ARM Assembly Programming

Computer Organization and Assembly Languages

Yung-Yu Chuang

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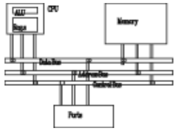
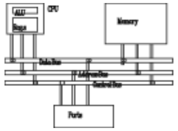
with slides by Peng-Sheng Chen

GNU compiler and binutils

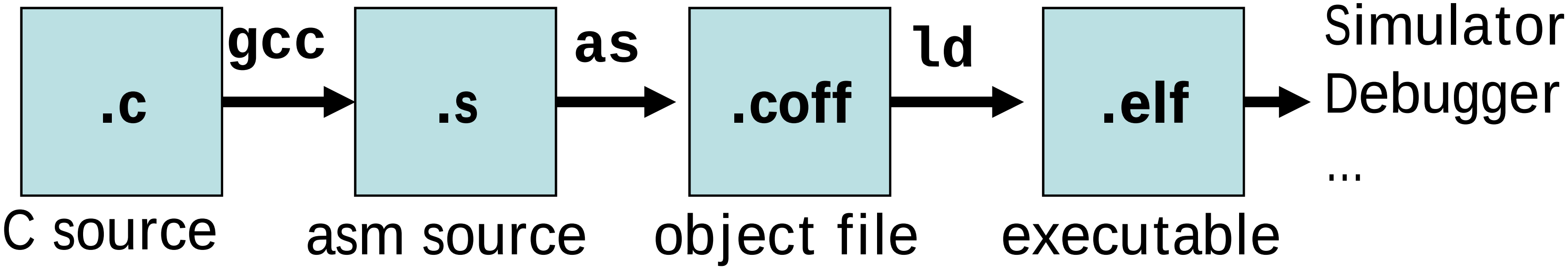


- HAM uses GNU compiler and binutils
  - gcc: GNU C compiler
  - as: GNU assembler
  - ld: GNU linker
  - gdb: GNU project debugger
  - insight: a (Tcl/Tk) graphic interface to gdb

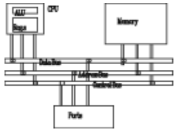
Pipeline



- 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

set the type of a symbol to be either a function or an object → %function

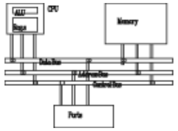
call interrupt to end the program → SWI #11

signals the end of the program → .end

ARM assembly program

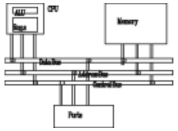
```
label   operation operand          comments

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)

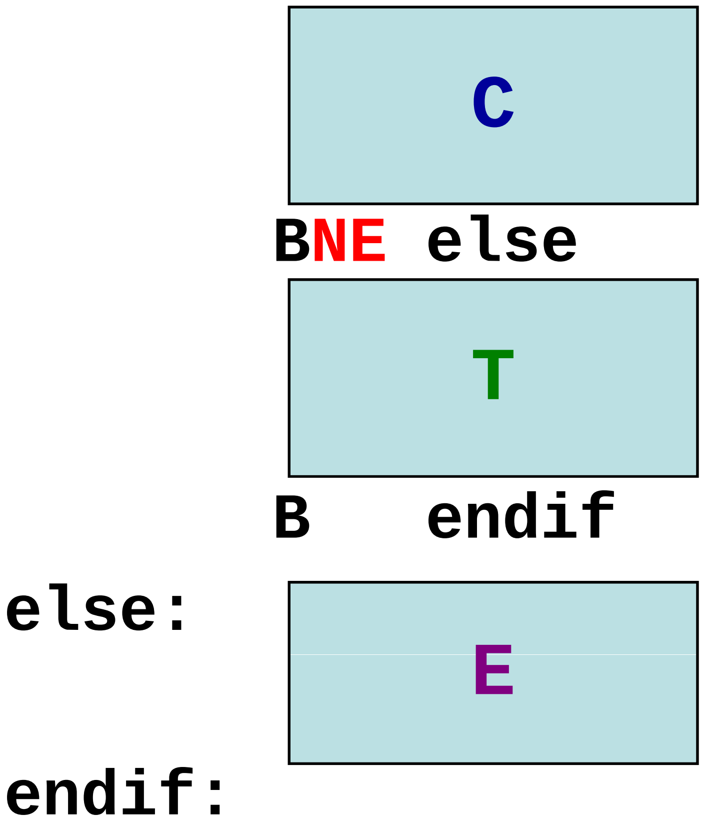
Decision



- If-then-else
- switch

If statements

```
if C then T else E
```

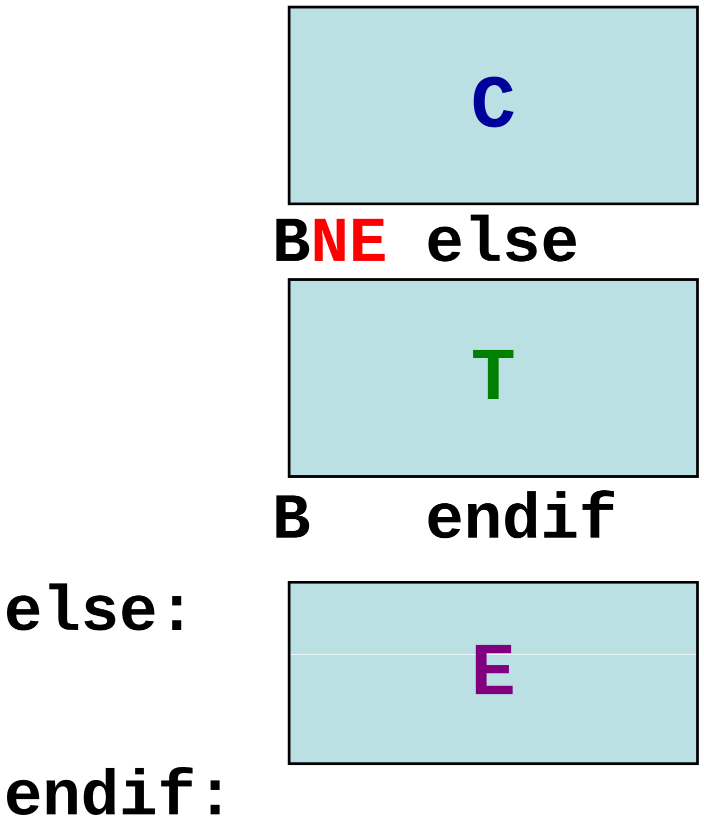


```
        C
        BNE else
        T
        B    endif
else:
        E
endif:
```

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

If statements

if C then T else E

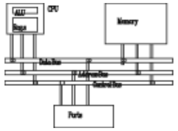


```
             C
      BNE else
             T
      B   endif
else:
             E
endif:
```

```
// 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

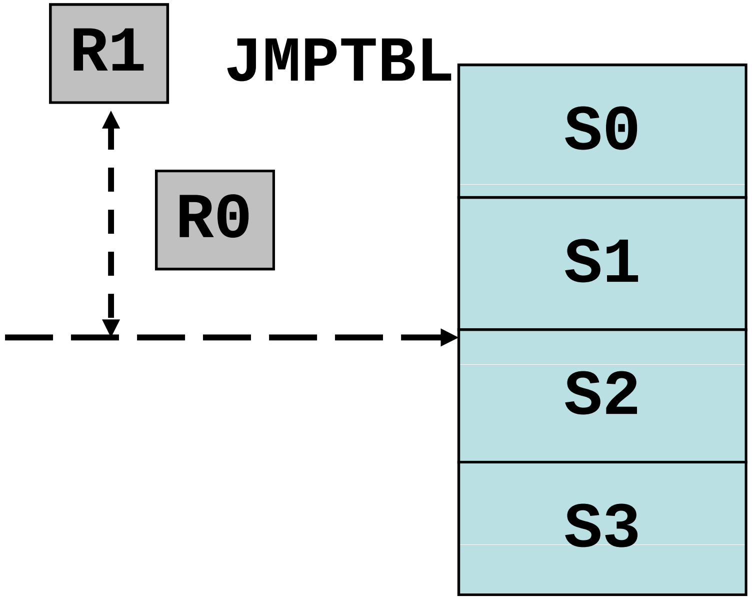
```
     CMP R0, #0
     BEQ S0
     CMP R0, #1
     BEQ S1
     CMP R0, #2
     BEQ S2
     CMP R0, #3
     BEQ S3
err: ...
     B exit
S0:  ...
     B exit
```

Switch statements

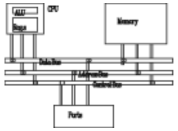
```
    ADR   R1, JMPTBL
    CMP   R0, #3
    LDRLS PC, [R1, R0, LSL #2]
err:...
    B     exit
S0: ...

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.

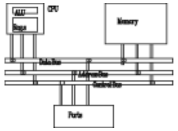


Iteration



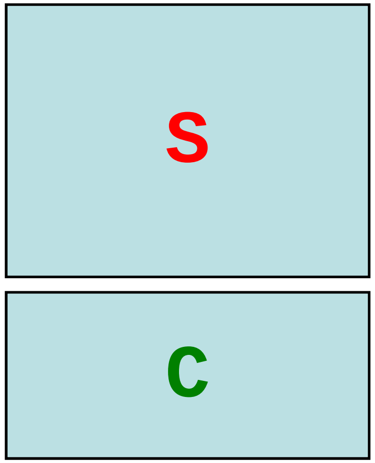
- repeat-until
- do-while
- for

repeat loops



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

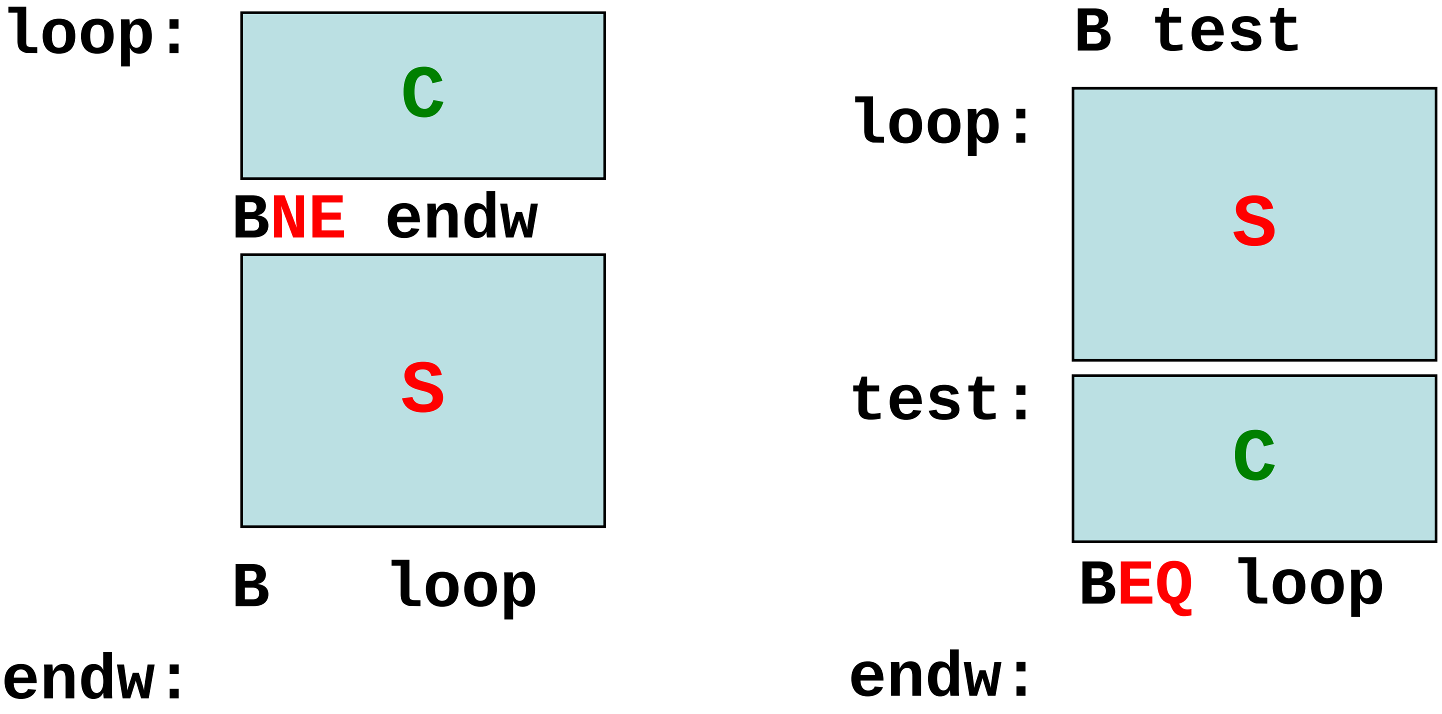
loop:



```
        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:
```

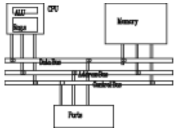
while loops

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

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

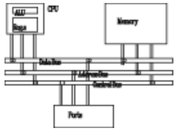
```
        C
        BNE endw
loop:   S
test:   C
        BEQ loop
endw:
```

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

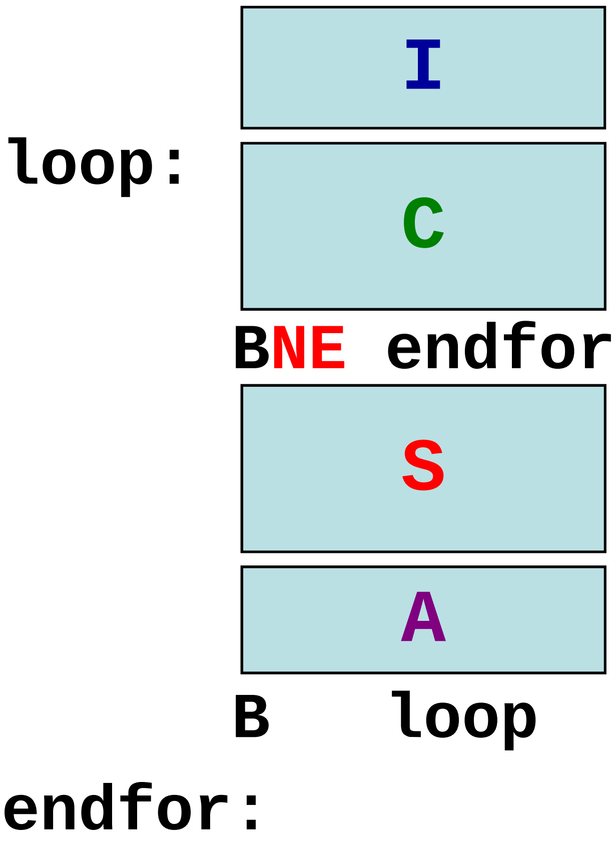
```
for ( I ; C ; A ) { S }        for (i=0; i<10; i++)
                                 { a[i]:=0; }
```

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

for loops

```
for ( I ; C ; A ) {S}
```

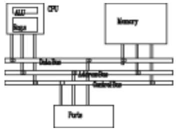
```
for (i=0; i<10; i++)
   { a[i]:=0; }
```



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

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

for loops



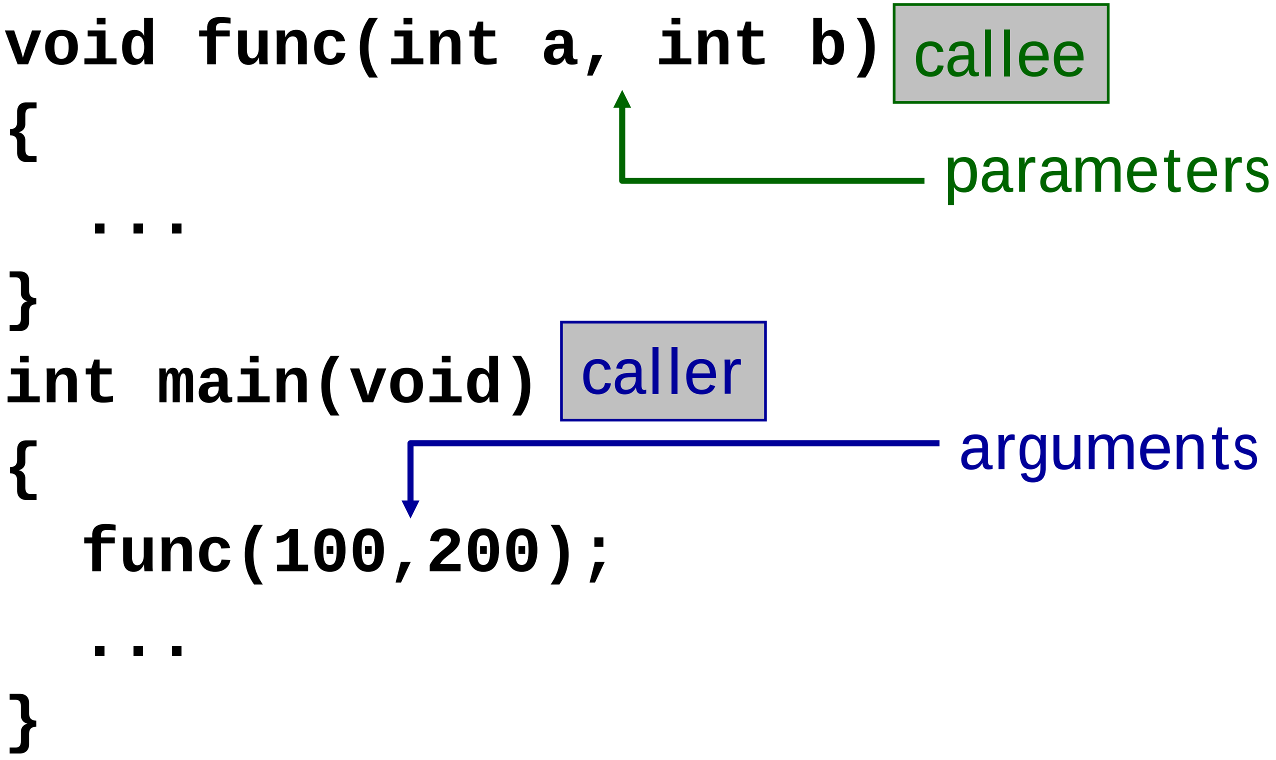
```
for (i=0; i<10; i++)
  { do something; }
```

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)
{
   ...
}
int main(void)
{
   func(100,200);
   ...
}
```

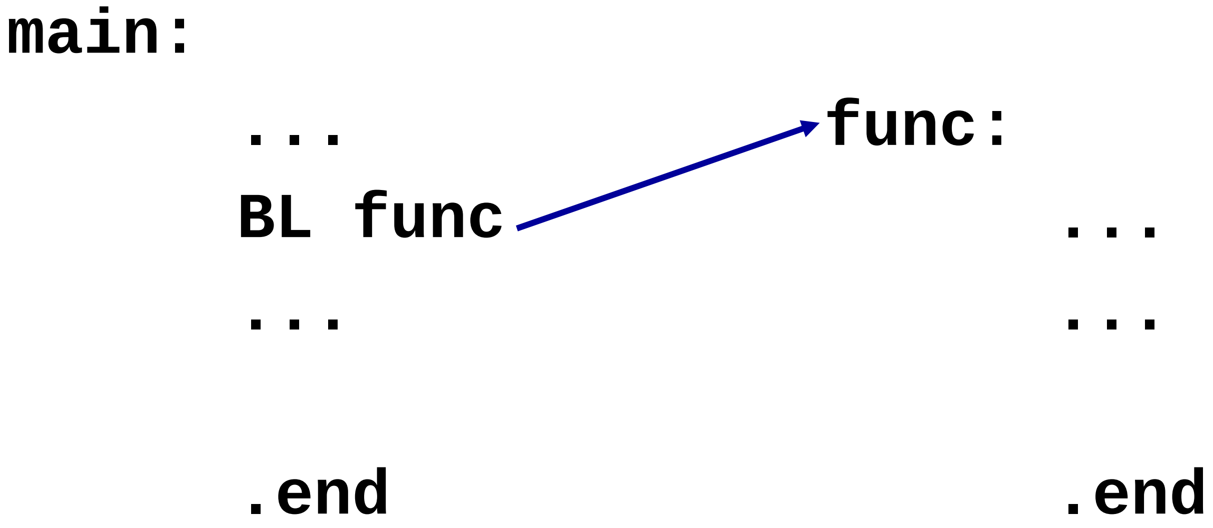
callee

parameters

caller

arguments

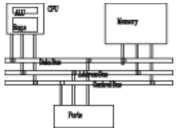
Procedures



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

        .end                            .end
```

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

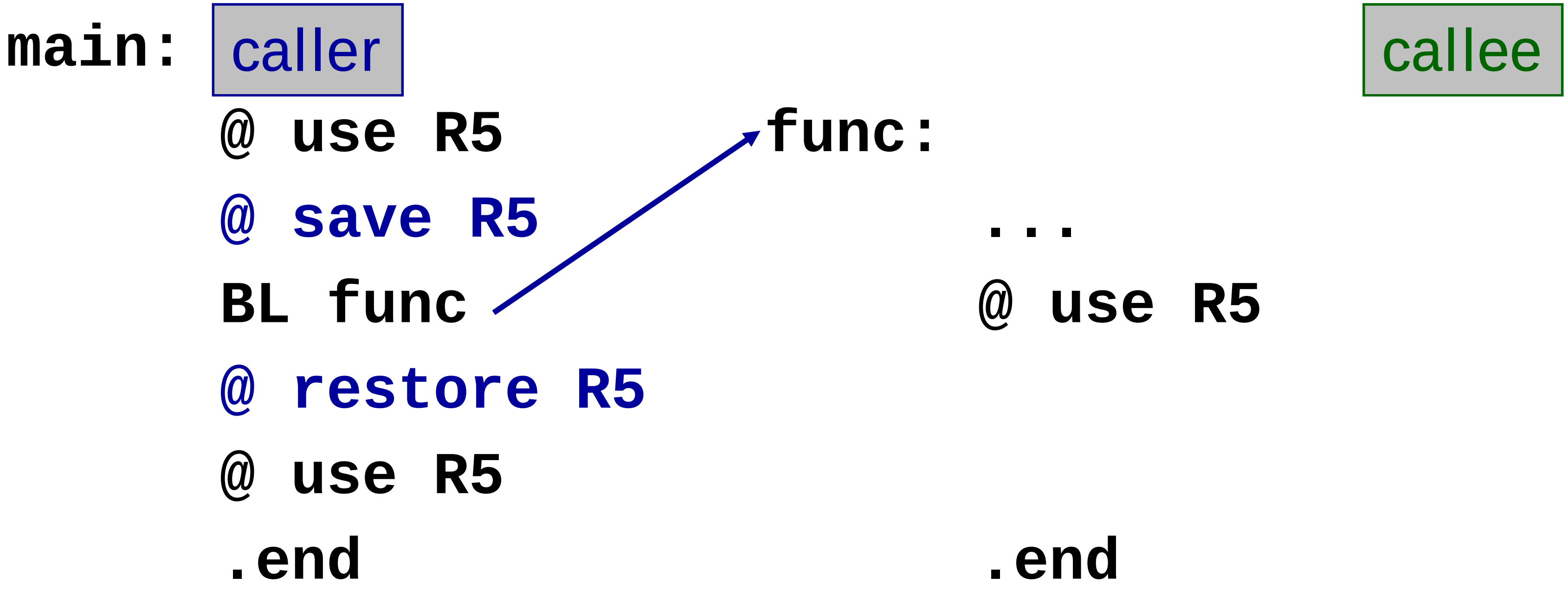
Procedures



```
main:  caller                                  callee
       @ 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

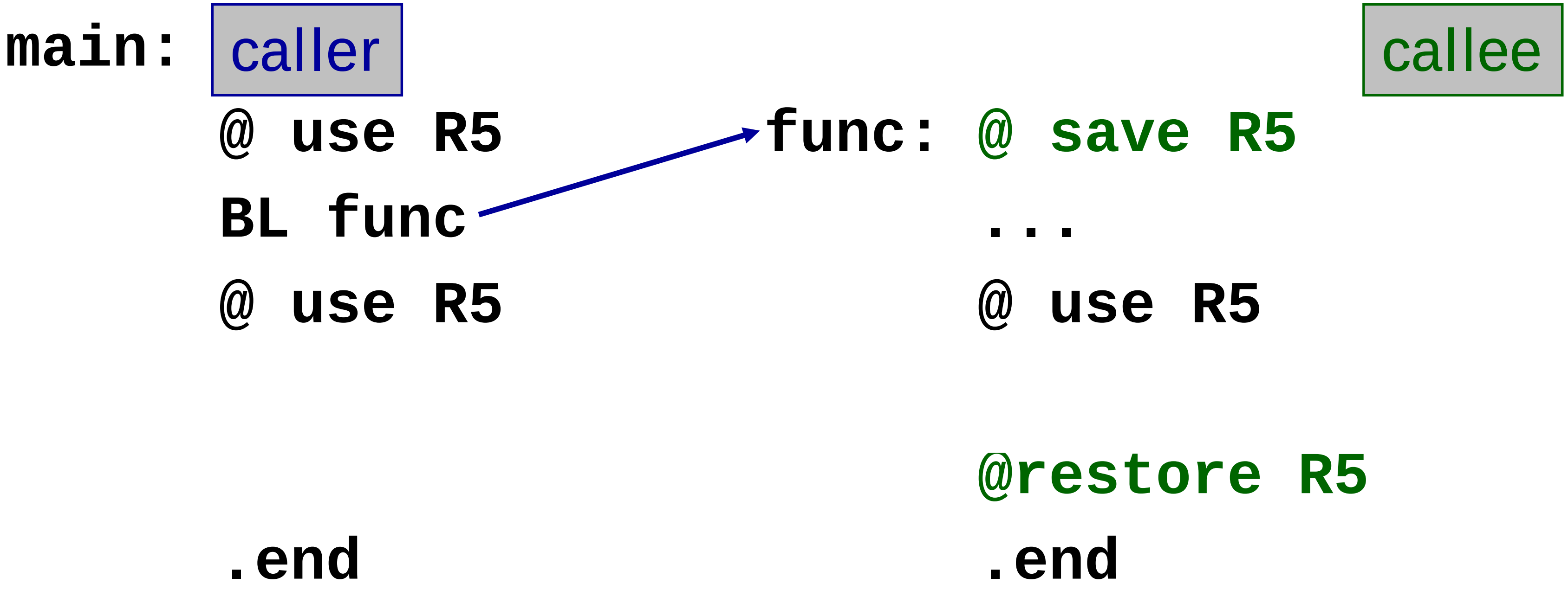
```
main:
        @ use R5
        @ save R5
        BL func
        @ restore R5
        @ use R5
        .end
```

callee

```
func:
        ...
        @ use R5


        .end
```

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

Procedures (callee save)



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


                                 @restore R5
       .end                      .end
```

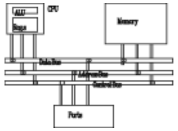
- How to pass arguments? By registers? By stack? By memory? In what order?
- Who should save R5? Caller? Callee?

Procedures

```
main:  caller                                          callee
       @ 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

APCS register usage convention

Register	APCS name	APCS role
0	a1	Argument 1 / integer result / scratch register
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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
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

- Used to pass the first 4 parameters
- Caller-saved if necessary

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

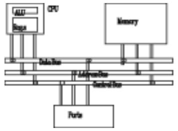
- Register variables, must return unchanged
- Callee-saved

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

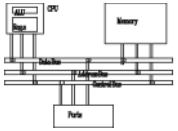
- Registers for special purposes
- Could be used as temporary variables if saved properly.

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



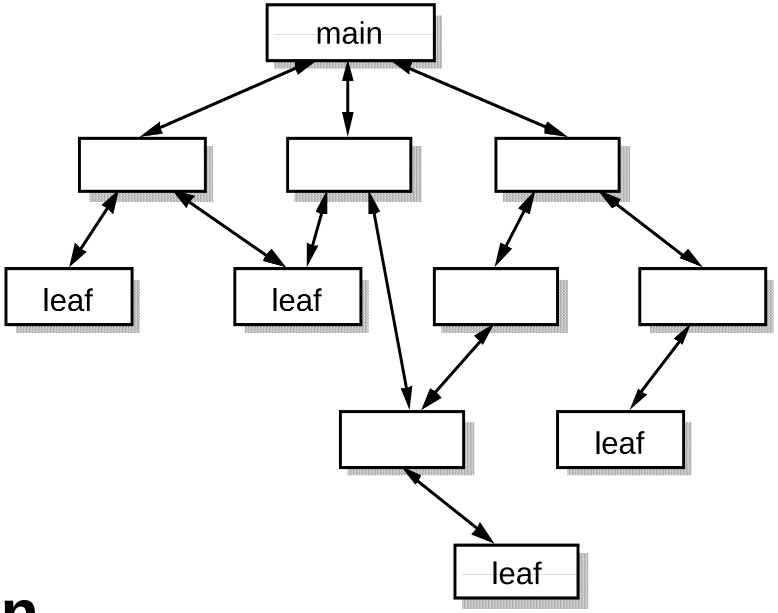
- One word value in R0
- A value of length 2~4 words (R0-R1, R0-R2, R0-R3)

Function entry/exit

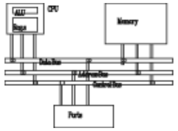
- A simple leaf function with less than four parameters has the minimal overhead. 50% of calls are to leaf functions

```
       BL leaf1
       ...

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



Function entry/exit

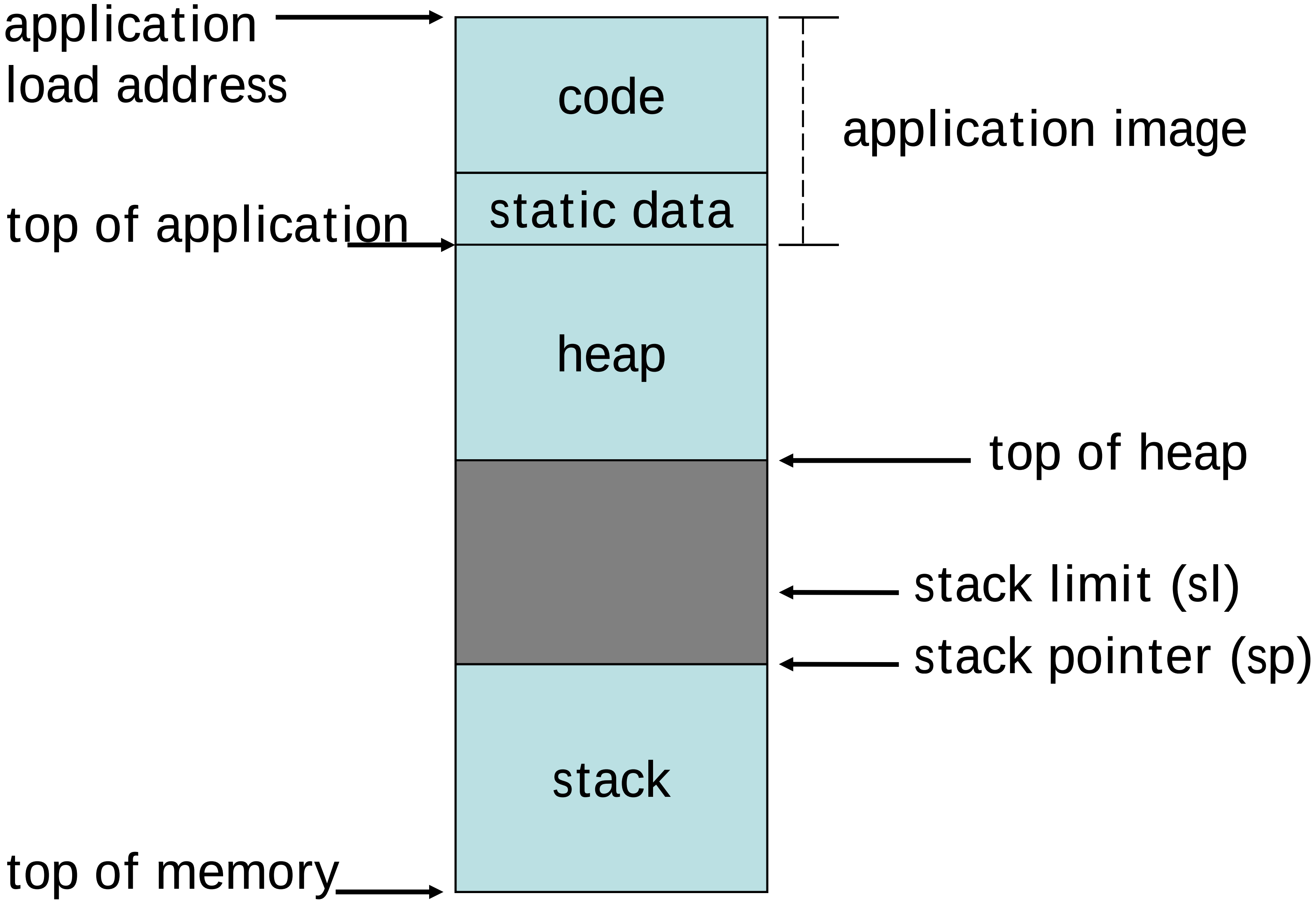


- Save a minimal set of temporary variables

```
        BL leaf2
        ...

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

Standard ARM C program address space



application load address

code

static data

application image

top of application

heap

top of heap

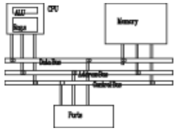
stack limit (sl)

stack pointer (sp)

stack

top of memory

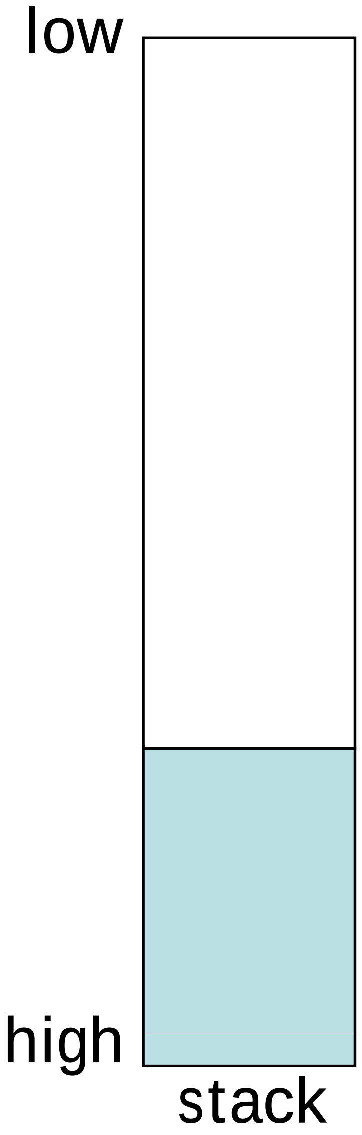
Accessing operands



- 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

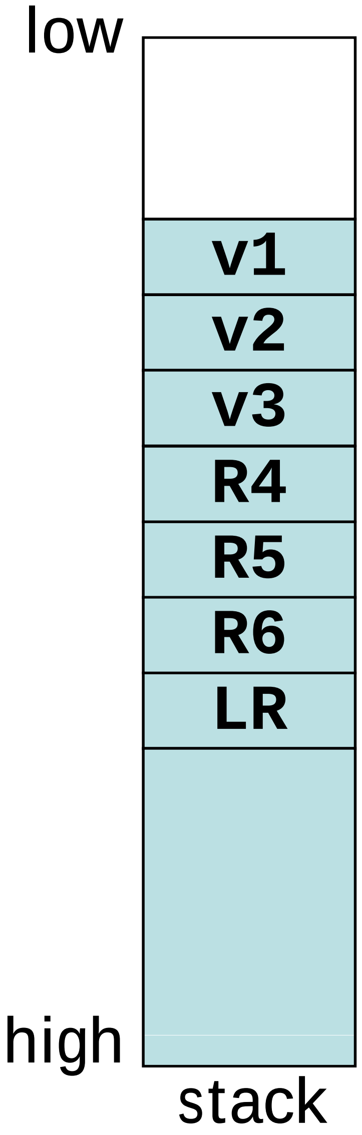
```
main:
        LDR   R0, #0
        ...
        BL    func
        ...
```



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}
```



low

v1

v2

v3

R4

R5

R6

LR

high

stack