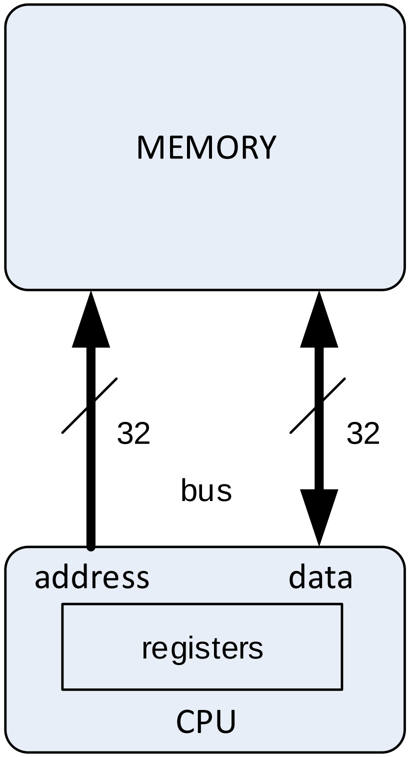
Simple Model of an ARM Microprocessor System

- comprises a central processing unit (CPU) and memory
- instructions and data are stored in memory
- the CPU reads instructions from memory (one after another) and executes them
- when the CPU executes an instruction
  - it performs operations between its registers OR
  - it reads data from memory and stores it in a register OR
  - it writes data from a register and stores it in memory



Memory

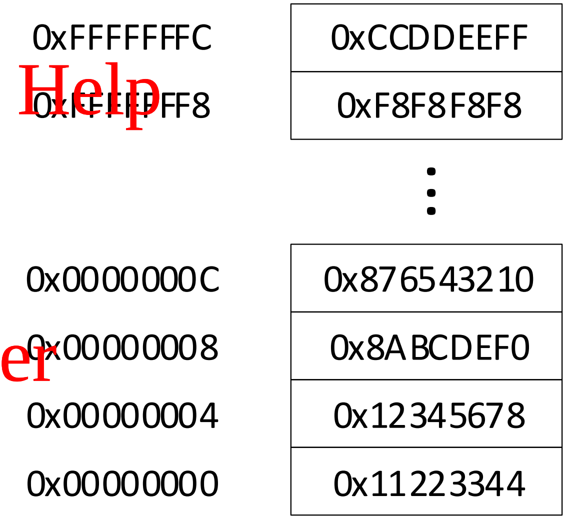
- memory comprises an array of memory locations
- each location stores a byte of data
- each location location has a unique 32 bit address 0x00000000 to 0xFFFFFFFF
- the address space, 2^{32} bytes (4GB), is the amount of memory that can be physically attached to the CPU
- the byte stored at each location may be part of an instruction (as each instruction is 4 bytes) **or** data

0xFFFFFFFF	0xFF
0xFFFFFFFE	0xEE
0xFFFFFFFD	0xDD
0xFFFFFFFC	0xCC
	⋮
0x00000005	0x05
0x00000004	0x04
0x00000003	0x11
0x00000002	0x22
0x00000001	0x33
0x00000000	0x44

memory as an
array of BYTEs

Memory

- often easier to view memory as an array of WORDs (32 bits) rather than an array of BYTEs
- as each WORD location is aligned on a 4 byte boundary, the low order 2 bits of each address is 0
- making a comparison with the previous slide, the byte of data stored at memory location 0 is the least significant byte of the WORD stored in location 0
- this way of storing a WORD is termed LITTLE ENDIAN - the least significant byte is stored at the lowest address (the other way is BIG ENDIAN)
- ARM CPUs can be configured to be LITTLE ENDIAN or BIG ENDIAN (term from Gulliver's Travels)



0xFFFFFFFC	0xCCDDEEFF
0xFFFFFFF8	0xF8F8F8F8
	⋮
0x0000000C	0x876543210
0x00000008	0x8ABCDEF0
0x00000004	0x12345678
0x00000000	0x11223344

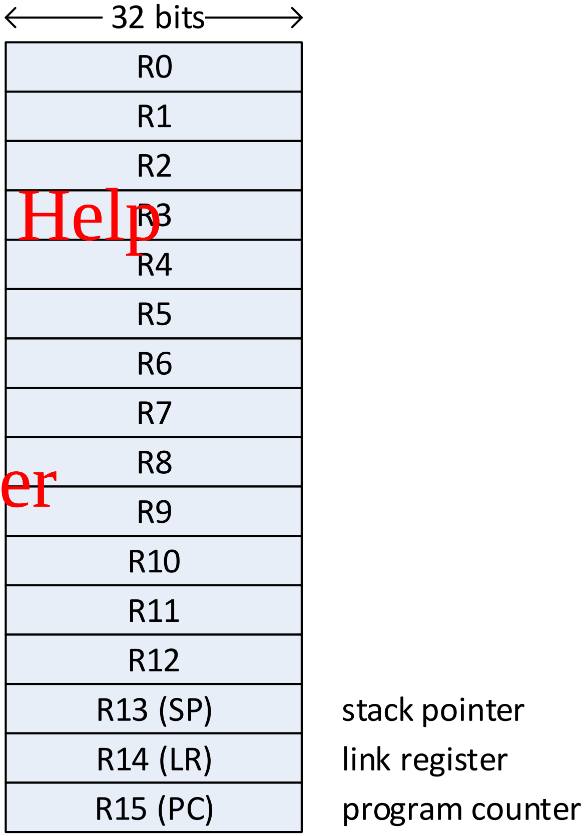
memory as an array of WORDs

ARM CPU Registers

- the ARM CPU contains 16 x 32bit registers R0 to R15
- data can be read from memory and stored in a register
- data in a register can be written to memory
- arithmetic operations can be performed between the registers

```
ADD   R0, R1, R2                ; R0 = R1 + R2
```

- R0 to R12 are considered general purpose registers
- R13, R14 and R15 are specialised
- registers are far quicker to access than memory



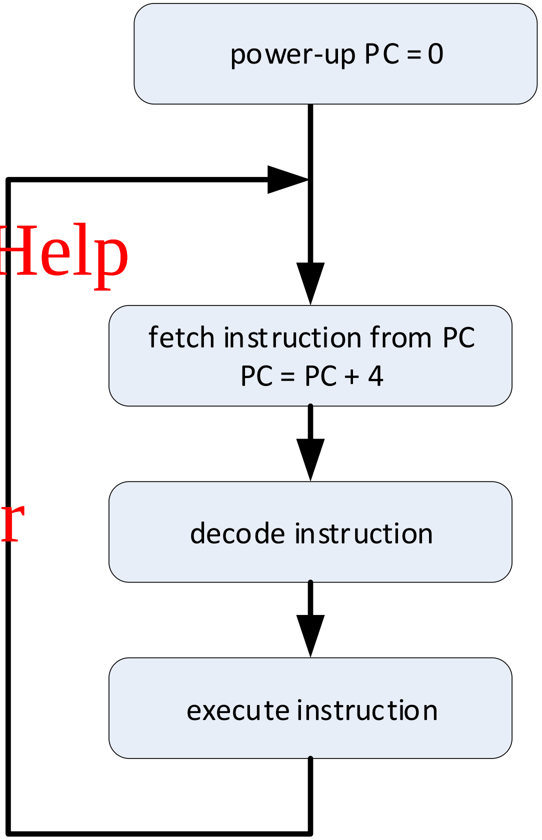
32 bits

R0	
R1	
R2	
R3	
R4	
R5	
R6	
R7	
R8	
R9	
R10	
R11	
R12	
R13 (SP)	stack pointer
R14 (LR)	link register
R15 (PC)	program counter

ARM CPU registers

Program Execution

- the CPU continuously fetches, decodes and executes instructions stored in memory at the address specified by the Program Counter (R15 or PC)
- on power-up, the PC is initialised to 0 so that the first instruction executed is a memory address 0
- after fetching each instruction, 4 is added to the PC so that the PC contains the address of the next sequential instruction (ALL instructions are 4 bytes)
- CPU keeps fetching, decoding and executing instructions until it is switched off



ARM data processing instructions

- consider the following ARM assembly language instructions

ADD - add
SUB - subtract
RSB - reverse subtract
MOV – move
MUL - multiply

- three address instructions, need to specify dst, src1 and src2 registers

```
ADD     R0, R1, R2      ; R0 = R1 + R2 (R0:dst R1:src1 R2:src2)
SUB     R0, R1, R2      ; R0 = R1 – R2
RSB     R0, R1, R2      ; R0 = R2 – R1
MOV     R0, R1          ; R0 = R1 (makes a copy of R1, src1 ignored)
MUL     R0, R1, R2      ; R0 = R1 * R2 (NB: dst and src1 registers cannot be the same)

ADD     R0, R0, R0      ; R0 = R0 + R0
```

Immediate src2 Operand

- the src2 operand can be a register **OR** a constant value
- there are limitations to the constant values that can "fit" in src2 field (these will be explained later)
- the fall-back position is to use a LDR instruction as it can load a register with any 32bit constant (also explained later)

```
ADD  R0, R1, #1         ; R0 = R1 + 1
ADD  R2, R3, #0x0F      ; R2 = R3 + 0x0F
SUB  R1, R1, #2         ; R1 = R1 – 2
MOV  R0, #3             ; R0 = 3
```

- note the # symbol – means an immediate constant
- MUL instruction is an exception, src2 cannot be an immediate constant

ARM LDR instruction

- LDR can be used to load an immediate (or constant) value into a register

```
LDR    R0, =0x1234          ; R0 = 0x1234
```

- = symbol for an immediate LDR operand, other instructions use the # symbol

- ; indicates the start of a comment

- LDR is not quite what it seems, explained in more detail later

ARM data processing example

- if x = 50, compute $x^2 + 10*x - 3$

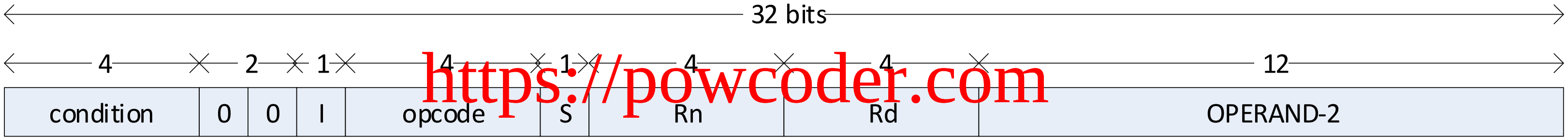
- need to decide how best to use the registers
- compute result in R0
- use R1 to hold x
- use R2 as a temporary register for performing the computation

```
MOV  R1, #50         ; R1 = x = 50
MUL  R0, R1, R1      ; R0 = x^2
MOV  R2, #10         ; R2 = 10
MUL  R2, R1, R2      ; R2 = 10x (MUL R2, R2, R1 would not work)
ADD  R0, R0, R2      ; R0 = x^2 + 10x
SUB  R0, R0, #3      ; R0 = x^2 + 10x - 3
```

- work around limitations of MUL instruction
  - dst and src1 cannot be the same register
  - src2 cannot be an immediate constant

Assembly Language => Machine Code Example

- assembly language instructions are converted into machine code by the assembler
- the CPU fetches, decodes and executes machine code instructions stored in memory
- each machine code instruction is 4 bytes (32 bits)
- the 32-bit machine code instruction encodes the operation (eg ADD) and operands



32 bits

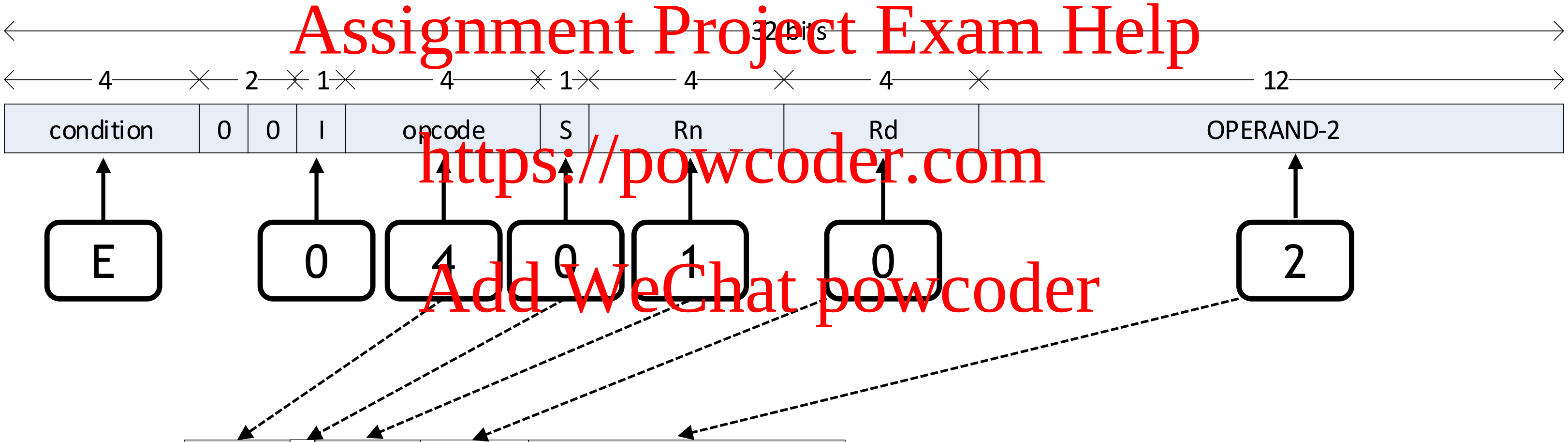
4	2		1	4	1	4	4	12
condition	0	0	I	opcode	S	Rn	Rd	OPERAND-2

- 4 bit condition field (instruction can be conditionally executed, if value = 0xE instruction always executed)
- single I bit which determines how the OPERAND-2 field is interpreted
- 4 bit opcode field specifying the operation (16 possible operations)
- single S bit which determines if the instruction updates the condition codes
- 4 bit Rn field specifying src1 register (R0 .. R15)
- 4 bit Rd field specifying dst register (R0 .. R15)
- 12 bit src2 field (if I bit = 0 interpreted as a register or if I = 1 as an immediate value)
- fields will be described in more detail later in module

Assembly Language => Machine Code

De
Op
Ro

- what is the machine code for ADD R0, R1, R2



- 1110 0000 1000 0001 0000 0000 0000 0010$_2$
- 0xE0810002

- don’t have to remember the machine code, but looking at how instructions are encoded can help with figuring out what the instruction can do

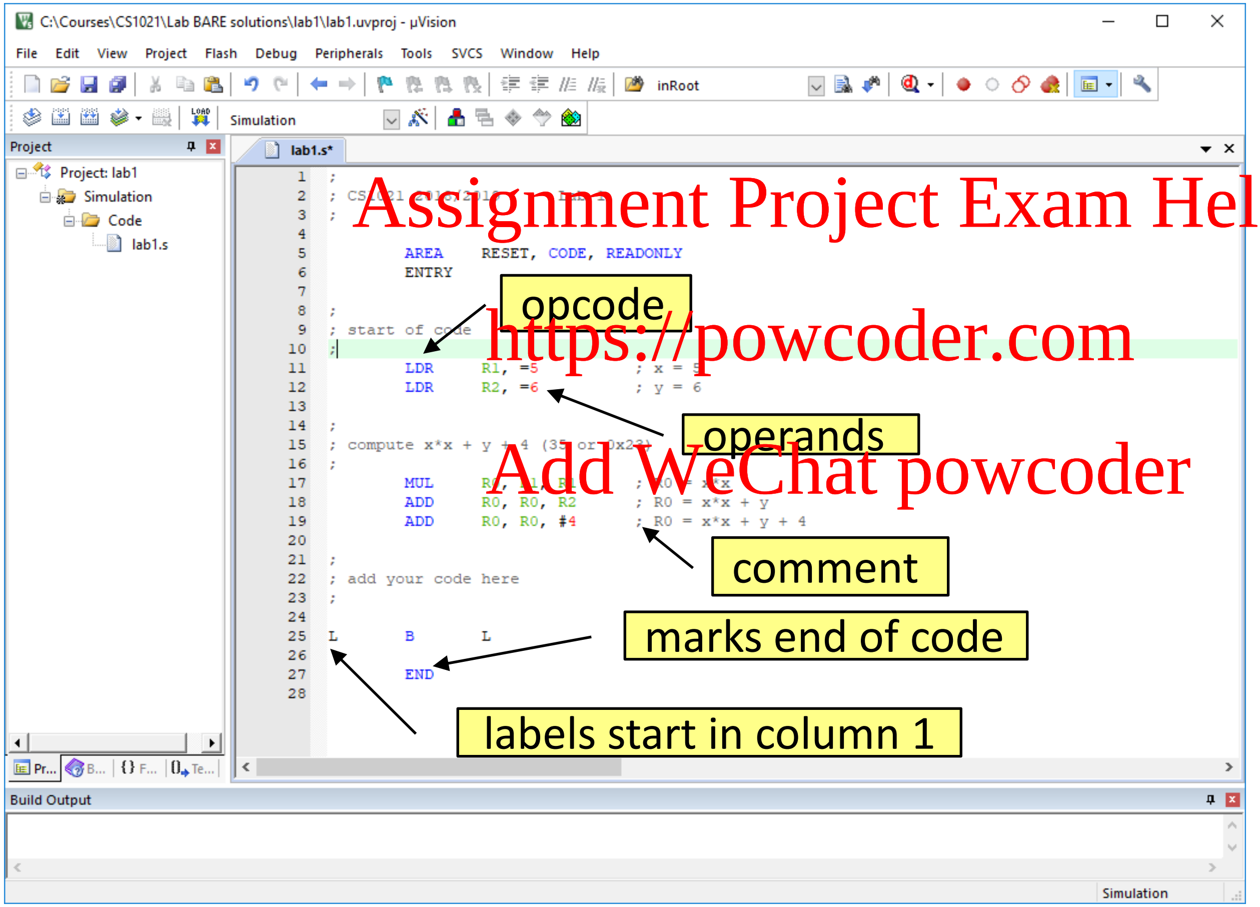
Writing Assembly Language Programs

- writing programs using machine code is possible, but NOT practical
- much easier to write programs using assembly language
  - instructions are written using mnemonics (ADD instead 0x04, R2 instead of 0x2, …)

- assembly language translated into machine code by the assembler, stored in memory and then executed by CPU
- ARM assembly opcodes and operands NOT case sensitive
- one assembly language instruction per line
- labels start in column 1, otherwise leave blank except if a comment
- opcode followed by operands (separated by commas)
- comments start with a semicolon

ARM Assembly Language

Writing Assembly Language Programs


C:\Courses\CS1021\Lab BARE solutions\lab1\lab1.uvproj - µVision
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
inRoot
Simulation
Project
Project: lab1
Simulation
Code
lab1.s
lab1.s*
Build Output
Simulation

```
;
; CS1021 2018/2019 Lab 1
;

        AREA    RESET, CODE, READONLY
        ENTRY

;
; start of code
;
        LDR     R1, =5          ; x = 5
        LDR     R2, =6          ; y = 6

;
; compute x*x + y + 4 (35 or 0x23)
;
        MUL     R0, R1, R1      ; R0 = x*x
        ADD     R0, R0, R2      ; R0 = x*x + y
        ADD     R0, R0, #4      ; R0 = x*x + y + 4

;
; add your code here
;

L       B       L

        END

```

opcode

operands

comment

marks end of code

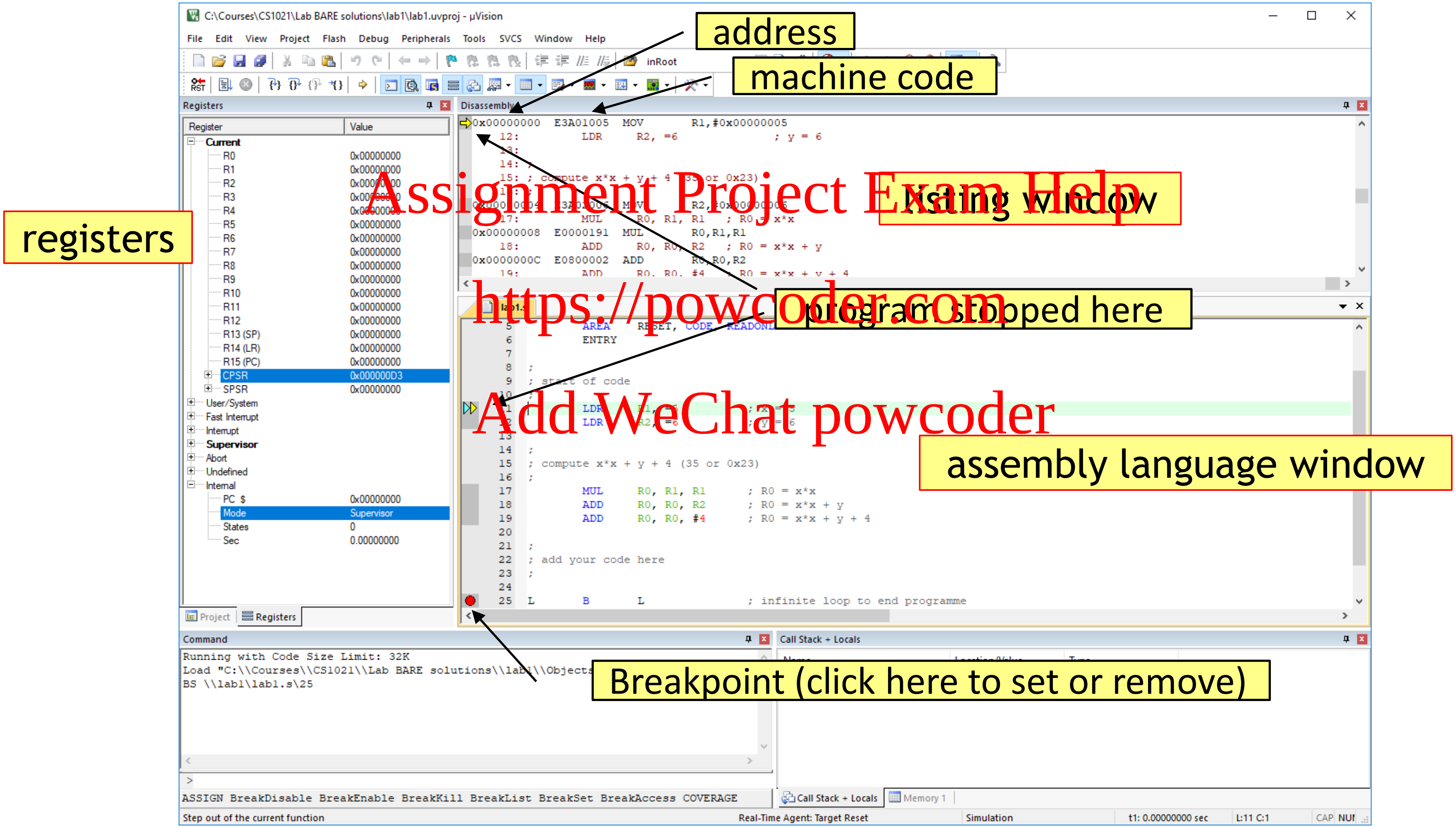
labels start in column 1

Executing/Debugging Assembly Language Programs

- build target [Project][Build Target]
- correct any assembly language errors and **REBUILD**

- run program [Debug][Start/Stop Debug Session]
- programs stops before first instruction executed

Executing/Debugging Assembly Language Programs



C:\Courses\CS1021\Lab BARE solutions\lab1\lab1.uvproj - µVision
File Edit View Project Flash Debug Peripherals Tools SVCS Window Help
inRoot
Registers
Disassembly
lab1.s
Project
Registers
Command
Call Stack + Locals
Memory 1
address
machine code
registers
listing window
program stopped here
assembly language window
Breakpoint (click here to set or remove)

Register	Value
Current	
R0	0x00000000
R1	0x00000000
R2	0x00000000
R3	0x00000000
R4	0x00000000
R5	0x00000000
R6	0x00000000
R7	0x00000000
R8	0x00000000
R9	0x00000000
R10	0x00000000
R11	0x00000000
R12	0x00000000
R13 (SP)	0x00000000
R14 (LR)	0x00000000
R15 (PC)	0x00000000
CPSR	0x000000D3
SPSR	0x00000000
User/System	
Fast Interrupt	
Interrupt	
Supervisor	
Abort	
Undefined	
Internal	
PC $	0x00000000
Mode	Supervisor
States	0
Sec	0.00000000

```
0x00000000  E3A01005  MOV      R1,#0x00000005
    12:          LDR     R2, =6              ; y = 6
    13:
    14: ;
    15: ; compute x*x + y + 4 (35 or 0x23)
    16: ;
0x00000004  E3A02006  MOV      R2,#0x00000006
    17:          MUL     R0, R1, R1    ; R0 = x*x
0x00000008  E0000191  MUL      R0,R1,R1
    18:          ADD     R0, R0, R2    ; R0 = x*x + y
0x0000000C  E0800002  ADD      R0,R0,R2
    19:          ADD     R0, R0, #4    ; R0 = x*x + y + 4
```

```
        AREA    RESET, CODE, READONLY
        ENTRY

;
; start of code
;
        LDR     R1, =5          ; x = 5
        LDR     R2, =6          ; y = 6

;
; compute x*x + y + 4 (35 or 0x23)
;
        MUL     R0, R1, R1      ; R0 = x*x
        ADD     R0, R0, R2      ; R0 = x*x + y
        ADD     R0, R0, #4      ; R0 = x*x + y + 4

;
; add your code here
;

L       B       L               ; infinite loop to end programme
```

```
Running with Code Size Limit: 32K
Load "C:\\Courses\\CS1021\\Lab BARE solutions\\lab1\\Objects
BS \\lab1\\lab1.s\25
>
ASSIGN BreakDisable BreakEnable BreakKill BreakList BreakSet BreakAccess COVERAGE
```

Step out of the current function   Real-Time Agent: Target Reset   Simulation   t1: 0.00000000 sec   L:11 C:1   CAP NUI

Executing/Debugging Assembly Language Programs

- press F11 or [Debug][Step] to single step one instruction at a time
- check instruction execution by examining register contents (remember register contents in hexadecimal)

- set breakpoints (red circle) by clicking on assembly language instruction (left hand side of assembly language window)
- press F5 or [Debug][Run] to run to next breakpoint (or forever if no breakpoint hit)
- check instruction execution by examining register contents

- break program in to sections and get each section working before moving on to next section

- [Debug][Start/Stop Debug Session] to exit debug session

Some Assembly Language Programming Guidelines

- comment every line of code with a helpful comment
- assume someone else may be reading your code

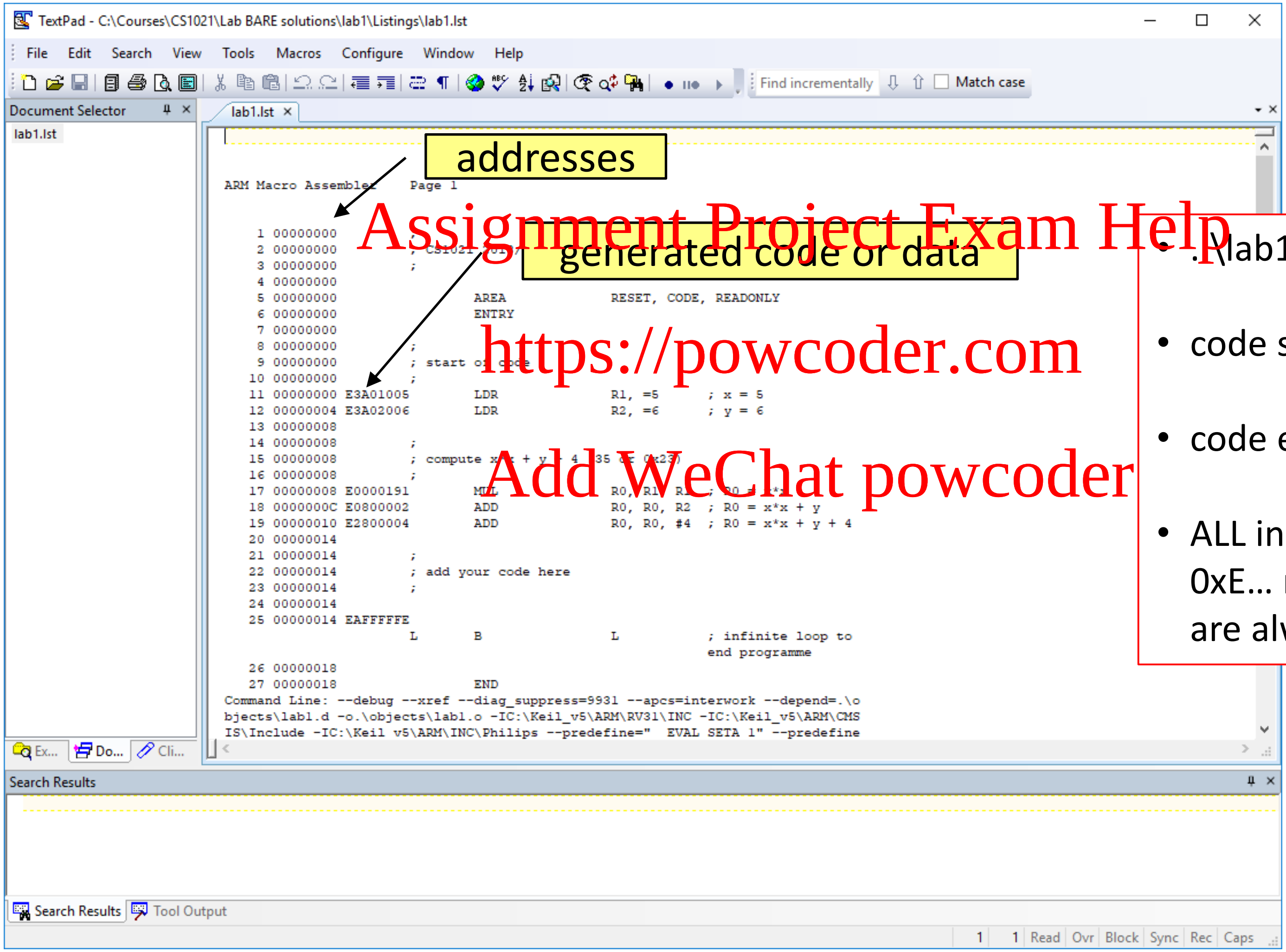
```
ADD  R0, R0, R2            ; R0 = R0 + R2                - poor
ADD  R0, R0, R2            ; R0 = x*x + 10x + 3          - better
```

- break your programs into small sections, separated by blank lines or comments
- try to keep your programs simple and easy to follow
- use TABs to align operator, operands and comments into columns
- tidy code = tidy mind

- remember to initialise values in registers and memory
- don't assume everything is set to zero when you start or switch on

ARM Assembly Language

Assembly Language Listing


TextPad - C:\Courses\CS1021\Lab BARE solutions\lab1\Listings\lab1.lst
File Edit Search View Tools Macros Configure Window Help
Find incrementally
Match case
Document Selector
lab1.lst
addresses
generated code or data
Search Results
Tool Output
1 1 Read Ovr Block Sync Rec Caps

```
ARM Macro Assembler    Page 1


    00000000          ;
    00000000          ; CS1021 2017
    00000000          ;
    00000000
    00000000                  AREA            RESET, CODE, READONLY
    00000000                  ENTRY
    00000000
    00000000          ;
    00000000          ; start of code
    00000000          ;
    00000000 E3A01005         LDR             R1, =5       ; x = 5
    00000004 E3A02006         LDR             R2, =6       ; y = 6
    00000008
    00000008          ;
    00000008          ; compute x*x + y + 4 (35 or 0x23)
    00000008          ;
    00000008 E0000191         MUL             R0, R1, R1  ; R0 = x*x
    0000000C E0800002         ADD             R0, R0, R2  ; R0 = x*x + y
    00000010 E2800004         ADD             R0, R0, #4  ; R0 = x*x + y + 4
    00000014
    00000014          ;
    00000014          ; add your code here
    00000014          ;
    00000014
    00000014 EAFFFFFE
                      L       B               L           ; infinite loop to
                                                          end programme
    00000018
    00000018                  END
Command Line: --debug --xref --diag_suppress=9931 --apcs=interwork --depend=.\o
bjects\labl.d -o.\objects\labl.o -IC:\Keil_v5\ARM\RV31\INC -IC:\Keil_v5\ARM\CMS
IS\Include -IC:\Keil v5\ARM\INC\Philips --predefine="  EVAL SETA 1" --predefine
```

- .\lab1\Listings\lab1.lst
- code starts at 0x00000000
- code ends at 0x00000017
- ALL instructions start with 0xE… meaning that they are always executed

This week's Tutorial and Lab

- will put this week's lecture notes on CS1021 web site today
- look at the this week's notes before Thursday's tutorial
- lab1 this Friday - you'll write your first assembly language program
- will put the lab question on the CS1021 web site on Thursday, so take some time to look at it in advance so you know what you have to do