1         ...
TEQNE R1, #5         ...
TEQNE R1, #12        ...
MOVEQ R0, #1         BNE fail
```

## If statements

```
if (R1==0) zero
else if (R1>0) plus
else if (R1<0) neg

      TEQ   R1, #0
      BMI   neg
      BEQ   zero
      BPL   plus
neg:  ...
      B exit
Zero: ...
      B exit
      ...
```

## If statements

```
R0=abs(R0)

TEQ     R0, #0
RSBMI   R0, R0, #0
```

## Multi-way branches

```
        CMP R0, #`0'
        BCC other   @ less than '0'
        CMP R0, #`9'
        BLS digit   @ between '0' and '9'
        CMP R0, #`A'
        BCC other
        CMP R0, #`Z'
        BLS letter  @ between 'A' and 'Z'
        CMP R0, #`a'
        BCC other
        CMP R0, #`z'
        BHI other  @ not between 'a' and 'z'
letter: ...
```

## Switch statements

```
switch (exp) {              e=exp;
  case c1: S1; break;       if (e==c1) {S1}
  case c2: S2; break;       else
  ...                         if (e==c2) {S2}
  case cN: SN; break;         else
  default: SD;                ...
}
```

## Switch statements

```
switch (R0) {
  case 0: S0; break;
  case 1: S1; break;
  case 2: S2; break;
  case 3: S3; break;
  default: err;
}
```

The range is between 0 and N

Slow if N is large

```
      CMP R0, #0
      BEQ S0
      CMP R0, #1
      BEQ S1
      CMP R0, #2
      BEQ S2
      CMP R0, #3
      BEQ S3
err:  ...
      B exit
S0:   ...
      B exit
```

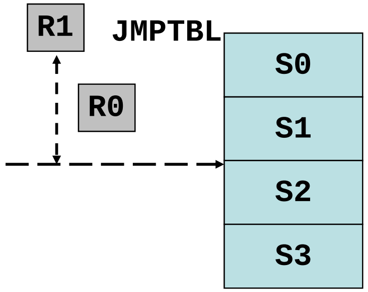
## Switch statements

```
    ADR   R1, JMPTBL
    CMP   R0, #3
    LDRLS PC, [R1, R0, LSL #2]
err:...
    B     exit
S0: ...

JMPTBL:
    .word S0
    .word S1
    .word S2
    .word S3
```

What if the range is between M and N?

For larger N and sparse values, we could use a hash function.



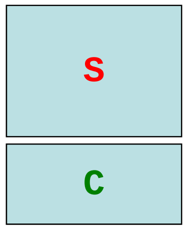

## Iteration

- repeat-until
- do-while
- for

## repeat loops

```
do {S} while ( C )
```

```
loop:
```




```
      BEQ   loop
endw:
```

## while loops

```
while (C) {S}
```

```
loop:   C
        BNE endw
        S
        B   loop
endw:
```

```
        B test
loop:   S
test:   C
        BEQ loop
endw:
```

## while loops

```
while (C) {S}
```

```
        B test
loop:   S
test:   C
        BEQ loop
endw:
```

```
        C
        BNE endw
loop:   S
test:   C
        BEQ loop
endw:
```

## GCD

```
int gcd (int i, int j)
{
    while (i!=j)
    {
      if (i>j)
        i -= j;
      else
        j -= i;
    }
}
```

## GCD

```
Loop:  CMP   R1, R2
       SUBGT R1, R1, R2
       SUBLT R2, R2, R1
       BNE   loop
```

## for loops

```
for ( I ; C ; A ) { S }        for (i=0; i<10; i++)
                                 { a[i]:=0; }

         I
loop:    C
       BNE endfor
         S
         A
       B    loop
endfor:
```

## for loops

```
for ( I ; C ; A ) { S }        for (i=0; i<10; i++)
                                 { a[i]:=0; }

         I
loop:    C                           MOV R0, #0
       BNE endfor                    ADR R2, A
         S                           MOV R1, #0
         A                     loop: CMP R1, #10
       B    loop                     BGE endfor
endfor:                              STR R0,[R2,R1,LSL #2]
                                     ADD R1, R1, #1
                                     B   loop
                               endfor:
```

## for loops

```
for (i=0; i<10; i++)
  { do something; }
```

Execute a loop for a constant of times.

```
      MOV R1, #0                  MOV R1, #10
loop: CMP R1, #10           loop:
      BGE endfor
      @ do something              @ do something
      ADD R1, R1, #1              SUBS R1, R1, #1
      B   loop                    BNE loop
endfor:                     endfor:
```

## Procedures

- Arguments: expressions passed into a function
- Parameters: values received by the function
- Caller and callee

```
void func(int a, int b)   callee
{                          ← parameters
  ...
}
int main(void)   caller
{                          ← arguments
  func(100,200);
  ...
}
```

## Procedures

```
main:
        ...              func:
        BL func               ...
        ...                   ...

        .end                  .end
```

- How to pass arguments? By registers? By stack? By memory? In what order?

## Procedures

caller | callee

```
main:
        @ use R5         func:
        BL func               ...
        @ use R5              @ use R5
        ...                   ...
        ...                   ...
        .end                  .end
```

- How to pass arguments? By registers? By stack? By memory? In what order?
- Who should save R5? Caller? Callee?

## Procedures (caller save)

caller | callee

```
main:
        @ use R5         func:
        @ save R5             ...
        BL func               @ use R5
        @ restore R5
        @ use R5
        .end                  .end
```

- How to pass arguments? By registers? By stack? By memory? In what order?
- Who should save R5? Caller? Callee?

## Procedures (callee save)

caller | callee

```
main:
        @ use R5         func: @ save R5
        BL func               ...
        @ use R5              @ use R5

                              @restore R5
        .end                  .end
```

- How to pass arguments? By registers? By stack? By memory? In what order?
- Who should save R5? Caller? Callee?

## Procedures

main: caller — callee

```
main:                    
        @ use R5       func:
        BL func            ...
        @ use R5           @ use R5
        ...                ...
        ...                ...
        .end               .end
```

- How to pass arguments? By registers? By stack? By memory? In what order?
- Who should save R5? Caller? Callee?
- We need a protocol for these.

## ARM Procedure Call Standard (APCS)

- ARM Ltd. defines a set of rules for procedure entry and exit so that
  - Object codes generated by different compilers can be linked together
  - Procedures can be called between high-level languages and assembly
- APCS defines
  - Use of registers
  - Use of stack
  - Format of stack-based data structure
  - Mechanism for argument passing

## APCS register usage convention

| Register | APCS name | APCS role |
|---|---|---|
| 0 | a1 | Argument 1 / integer result / scratch register |
| 1 | a2 | Argument 2 / scratch register |
| 2 | a3 | Argument 3 / scratch register |
| 3 | a4 | Argument 4 / scratch register |
| 4 | v1 | Register variable 1 |
| 5 | v2 | Register variable 2 |
| 6 | v3 | Register variable 3 |
| 7 | v4 | Register variable 4 |
| 8 | v5 | Register variable 5 |
| 9 | sb/v6 | Static base / register variable 6 |
| 10 | sl/v7 | Stack limit / register variable 7 |
| 11 | fp | Frame pointer |
| 12 | ip | Scratch reg. / new sb in inter-link-unit calls |
| 13 | sp | Lower end of current stack frame |
| 14 | lr | Link address / scratch register |
| 15 | pc | Program counter |

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| 4 | v1 | Register variable 1 |
| 5 | v2 | Register variable 2 |
| 6 | v3 | Register variable 3 |
| 7 | v4 | Register variable 4 |
| 8 | v5 | Register variable 5 |
| 9 | sb/v6 | Static base / register variable 6 |
| 10 | sl/v7 | Stack limit / register variable 7 |
| 11 | fp | Frame pointer |
| 12 | ip | Scratch reg. / new sb in inter-link-unit calls |
| 13 | sp | Lower end of current stack frame |
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- Used to pass the first 4 parameters
- Caller-saved if necessary

## APCS register usage convention

| Register | APCS name | APCS role |
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| 0 | a1 | Argument 1 / integer result / scratch register |
| 1 | a2 | Argument 2 / scratch register |
| 2 | a3 | Argument 3 / scratch register |
| 3 | a4 | Argument 4 / scratch register |
| 4 | v1 | Register variable 1 |
| 5 | v2 | Register variable 2 |
| 6 | v3 | Register variable 3 |
| 7 | v4 | Register variable 4 |
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- Register variables, must return unchanged
- Callee-saved

## APCS register usage convention

| Register | APCS name | APCS role |
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| 4 | v1 | Register variable 1 |
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| 6 | v3 | Register variable 3 |
| 7 | v4 | Register variable 4 |
| 8 | v5 | Register variable 5 |
| 9 | sb/v6 | Static base / register variable 6 |
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| 11 | fp | Frame pointer |
| 12 | ip | Scratch reg. / new sb in inter-link-unit calls |
| 13 | sp | Lower end of current stack frame |
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| 15 | pc | Program counter |

- Registers for special purposes
- Could be used as temporary variables if saved properly.

## Argument passing

- The first four word arguments are passed through R0 to R3.
- Remaining parameters are pushed into stack in the reverse order.
- Procedures with less than four parameters are more effective.

## Return value

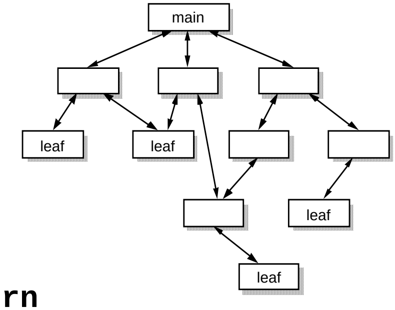
- One word value in R0
- A value of length 2~4 words (R0-R1, R0-R2, R0-R3)

## Function entry/exit

- A simple leaf function with less than four parameters has the minimal overhead. 50% of calls are to leaf functions

```
        BL leaf1
        ...

leaf1:  ...
        ...
        MOV PC, LR @ return
```



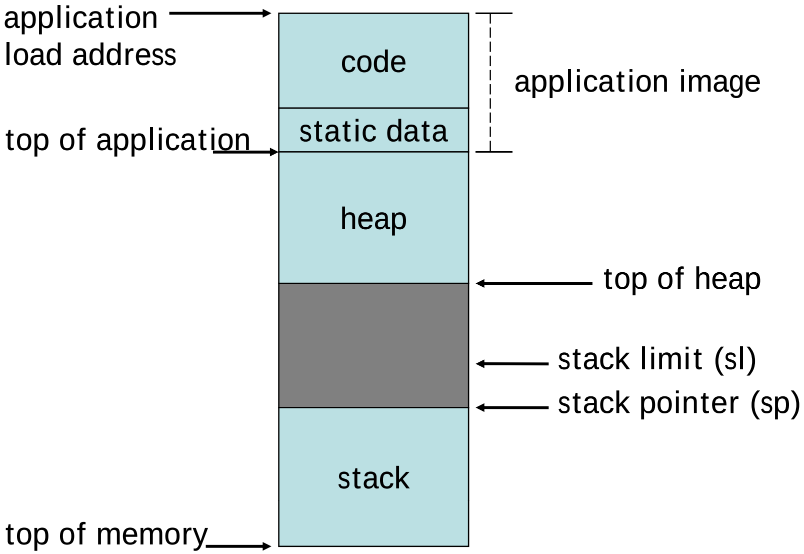

## Function entry/exit

- Save a minimal set of temporary variables

```
        BL leaf2
        ...

leaf2:  STMFD sp!, {regs, lr} @ save
        ...
        LDMFD sp!, {regs, pc} @ restore and
                              @ return
```

## Standard ARM C program address space

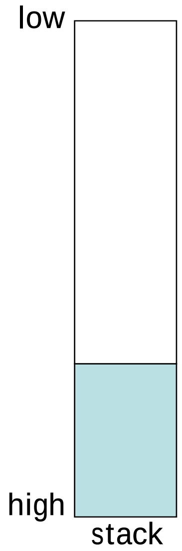



## Accessing operands

- A procedure often accesses operands in the following ways
  - An argument passed on a register: no further work
  - An argument passed on the stack: use stack pointer (R13) relative addressing with an immediate offset known at compiling time
  - A constant: PC-relative addressing, offset known at compiling time
  - A local variable: allocate on the stack and access through stack pointer relative addressing
  - A global variable: allocated in the static area and can be accessed by the static base relative (R9) addressing

## Procedure

```
main:
        LDR   R0, #0
        ...
        BL    func
        ...
```




## Procedure

```
func:   STMFD SP!, {R4-R6, LR}
        SUB   SP, SP, #0xC
        ...
        STR   R0, [SP, #0] @ v1=a1

        ...
        ADD   SP, SP, #0xC
        LDMFD SP!, {R4-R6, PC}
```