ARM Assembly Programming

Computer Organization and Assembly Languages
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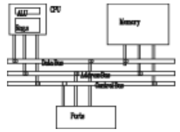
with slides by Peng-Sheng Chen

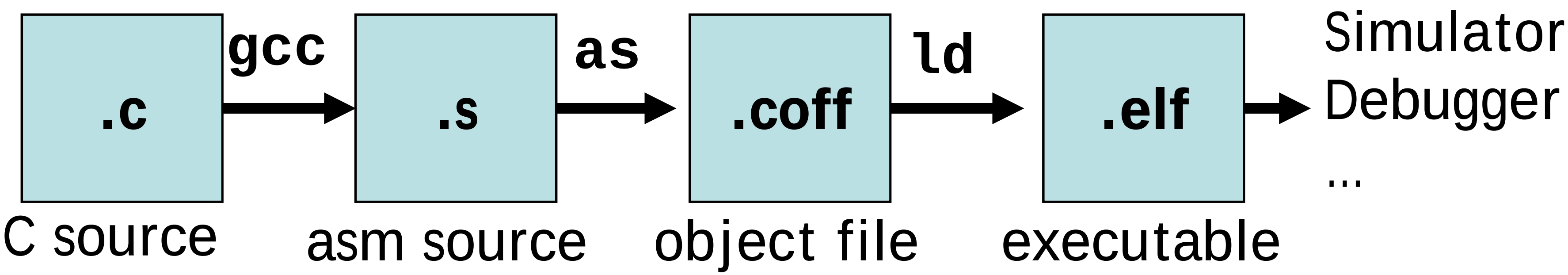
GNU compiler and binutils



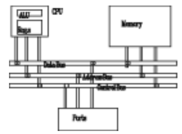
- HAM uses GNU compiler and binutils
  - gcc: GNU C compiler
  - as: GNU assembler
  - ld: GNU linker
  - gdb: GNU project debugger
  - insight: a (Tcl/Tk) graphic interface to gdb

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

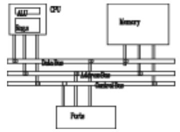


GAS program format



```
        .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
```

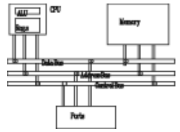
export variable → .global

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

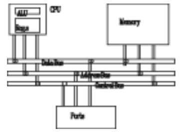
ARM assembly program



label | operation | operand | comments

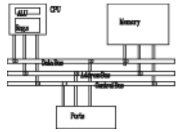
```
main:
        LDR     R1, value       @ load value
        STR     R1, result
        SWI     #11

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

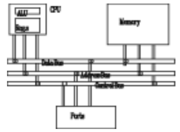
If statements

```
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

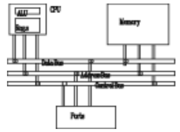
```
// find maximum
if (R0>R1) then R2:=R0
else R2:=R1
```

Two other options:

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

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

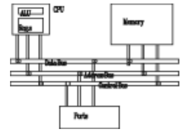
```
       CMP R0, R1
       BLE else
       MOV R2, R0
       B   endif
else:  MOV R2, R1
endif:
```

If statements



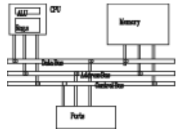
```
if (R1==1 || R1==5 || R1==12) R0=1;

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) {
  case c1: S1; break;
  case c2: S2; break;
  ...
  case cN: SN; break;
  default: SD;
}
```

```
e=exp;
if (e==c1) {S1}
else
  if (e==c2) {S2}
  else
  ...
```

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

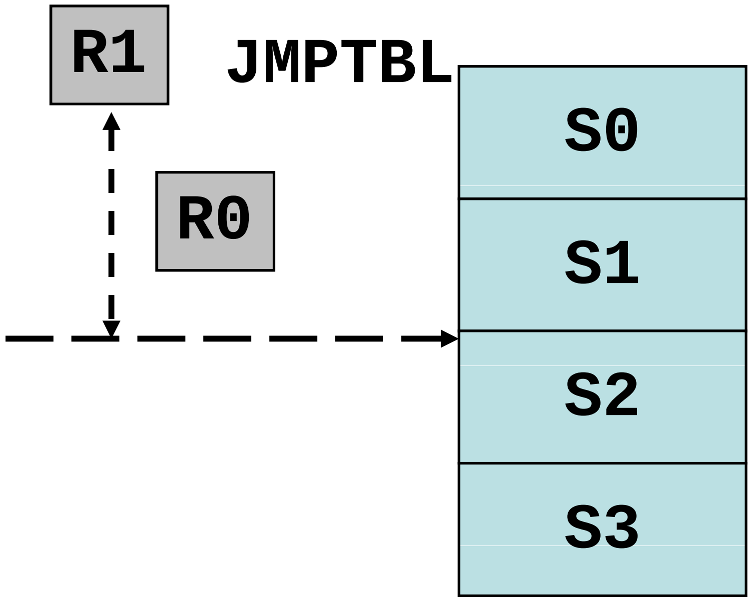
```
     CMP R0, #0
     BEQ S0
     CMP R0, #1
     BEQ S1
     CMP R0, #2
     BEQ S2
     CMP R0, #3
     BEQ S3
err: ...
     B exit
S0:  ...
     B exit
```

Switch statements

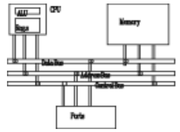
```
     ADR    R1, JMPTBL
     CMP    R0, #3
     LDRLS PC, [R1, R0, LSL #2]
err:...
     B      exit
S0: ...

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.

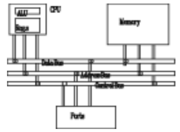


Iteration



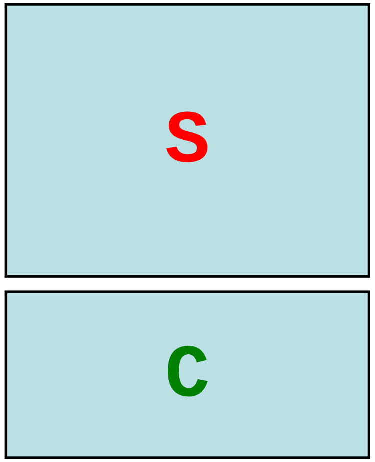
- repeat-until
- do-while
- for

repeat loops



`do {S} while ( C )`

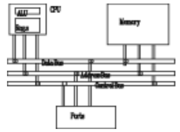
loop:



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; }
```

```
loop:    I
         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
loop:   CMP R1, #10
        BGE endfor
        @ do something
        ADD R1, R1, #1
        B   loop
endfor:
```

```
        MOV R1, #10
loop:


        @ do something
        SUBS R1, R1, #1
        BNE loop
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);
   ...
}
```

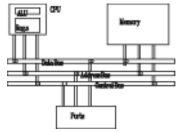
callee

parameters

caller

arguments

Procedures



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

        .end                        .end
```

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

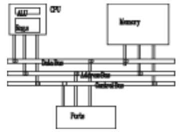
Procedures

main: caller | callee

```
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)



main: caller — callee

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

main: caller

```
        @ use R5
        BL func
        @ use R5

        .end
```

callee

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

        @restore R5
        .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
        BL func
        @ use R5
        ...
        ...
        .end

func:
        ...
        @ use R5
        ...
        ...
        .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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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

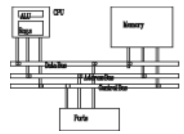
- Used to pass the first 4 parameters
- Caller-saved if necessary

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.

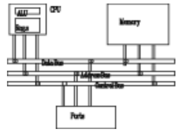
Argument passing

- 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)

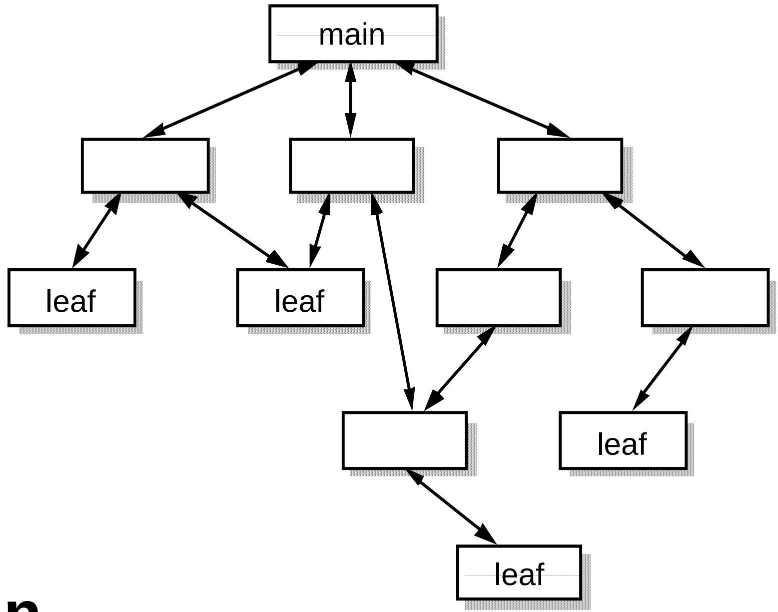
Function entry/exit



- 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
```



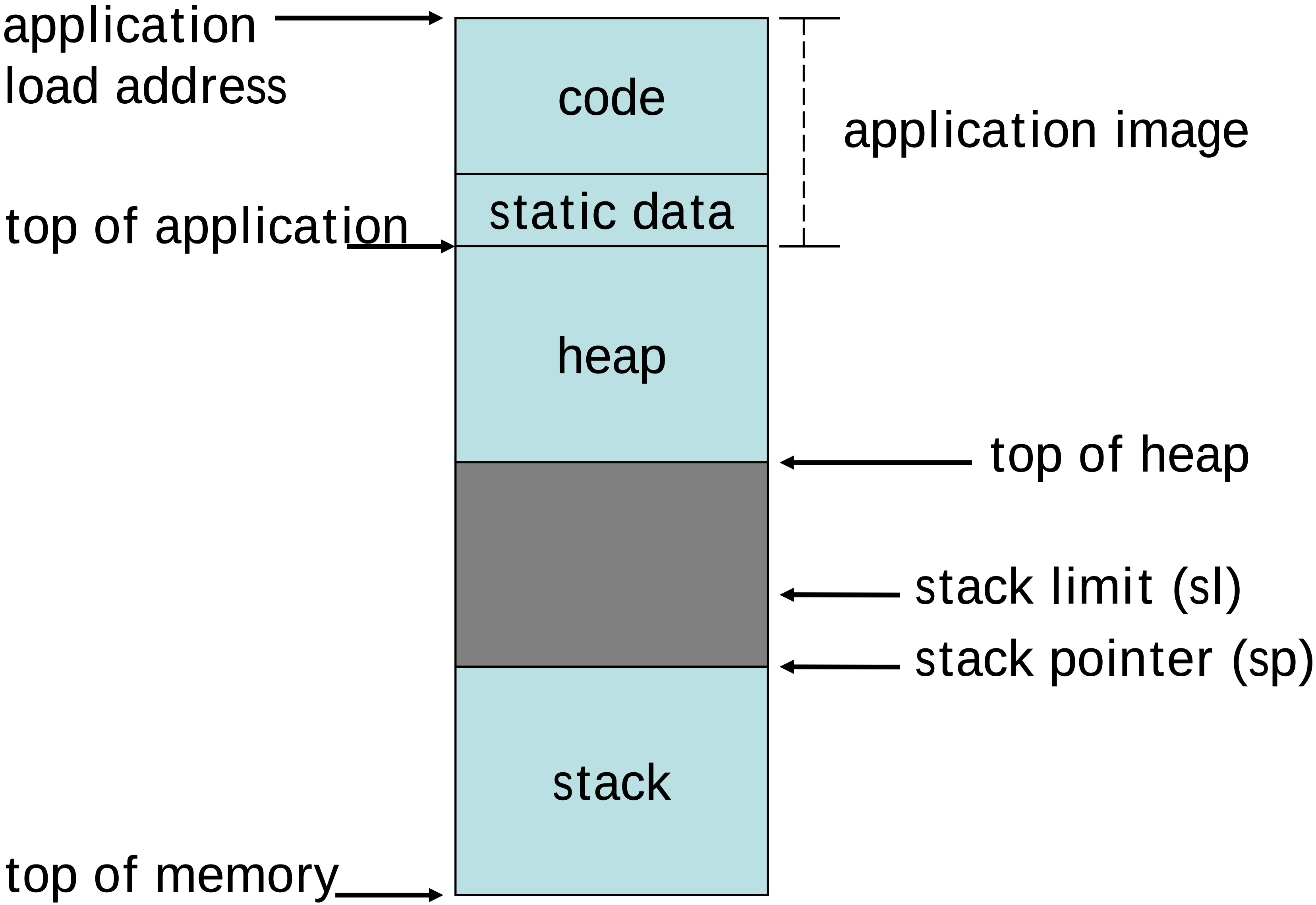
Function entry/exit

- 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

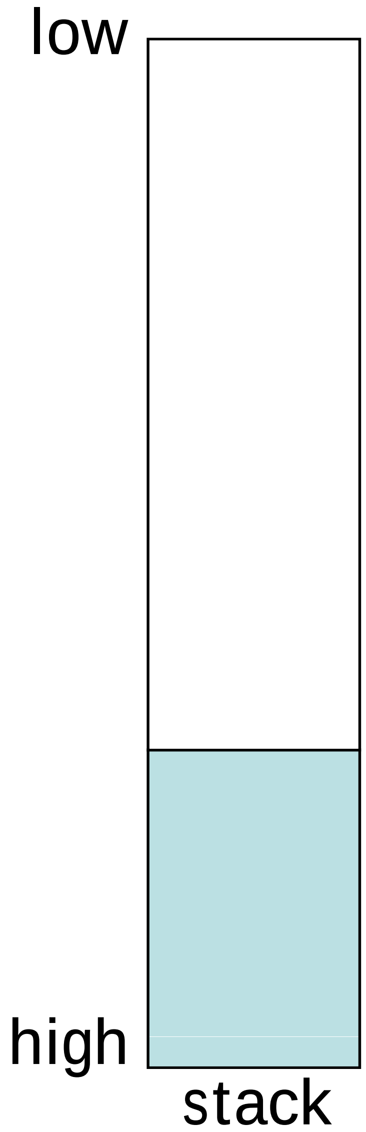


Accessing operands

- 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

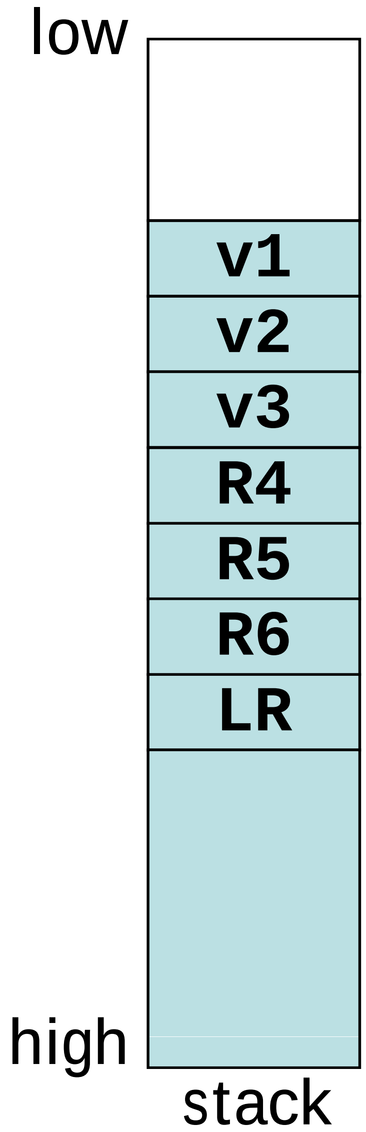
```
main:
        LDR    R0, #0
        ...
        BL     func
        ...
```



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}
```

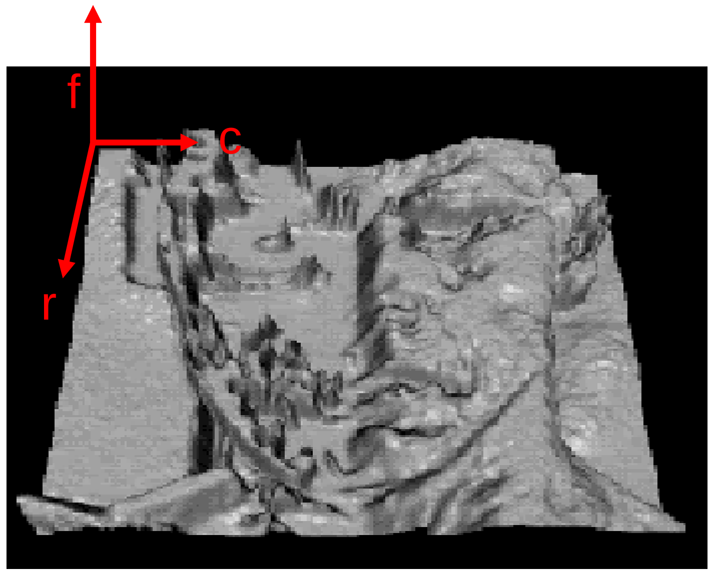


Assignment #3 Box Filter

Assignment #3 Box Filter

What is an image

- We can think of an **image** as a function, f: $R^2 \rightarrow R$:
  - $f(r, c)$ gives the **intensity** at position (r, c)
  - defined over a rectangle, with a finite range:
    - f: $[0, h-1] \times [0, w-1] \rightarrow [0, 255]$



A digital image

- The image can be represented as a matrix of integer values

$$k(r,c) = \frac{1}{(2M+1)(2N+1)} \sum_{r'=-M}^{M} \sum_{c'=-N}^{N} f(r+r', c+c')$$

c →

r ↓

110	110	100	100	100	100	100	100	100	100
120	130	100	100	100	100	100	100	100	100
110	100	100	100	130	110	120	110	100	100
100	100	100	110	90	100	90	100	100	110
130	100	100	130	100	90	130	110	120	100
100	100	100	120	100	130	110	120	110	100
100	100	100	90	110	80	120	100	100	100
100	100	100	100	100	100	100	100	100	100
100	100	100	100	100	100	100	100	100	100
100	100	100	100	100	100	100	100	100	100

Assignment #3 Box Filter

```
void boxfilter(u16 *ret,const u16* ori) {
        u32 r,g,b;
        u32 cc;
        int x,y,dx,dy;

        for(y=0;y<160;y++) {
            for(x=0;x<240;x++) {
                cc = r = g = b = 0;
            for(dy = -1;dy<=1;dy++) {
                    for(dx=-1;dx<=1;dx++) {
                        int nx = x+dx;
                        int ny = y+dy;
                    u16 ncolor;
                    if(nx < 0 || ny < 0 || nx >=240 || ny >= 160) continue;
                    ncolor = ori[ny*240+nx];
                    cc++;
                    r+= (ncolor&0x001f);
                    g+= ((ncolor&0x03e0)>>5);
                    b+= ((ncolor&0x7c00)>>10);
                }
            }
            r = r/cc;
            g = g/cc;
            b = b/cc;

            ret[y*240+x] = (b<<10)+ (g<<5) + r;
        }
    }

}
```