COMP2300/6300

Computer Organisation and Programmation

Data structures

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Semester 1, 2022

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Week 7: Data Structures

- why do we need data structure
- arrays
- records
- memory allocation

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Admin Time

Assignment 1 results

Mid-semester Exam

Psyche up for second half of the course

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Why do we need data structures?

to structure our **data** (um, ok…)

to minimise bookkeeping

to make our lives easier

to play nicely with others

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Arrays

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Arrays are for collections of homogeneous data

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Wikipedia has more (as usual)

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You might need an array if you've got

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- a string of ASCII characters (re houty McShoutface?)
- an audio file (e.g. an array of 1 d values to “send” to an audio output)
- a collection of red-green-blue (3 x 8-bit unsigned) values which represent a bitmap image

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Essential information for an array

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An array is just a bunch of things. There are the key things to figure out:

- what are the things?
- where are the things?
- how big are the things?
- how many things are there?

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Can you fit an array into a register?

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probably not

need to store it in memory

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Addressing

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Array addressing is about readin ng specific elements of the array

also called *indexing* (Latin: *indic* t, show")

```
//                the index
//                    ↓
int x = the_things[0]; // the 1st element
int y = the_things[4]; // the 5th element
```

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In assembly code

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it's just **loads and stores** (like you [illegible] oing all along)

```
   .data
the_things:
   .word 2, 3, 0, 0, 6, 3, 0, 0

   .text
get_elements:
   ldr r0, =the_things
   ldr r1, [r0]      @ the 1st element
   ldr r2, [r0, 16] @ the 5th element
```

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Alignment

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talk

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what's the big deal? why are una ds/stores a problem?

hint: check out the Cortex M4 Tec erence Manual section on **load store timings**

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you can put *anything* in an array, not just words

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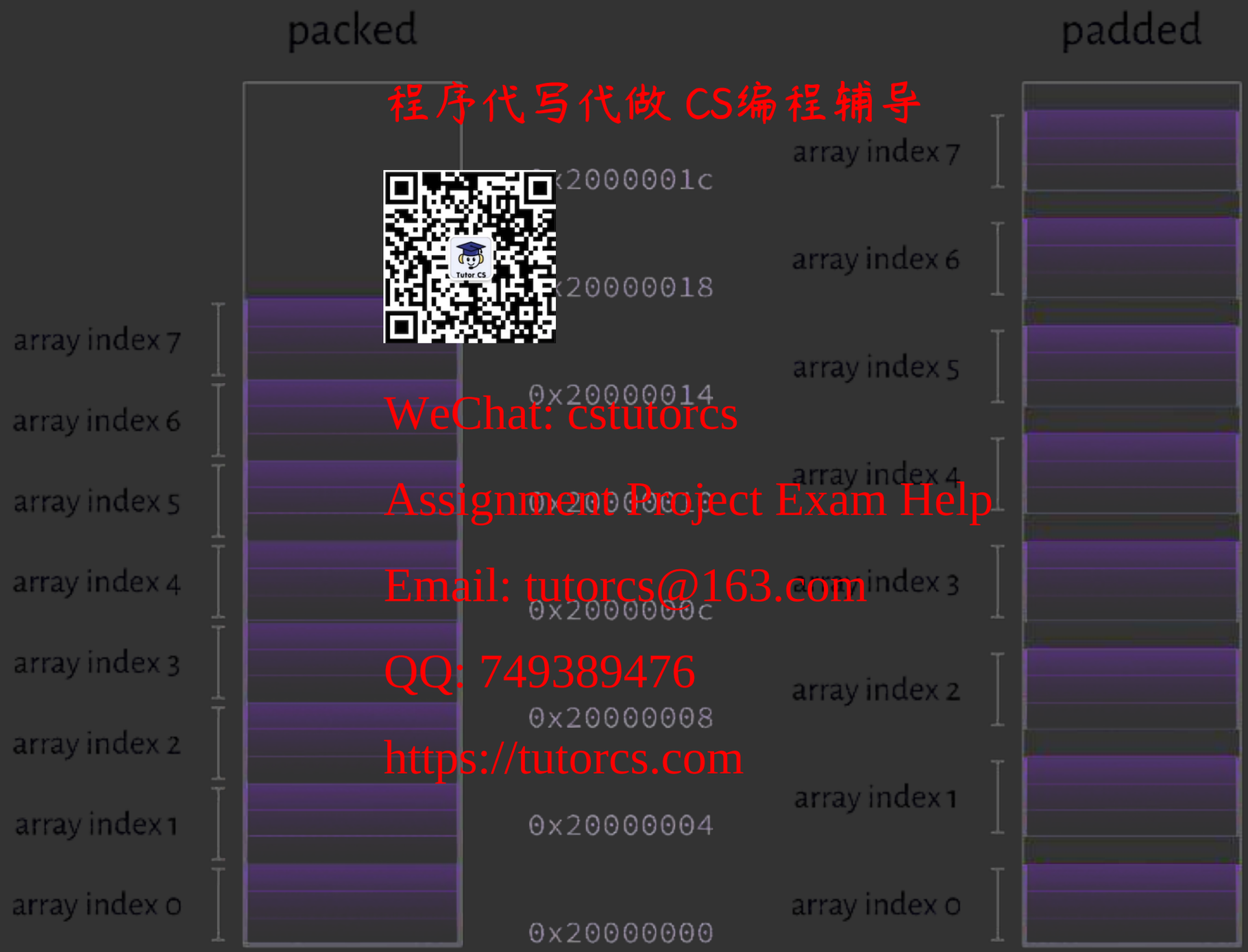

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abstract data type

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data structure

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Working with arrays

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they don’t fit in registers, so we h[illegible]rate on them one element at a time

we need **loops**!

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Array sum example

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given an array of (word-size) inte[illegible]he sum of the elements from `from_index` to `to_index`

```
int sum(int array[], int from_index, int to_index){
  int acc = 0; // the "accumulator" variable
  for(int i = from_index; i <= to_index; i++){
    acc += array[i];
  }
  return acc;
}
```

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The array in memory

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```
  .data
array:
  .word 2, 3, 0, 0, 6, 0
```

back-of-the-envelope maths: the sum is 14 (0xE)

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Array sum setup

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For the following examples, assu

- the base address of the array i
- the from (start) index is in `r1` (0 in the setup code below)
- the to (end) index is in `r2` (7 in the setup code below)

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```
ldr r0, =array @ base address
mov r1, 0      @ from_index
mov r2, 7      @ to_index
```

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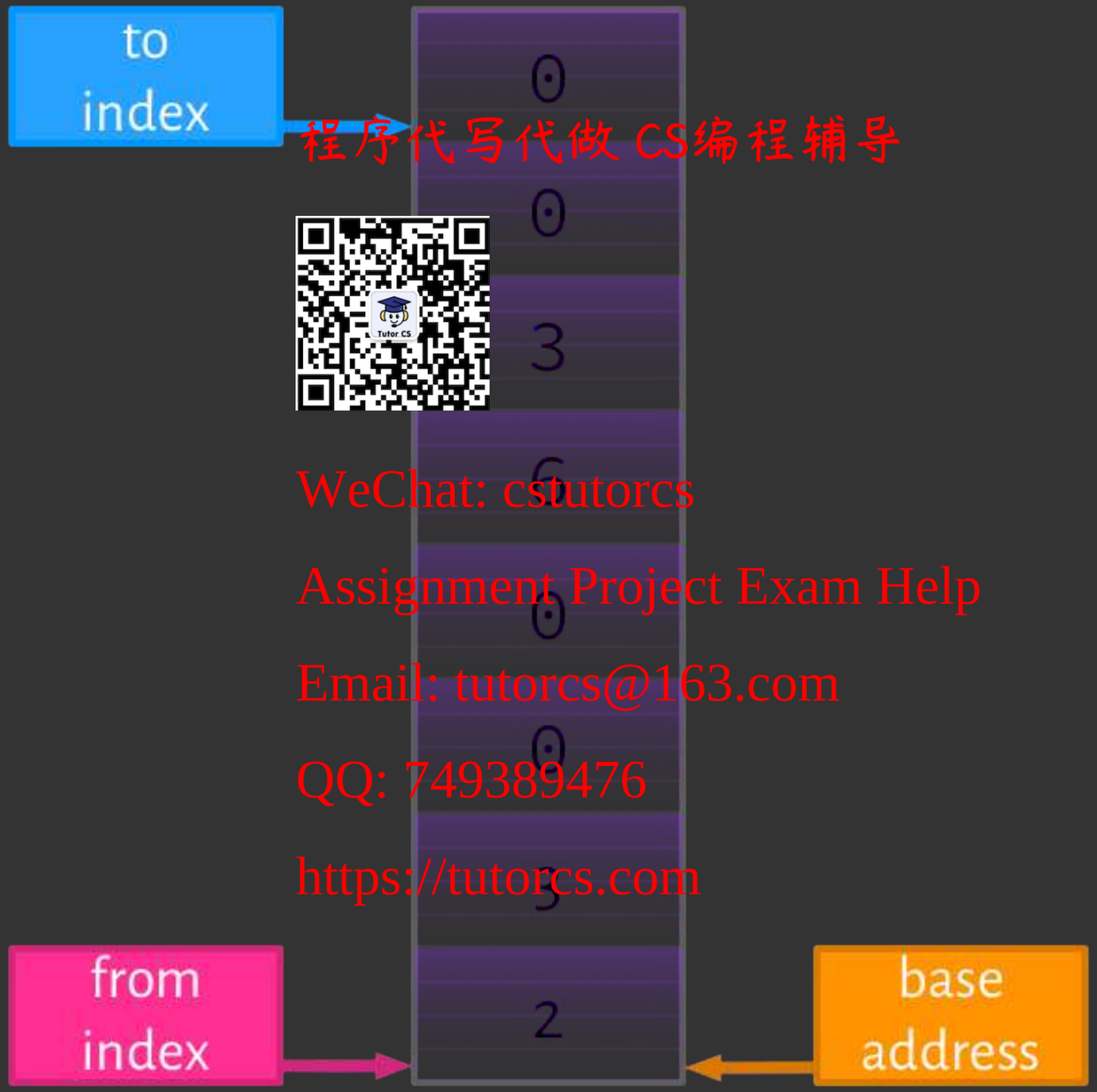

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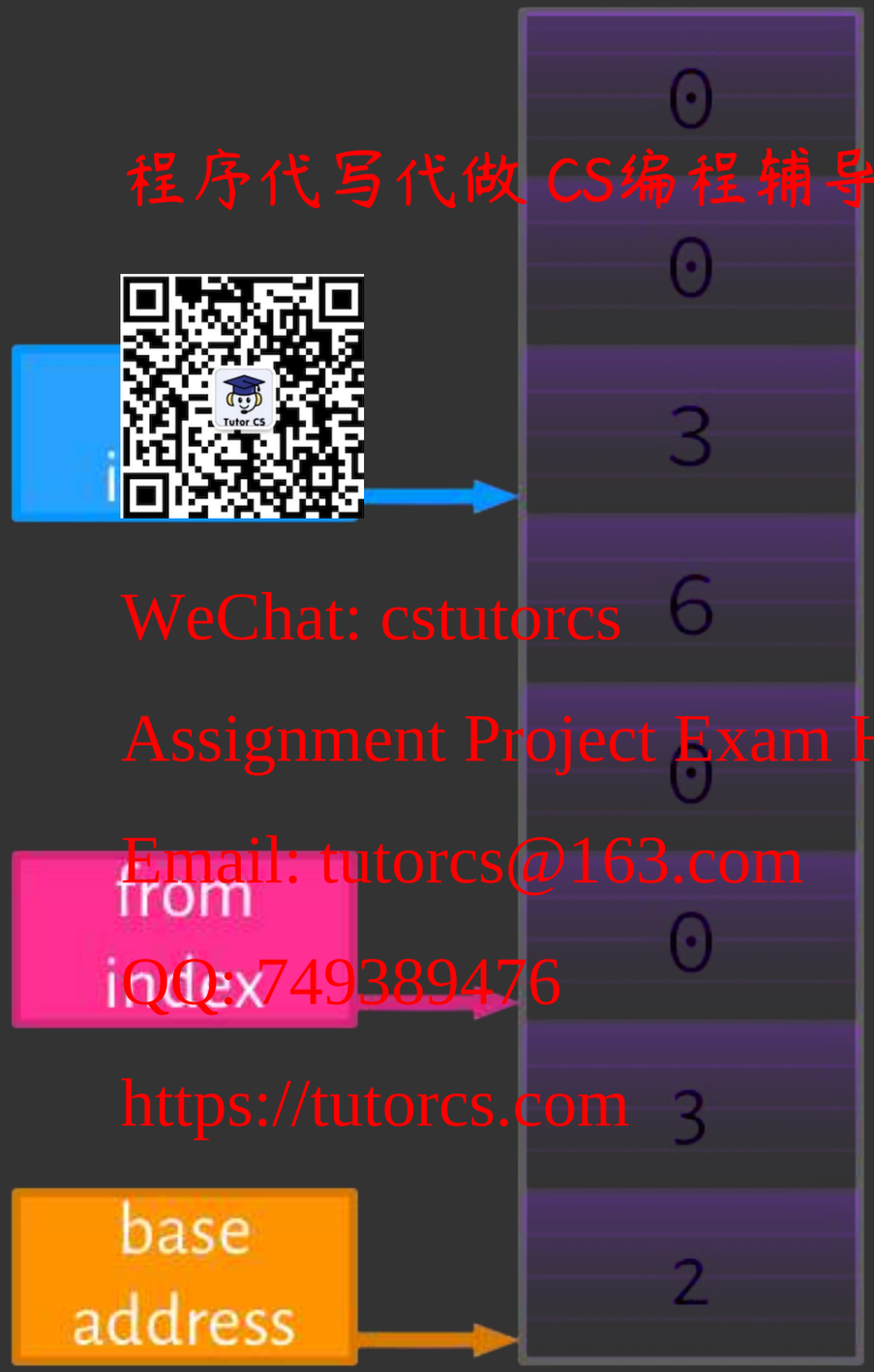

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Array sum #1

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```
@ setup
  mov r3, 0 @ "accumulator"
  mov r4, 4 @ element size

array_sum:
  mul r5, r1, r4    @ calculate offset
  ldr r6, [r0, r5]  @ load from offset
  add r3, r6        @ update accumulator
  add r1, 1         @ increment index
  cmp r1, r2        @ keep looping?
  ble array_sum

@ cleanup
  mov r0, r3
```

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2 instructions in setup, 6 in loop

Array sum #2

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```
@ setup
  mov r3, 0 @ acc

array_sum:

  @ load with shifted index register
  ldr r6, [r0, r1, lsl 2]
  add r3, r6      @ update running total
  add r1, 1       @ increment index
  cmp r1, r2      @ keep looping?
  ble array_sum

@ cleanup
end_array_sum:
mov r0, r3
```

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1 instruction in setup, 5 in loop, no need to explicitly calculate the offset (but size must be power of 2)

Array sum #3

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```
@ setup
  mov r3, 0      @ acc
  lsl r1, r1, 2 @ change inc set
  lsl r2, r2, 2 @ change inc set

array_sum:
  ldr r6, [r0, r1]
  add r3, r6     @ update running total
  add r1, 4      @ increment index
  cmp r1, r2
  ble array_sum

@ cleanup
mov r0, r3
```

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3 instruction in setup, 5 in loop

uses byte offset instead of element index

talk

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any more ideas for how we coulc s up?

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Array sum #4

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```
@ setup
  mov r3, 0       @ acc
  lsl r1, r1, 2   @ change in[illegible]fset
  add r1, r0, r1  @ address o[illegible]ement

  lsl r2, r2, 2   @ change index -> offset
  add r2, r0, r2  @ address of to element

array_sum:
  ldr r6, [r1], 4 @ load & post-index r1
  add r3, r6      @ update running total
  cmp r1, r2
  ble array_sum

@ cleanup
  mov r0, r3
```

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5 instructions in setup, **only 4 in loop**, note the **load with post-index**

On optimisation…

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loops are often the “hot” part of , therefore worth optimising

optimising compilers will do som ings to get the most optimised code

in general, write simple code first, and optimise later (if necessary)

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Gotchas

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- don't forget about **endianness**
- remember, `ldr`/`str` still ju **rds**, not elements (it's convenient if your elements are word-sized, but f they're not)
- no bounds checking so far!
- we weren't careful about the **AAPCS** in our array sum examples earlier

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Memory allocation for arrays

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static: memory is set aside at co (e.g. in the `.data` section)

- *pro*: allocation is already done program starts
- *con*: need to know the size of the array in advance

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dynamic: memory is made available (e.g. on the stack) at run-time

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- *pro*: can pick the best size at runtime, can re-size

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- *con*: takes time (while program is running)

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we'll return to this later…

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Better(?) array data structures

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The arrays we've looked at so far are bare-bones; containing just the raw data (at runtime, anyway)

there are several improvements

- null-termination
- store array size alongside the data
- can we make a resizeable array?

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Where are the array(s)?

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Records

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Records are for collections of heterogeneous data

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Wikipedia says:

A **record** is a collection of **fields**, possibly of different data types, typically in fixed number and sequence. The fields of a record may also be called members, … or elements, though these risk confusion with the elements of a collection.

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Overloaded names!

records might also be referred t s, tuples, objects

(although those terms can also mean different things)

context matters

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Array

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Simple examples

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Suppose we are making charact a computer game:

- HP (word)
- mana (word)
- name (16-byte, null-terminated ASCII array)

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Or a basic synthesizer

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- frequency (word)
- phase (word)
- amplitude (word)
- type (halfword)

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Field ordering

what's the difference here?

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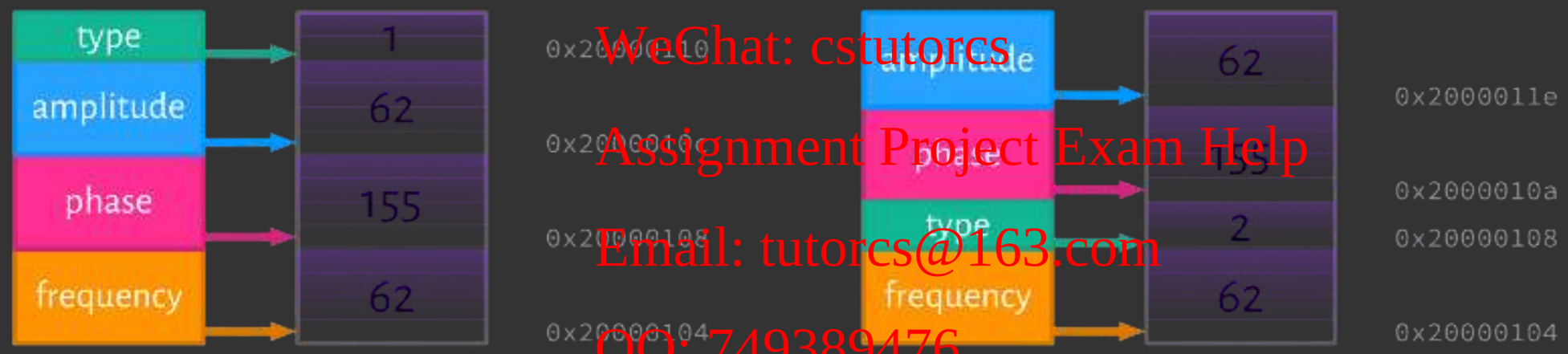

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the address of the first element is all you need

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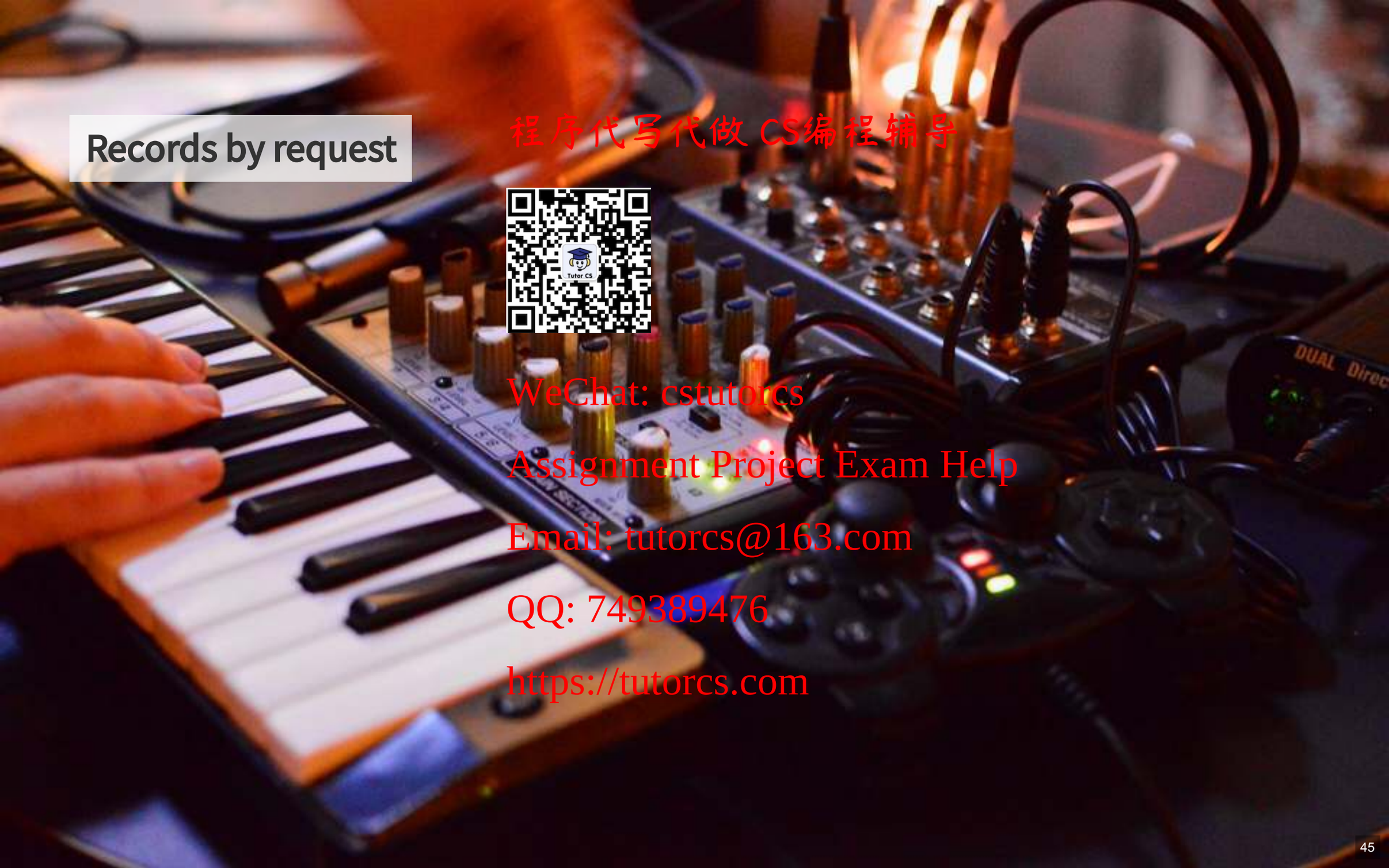

Records by request

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Composite data structures

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Things really get interesting and [illegible]n we combine things

- records inside records (nested
- records of arrays
- arrays of records

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Are these things OO *objects*? No. They have the variables but not the methods.

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Memory Allocation

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talk

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what does it mean to allocate memory for an array?

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`smalloc` (silly memory allocate)

Let's make a silly memory alloc

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Describing the `smalloc` function

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At a *minimum*, our memory allocation must

- take (as an input parameter) the number of bytes to allocate
- return a memory address which points to that many bytes of **free** memory

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there are many other things it could do, but this will do for now

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Silly Malloc

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```
@ r0 param is number o                    to allocate returns a memory addre
.type smalloc, %functi
smalloc:

  push {r0} @ just save r0 for a sec
  ldr r3, =smalloc_value
  ldr r0, [r3] @ get latest free memory address, this is the ret
  pop {r1} @ get back parameter
  add r1, r1, r0 @ new "smalloc value", just move it along by re
  str r1, [r3] @ save new smalloc_value
  bx lr
.size smalloc, . - smalloc

.data
smalloc_value:
.word 0x20000004 @ 4 because it starts AFTER this word!
```

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Real `malloc`

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real operating systems provide a function for dynamically allocating memory which sortof works like this, but tter:

- allows you to “release” memory after you’re done with it
- keeps track of the memory allocations using metadata
- (tries to) gracefully fail when it can’t give you enough memory

although it’s implementation dependent

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Data structures and argument passing

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how would you pass an array or an argument to a function? how about as a return value?

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it's alive

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Records as function parameters

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imagine an `is_alive` function

- takes one parameter: a *hearth* *aracter* data structure
- returns a (word-sized) `0` if the character is dead, and `1` if the character is alive

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```
  .data
zoltan_the_magnificent:
@ initialise hp and mana
  .word 100, 200 @ more mana because wizard
```

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It's alive #1: pass character in registers

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```
is_alive:
  movs r0, r0 @ cheeky trick
  mov r0, 0
  ble end_is_alive

  mov r0, 1
end_is_alive:
  bx lr

@ call
  ldr r2, =zoltan_the_magnificent
  ldr r0, [r2]     @ hp
  ldr r1, [r2, 4] @ mana
  bl is_alive
```

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It's alive #2: pass character on stack

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```
is_alive:
  pops {r0,r1} @ read args c
  mov r0, 0
  ble end_is_alive

  mov r0, 1
end_is_alive:
  bx lr

@ call (including copy record onto the stack)
@ for larger records this might require a loop
  ldr r2, =zoltan_the_magnificent
  ldr r0, [r2]
  ldr r1, [r2, 4]
  push {r0,r1}
  bl is_alive
```

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It's alive #3: pass character by reference

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```
is_alive:
@ load hp using the address
@ no need to load mana
  ldr r1, [r0]

  movs r1, r1
  mov r0, 0
  ble end_is_alive
  mov r0, 1
end_is_alive:
  bx lr

@ call (pass only address of "zoltan" record)
  ldr r0, =zardok
  bl is_alive
  cmp r0, 1
  beq whee
  b no
```

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Gotchas

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the records in these examples are small enough that they *could* be passed in registers, but large ones can't be

be aware of **stack discipline**

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pass by reference: no copying, but the caller can mess with the "source" data

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Further reading

Inside memory management: T, tradeoffs, and implementations of dynamic allocation

A look at how malloc works on mac

Plantz: Chapter 15 - Data Structures

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