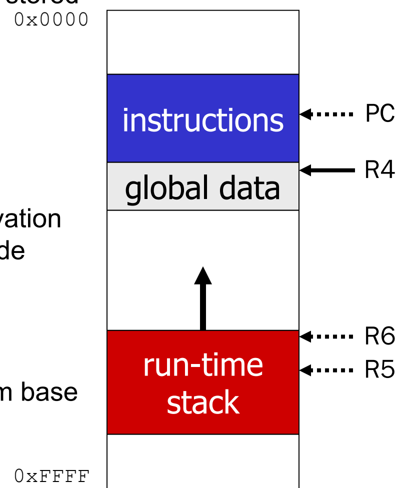
Pointers & Arrays in C & Translation to Assembly

(Chapters 16, 19)

LC3 Memory Allocation & Activation Records

- **Global data section:** global variables stored here
  - R4 points to beginning
- **Run-time stack:** for local variables
  - R6 points to top of stack
  - R5 points to top frame on stack
  - Local variables are stored in an activation record, i.e., stack frame, for each code block (function)
  - New frame for each block/function (goes away when block exited)
- symbol table "offset" gives distrance from base of frame (R5 for local var).
  - Address of local var = R5 + offset
  - Address of global var = R4 + offset
- return address from subroutines in R7



Next: Pointers, Arrays, (I/O), Structs . . .

- The real fun stuff in C…..
- Pointers and Arrays
  - Read Chapters 16, 18 of text
- Dynamic data structures
  - Allocating space during run-time
  - Read chapter 19 of text
- C skills...Labs will cover some of these
  - Make files
  - File I/O
  - Debugging – GDB
  - Valgrind
- why do you need to know these ?

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C Review: Pointers and Arrays

- Pointer
  - Address of a variable in memory
  - Allows us to indirectly access variables
    - in other words, we can talk about its *address* rather than its *value*
- Array
  - A list of values arranged sequentially in memory
  - Expression `a[4]` refers to the 5th element of the array `a`

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Pointers

- What are pointers?
  - a variable that contains the address of a memory location
- Ex: `int *my_ptr ;  // declaration`
  - Declares a variable called *my_ptr* that contains address of an int.
  - The asterisks: * tells compiler this isn't an integer variable
    - It is a variable that will hold the address of an integer!
  - We know this from Assembly:
    - R0 can hold address of a slot in data memory

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Pointers

- Example of use:

```
int  a=0 ; // declares a regular integer variable
int *b   ; // declares a pointer to an integer var.
b=&a ;     // finds "address" of a, assigns it to b
*b=5 ;     // dereferences b, sets value of a=5
```

Address	Contents
x4000 (a)	5
x4001 (b)	x4000

Dereferencing – fancy word for: contents at address

Dereferencing pointer b means:

get contents of memory at the address b is pointing to

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Pointers

- Two language mechanisms for supporting pointers in C
  - ***** : for dereferencing a pointer
    - called the “Indirection” or “Dereference” operator
  - **&** : for getting the address of a variable
    - :called the “Address Operator”
  - These “unary” operators are called Pointer Operators
- Note: There is a difference between pointer operators and declaring pointer variables:
  - **int *** my_pointer ;
    - “int *” in this context is a “type” not the use of the operator *
  - Confused? Chapter 16 in Patt/Patel is outstanding!

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Why use pointers….
Passing by value is not enough

- In C, arguments/parameters are passed by value
  - Arguments pushed onto run-time stack
- Example : you’ve seen this in *swap*:
  - function that's supposed to swap the values of its arguments.

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Executing the Swap Function

before call

R6 →	3	a
	4	b
	4	valueB
	3	valueA

```
void Swap(int a, int b)
{
  int temp = a;
  a = b;
  b = temp;
   return;
}
/* in main we call….*/
Swap(valueA, valueB);
```

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Executing the Swap Function

before call

R6 →	3	a
	4	b
	4	valueB
	3	valueA

after call

Swap		3	temp
	R6 →		
		4	a
		3	b
main		4	valueB
		3	valueA

These values changed...
a,b are local to temp

...but these did not.

Swap needs <u>addresses</u> of variables outside its own activation record/scope.

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Pointers as Arguments

- Passing a pointer into a function allows the function to *read/change memory outside its activation record*.
- Let's rewrite the swap function

```
•void swap(int *a, int *b)
{
   int t;
    t = *a;
   *a = *b;
   *b = t;
}
```

Arguments are integer pointers. Caller passes addresses of variables that it wants function to change.

We call it like this:

```
   int x = 42;
   int y = 84;
swap(&x, &y);
```

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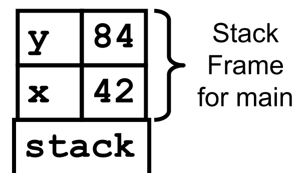
Tracing the run-time stack

```
int x = 42;
int y = 84;
swap(&x, &y);
```

```
void swap(int *a, int *b)
{
   int t;
   t = *a;
   *a = *b;
   *b = t;
}
```

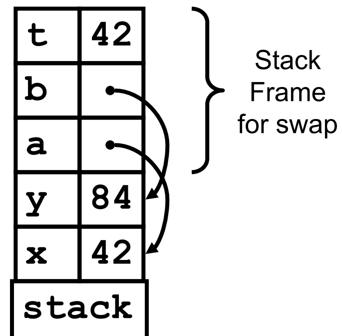


Stack Frame for main

Tracing the call to swap

```
int x = 42;
int y = 84;
swap(&x, &y);


void swap(int *a, int *b)
{
   int t;
   t = *a;
   *a = *b;
   *b = t;
}
```



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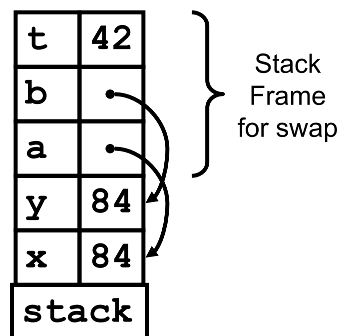
Trace

```
int x = 42;
int y = 84;
swap(&x, &y);


void swap(int *a, int *b)
{
   int t;
   t = *a;
   *a = *b;
   *b = t;
}
```



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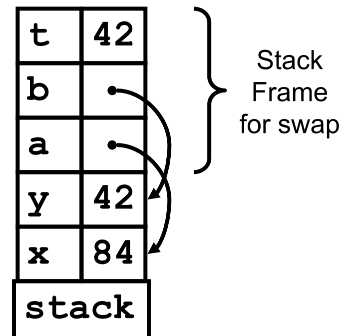
Trace

```
int x = 42;
int y = 84;
swap(&x, &y);


void swap(int *a, int *b)
{
   int t;
   t = *a;
   *a = *b;
   *b = t;
}
```



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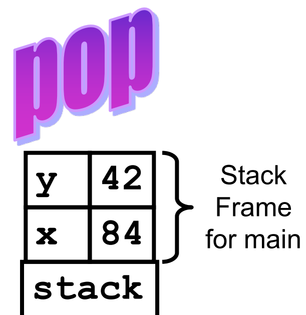
Trace

```
int x = 42;
int y = 84;
swap(&x, &y);


void swap(int *a, int *b)
{
   int t;
   t = *a;
   *a = *b;
   *b = t;
}
```



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Passing Pointers & LC3 Code generation

- How do you pass pointers in the activation record (in LC3 compiler) ?

- Parameters to the function are the addresses of the arguments!
  - Address for a local var is R5 + offset
  - Set value of argument = R5+offset

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Passing Pointers to a Function

- main() wants to swap the values of **x** and **y**
- passes the addresses to Swap:
-

```
swap(&x, &y);
```

Address of x,y pushed onto stack

R5= #3000

- Code for passing arguments:

```
ADD R0, R5, #-1 ; addr of x
ADD R6, R6, #-1 ; push
STR R0, R6, #0
ADD R0, R5, #0  ; addr of y
ADD R6, R6, #-1 ; push
STR R0, R6, #0
```

temp
R6 → #3000 a
#2999 b
4 y
R5 → 3 x
xEFFD

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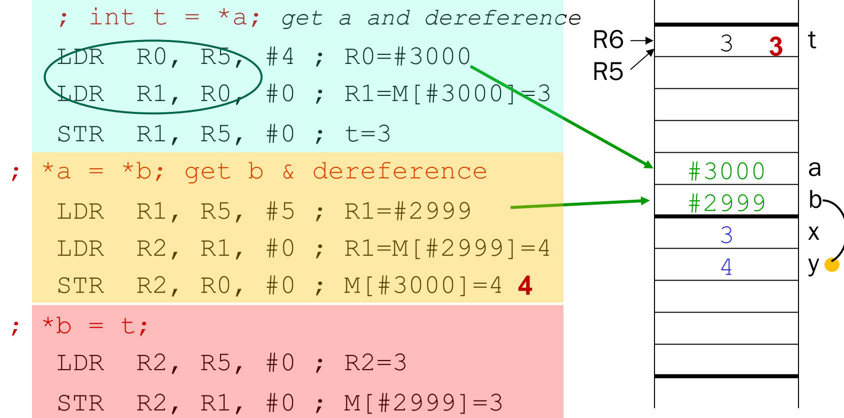
LC3 Code generation (for swap)

• Inside the Swap routine



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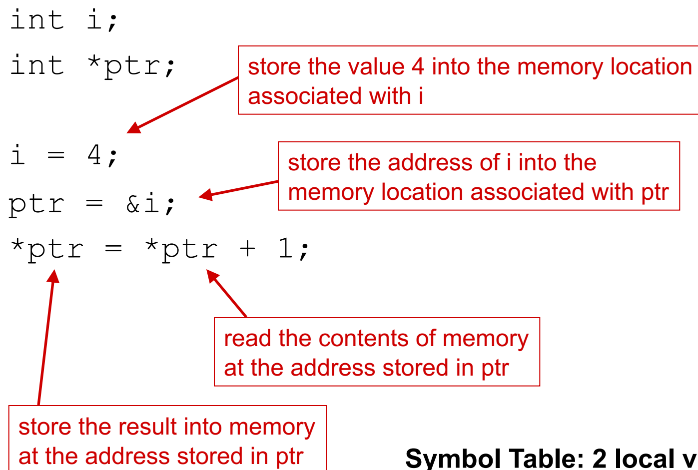
Example and C to LC3 translation



Symbol Table: 2 local variables `i, ptr`

Offset for `i` =0

Offset for `ptr = -1`

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Example: LC-3 Code – Questions 1,2 in inclass-nov10.pdf

- **Symbol Table:** *i is 1st local (offset = 0), ptr is 2nd (offset = -1)*
- ; i = 4;

```
•       AND  R0, R0, #0   ; clear R0
        ADD  R0, R0, #4   ; put 4 in R0
        STR  R0, R5, #0   ; store in i
;ptr = &i;
        ADD R0, R5, #0    ; get  addr of I R0= R5+0
        STR R0, R5, #-1   ;  store in ptr (address R5 -1)
•; *ptr = *ptr + 1;
        LDR R0, R5, #-1   ; get  R0= ptr
        LDR R1, R0, #0    ; dereference/load contents (*ptr)
        ADD R1, R1, #1    ; add one
        STR R1, R0, #1    ;  store result where ptr  points
```

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Pointers

- Powerful and dangerous
- No runtime checking (for efficiency)
- Bad reputation
- Java attempts to remove the features of pointers that cause many of the problems hence the decision to call them references
  - No address of operators
  - No dereferencing operator (always dereferencing)
  - No pointer arithmetic

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Pointers & Arrays in C & Translation to Assembly: Part 2 – Arrays

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Array Syntax

- Declaration
  - `type  variable[num_elements];`

all array elements are of the same type

number of elements must be known at compile-time

- Array Reference
  - `variable[index];`

i-th element of array (starting with zero);
no limit checking at compile-time or run-time

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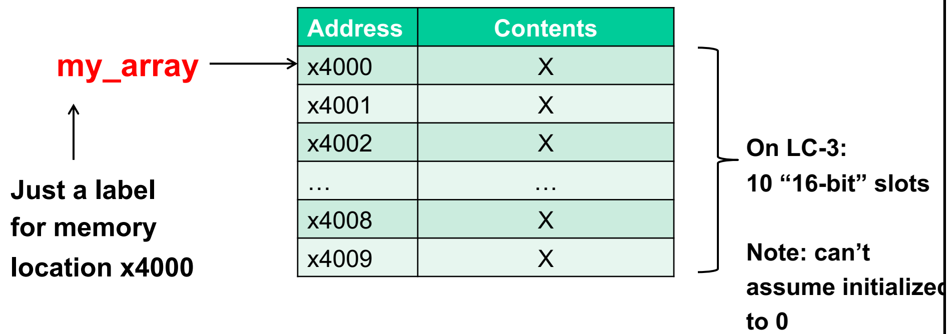
Arrays

- What are arrays?
  - a collection of many variables of the same type with an index
- Ex: `int my_array[10] ;   // declaration`
  - LC-3: allocates 10 slots for 16-bit integers in Data Memory
  - These are ***stored in consecutive locations in memory***



Address	Contents
x4000	X
x4001	X
x4002	X
…	…
x4008	X
x4009	X

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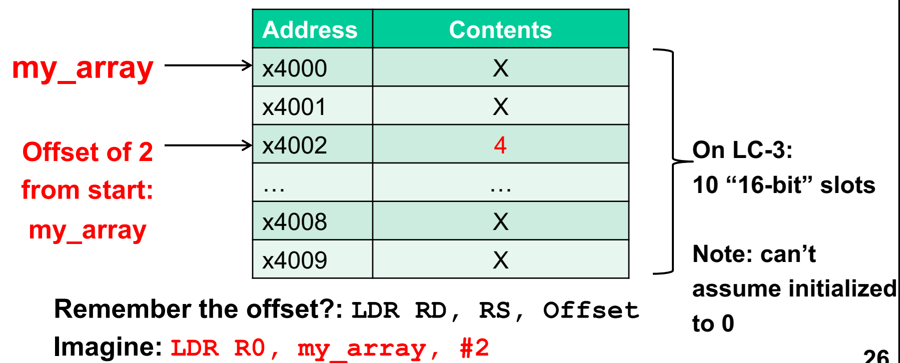
Arrays

- Indexing Arrays
  - C offers "indexing" capability on array variables
- Ex: In this example: `my_array[2]` equals `4`
  - Allocates 10 slots for 16-bit integers in Data Memory
  - What happens when you type: my_array [11] ???



Address	Contents
x4000	X
x4001	X
x4002	4
…	…
x4008	X
x4009	X

Remember the offset?: `LDR RD, RS, Offset`

Imagine: `LDR R0, my_array, #2`

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Arrays and pointers

- Arrays and pointers are intimately connected in C
  - Array declarations allocate areas of memory for use
  - We are really defining an address (aka – a pointer) to the first element of the array
- Example – mixing arrays and pointers!

```
int my_array[10]; // declares array of 10 ints
int *my_ptr;  // declares a pointer to an int var.
my_ptr = my_array + 2; // points to 3rd row in array
```

my_array → x4000

my_ptr=x4002 → x4002

Address	Contents
x4000	X
x4001	X
x4002	4
…	…
x4008	X
x4009	X

Dereferencing ptr:

`*my_ptr` **equals** 4

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Pointers and Arrays – Assembly code versions

- In terms of assembly we can make a distinction between the address of the start of a block of memory and the values stored in that block of memory

C Code	Assembly Code
`int my_array[10]`	`my_array` `.BLKW #10`

`int *my_ptr;`
`my_ptr = my_array;`
	`LEA R0, my_array`
	
	`; R0 is equiv to`
	`; "my_ptr"`

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Arrays: Memory layout

```
int ia[6];
```

- Allocates consecutive spaces for 6 integers
- How much space is allocated?
  - Depends on the type of the array
  - How many bytes for an int ?
  - How many bytes for a char?
  - Ex: if 4 bytes for int, then we need 24 bytes for 6 integers
  - Ex: 1 byte for char, then we need 6 bytes for 6 character array

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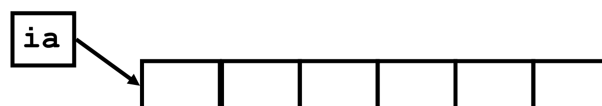
Arrays

```
int ia[6];
```

- Allocates consecutive spaces for 6 integers
- How much space is allocated?

```
6 * sizeof(int)
```

- Also creates `ia` which is effectively a constant pointer to the first of the six integers
- What does `ia[4]` mean?



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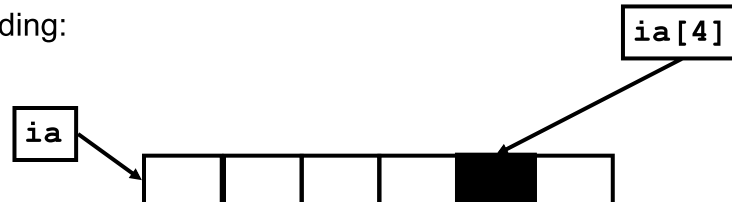
Arrays

```
int ia[6];
```

- Allocates consecutive spaces for 6 integers
- How much space is allocated?

```
6 * sizeof(int)
```

- Also creates `ia` which is effectively a *constant* pointer to the first of the six integers
  - Cannot change ia
- What does `ia[4]` mean?
- Multiply 4 by `sizeof(int)`. Add to `ia` and dereference yielding:



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sizeof

- Compile time operator
- Two forms

```
sizeof object
sizeof ( type name )
```

- Returns the size of the object or the size of objects of type name in bytes
- Note: Parentheses can be used in the first form with no adverse effects

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sizeof

- if sizeof(int) == 4 then sizeof(i) == 4
- On a typical 32 bit machine...

```
sizeof(*ip) → 4
sizeof(ip) → 4
char *cp;
sizeof(char) → 1
sizeof(*cp) → 1
sizeof(cp) → 4

int ia[6];
sizeof(ia) → 24
```

Not the same thing!!!

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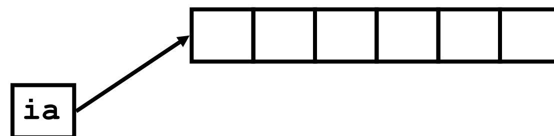
Arrays

```
int ia[6];
```



- **ia[4]** means ***(ia + 4)**

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Pointer Arithmetic

- Note on the previous slide when we added the literal 4 to a pointer it actually gets interpreted to mean

  4 * sizeof(thing being pointed at)

- This is why pointers have associated with them what they are pointing at!
- C does size calculations under the covers, depending on size of item being pointed to:

```
•double x[10];
•double *y = x;
     *(y + 3) = 13;
```

allocates 20 words (2 per element)

same as x[3] -- base address plus 6

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Pointer Arithmetic

•Address calculations depend on size of elements

- In our LC-3 code, we've been assuming one word per element.
  - e.g., to find 4th element, we add 4 to base address
- It's ok, because we've only shown code for int and char, both of which take up one word.
- If double, we'd have to add 8 to find address of 4th element.

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Pointer Arithmetic

- Just as we used arithmetic on address values to iterate through arrays in assembly, we can use arithmetic on pointer values in C

```
•float my_array[10]; // declares array of 10 floats
•float *my_ptr;      // declares a pointer to a float
•my_ptr = my_array + 2; // points to 3rd row in array
•my_ptr = my_ptr + 1;   // points to 4th row in array
```

  - Compiler looks at the type of variable being pointed to and increments by the correct amount to point to the next element
  - In this case ptr may actually be incremented by 4 since each float takes up 4 bytes

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Pointers/Arrays/Strings

- There is no "string" datatype in C
  - But we can use arrays of char's to mimic behavior
- Simplest Ways to Declare "Strings":
  - **`char my_string [256] ;`**
    - Works just like any array, each element is character

      `my_string[0]='T' ;`
      `my_string[1]='h' ;`
    - You must "null terminate" this array
    - Note: no way to know length of an array
      - Unless one loops through it entirely and determines ending
    - Pass "my_string" as argument to functions!
      - That's the 1st address of the string in memory
  - **`char *my_string = "This is a string" ;`**
    - Will be null terminated
    - Cannot be modified

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Relationship between Arrays and Pointers

•An array name is essentially a pointer to the first element in the array

```
char word[10];
char *cptr;

cptr = word;/* points to word[0] */
```

•Difference:

Can change the contents of cptr, as in

- `cptr = cptr + 1;`

•(The identifier "word" is not a variable.)

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Correspondence between Ptr and Array Notation

•Given the declarations,

each line below gives three equivalent expressions:

•cptr	word	&word[0]
•(cptr + n)	word + n	&word[n]
•*cptr	*word	word[0]
•*(cptr + n)	*(word + n)	word[n]

```
char word[10];
char *cptr;
cptr = word;/* points to word[0] */
```

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Passing Arrays as Arguments

- C passes arrays by reference
  - the address of the array (i.e., of the first element) is written to the function's activation record
  - otherwise, would have to copy each element

```
main() {
   int numbers[MAX_NUMS];
   …
   mean = Average(numbers);
   …
}
int Average(int inputValues[MAX_NUMS]) {
   …
   for (index = 0; index < MAX_NUMS; index++)
       sum = sum + inputValues[index];
   return (sum / MAX_NUMS);
}
```

This must be a constant, e.g., `#define MAX_NUMS 10`

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Array as a Local Variable

```
int foo(int myarray[ ] )
{
  int grid[10];
…
}
```

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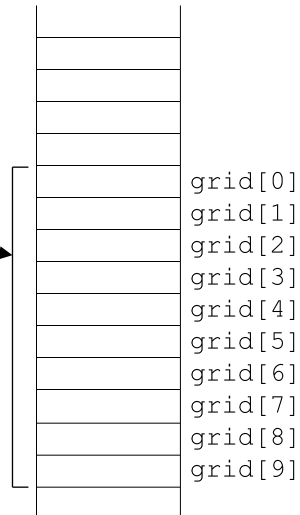
Array as a Local Variable

•Array elements are allocated as part of the activation record.

`int grid[10];`



•First element (`grid[0]`) is at lowest address of allocated space.

If `grid` is first variable allocated, then R5 will point to `grid[9]`.

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C to Assembly Translation- Arrays

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Example and C to LC3 translation

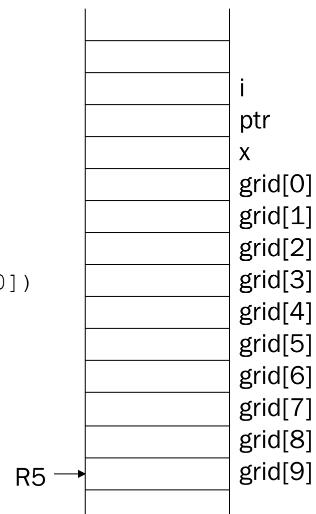
```
int foo(){
int grid[10];
int x,
int *ptr;
int i;
     ….
     grid[6] =5;
     x = grid[3] + 1;
     grid[i] = x;
     ptr = grid;
     grid[x] = grid[x] +2;
     …
}
```

Symbol Table

Identifier	offset
grid	-9
x	-10
ptr	-11
i	-12

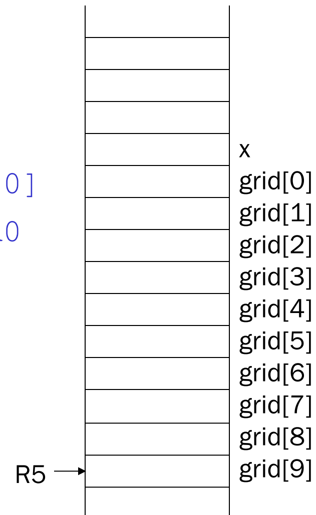
LC-3 Code for Array References

```
grid[6] =5;
x = grid[3] + 1;
grid[i] = x;
ptr=grid;
grid[x+1] = grid[x] +2;
 where is @grid[0] (address grid[0])
 ??? @grid[6] = @grid[0} +6
??? ; plus 1
 STR ??? ; store into x
@grid[i] = @grid[0] + i
```



LC-3 Code for Array References

```
; grid[6] = 5;
  AND R0, R0, #0
  ADD R0, R0, #5   ; R0 = 5
  ADD R1, R5, #-9  ; R1 = &grid[0]
  STR R0, R1, #6   ; grid[6] = R0
```



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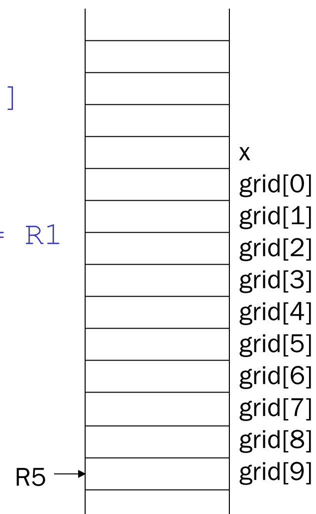
LC-3 Code for Array References

```
; x = grid[3] + 1
  ADD R0, R5, #-9; R0 = &grid[0]
  LDR R1, R0, #3; R1 = grid[3]
  ADD R1, R1, #1; add 1
  STR R1, R5, #-10;store to x = R1
```



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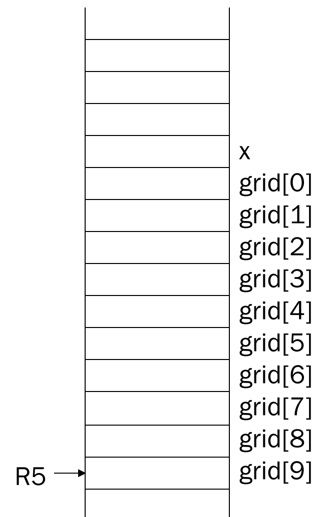
More LC-3 Code

```
; grid[x+1] = grid[x] + 2
  LDR R0, R5, #-10  ; R0 = x
  ADD R1, R5, #-9   ; R1 = &grid[0]
  ADD R1, R0, R1    ; R1 = &grid[x]
  LDR R2, R1, #0    ; R2 = grid[x]
  ADD R2, R2, #2    ; add 2

  LDR R0, R5, #-10  ; R0 = x
  ADD R0, R0, #1    ; R0 = x+1
  ADD R1, R5, #-9   ; R1 = &grid[0]
  ADD R1, R0, R1    ; R1 = &grix[x+1]
  STR R2, R1, #0    ; grid[x+1] = R2
```



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Common Pitfalls with Arrays in C

- Overrun array limits
  - There is no checking at run-time or compile-time to see whether reference is within array bounds.

```
int array[10];
int i;
for (i = 0; i <= 10; i++) array[i] = 0;
```

- Declaration with variable size
  - Size of array must be known at compile time.

```
void SomeFunction(int num_elements) {
  int temp[num_elements];
  …
}
```

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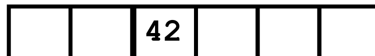
Recall

```
int ia[6];

ia[2] = 42;
```



Address calculation:

```
2 * sizeof(*ia) + ia
```

Access is by dereferencing

```
*(2 * sizeof(*ia) + ia)
```

Remember!
You don't type in
the sizeof part!

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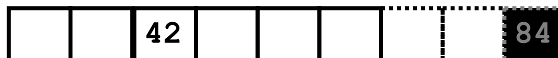
What happens?

```
int ia[6];

ia[8] = 84;
```



Address calculation:

```
8 * sizeof(*ia) + ia
```

Remember!
You don't type in
the sizeof part!

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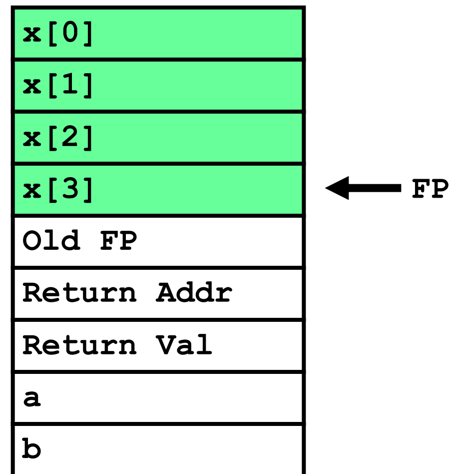
Stack Smashing

```
int another(int a, int b) {
    int x[4];
```



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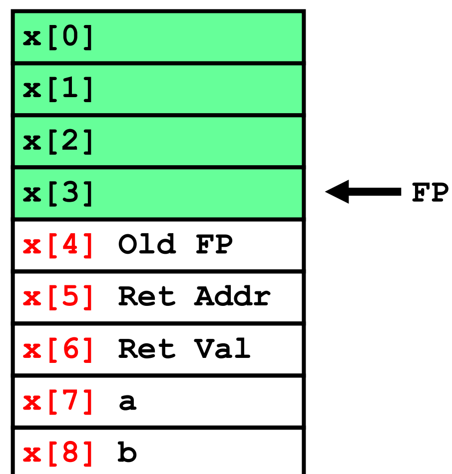
Stack Smashing

```
int another(int a, int b) {
    int x[4];
```



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Multidimensional Arrays in C

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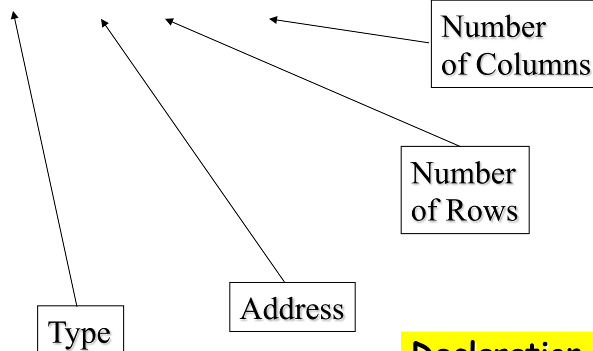
Declaration

```
int ia[3][4];
```



Declaration at compile time i.e. size must be known

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How does a two dimensional array work?

	0	1	2	3
0				
1				
2				

How would you store it?

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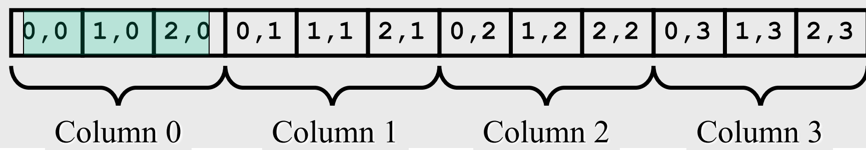
How would you store it?

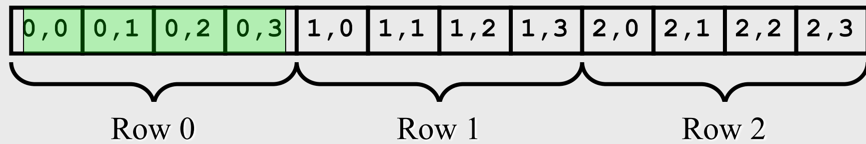
	0	1	2	3
0				
1				
2				

Column Major Order



Column 0 Column 1 Column 2 Column 3

Row Major Order



Row 0 Row 1 Row 2

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Advantage

- Using Row Major Order allows visualization as an array of arrays

`ia[1]`

0,0	0,1	0,2	0,3	1,0	1,1	1,2	1,3	2,0	2,1	2,2	2,3

`ia[1][2]`

0,0	0,1	0,2	0,3	1,0	1,1	1,2	1,3	2,0	2,1	2,2	2,3

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Element Access

- Given a row and a column index
- How to calculate location?
- To skip over required number of rows:

```
    row_index * sizeof(row)
row_index * Number_of_columns * sizeof(arr_type)
```

- This plus *address of array* gives address of first element of desired row
- Add `column_index * sizeof(arr_type)` to get actual desired element

0,0	0,1	0,2	0,3	1,0	1,1	1,2	1,3	2,0	2,1	2,2	2,3

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Element Access

```
Element_Address =

      Array_Address +
        Row_Index * Num_Columns * Sizeof(Arr_Type) +
        Column_Index * Sizeof(Arr_Type)


Element_Address =

      Array_Address +
        (Row_Index * Num_Columns + Column_Index) *
           Sizeof(Arr_Type)
```

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What if array is stored in Column Major Order?

```
Element_Address =

   Array_Address +
     (Column_Index * Num_Rows + Row_Index) *
        Sizeof(Arr_Type)
```

0,0	1,0	2,0	0,1	1,1	2,1	0,2	1,2	2,2	0,3	1,3	2,3

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How does C store arrays

- Row major
  - Pointer arithmetic stays unmodified
- Remember this…..
  - Affects how well your program does when you access memory

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Now think about

- A 3D array

```
int a
```

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Now think about

- A 3D array

`int a[5]`

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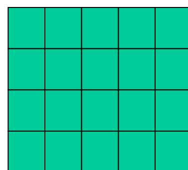
Now think about

- A 3D array



`int a[4][5]`

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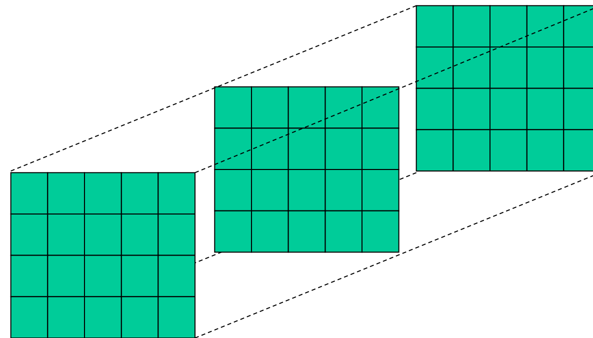
Now think about

- A 3D array



`int a[3][4][5]`

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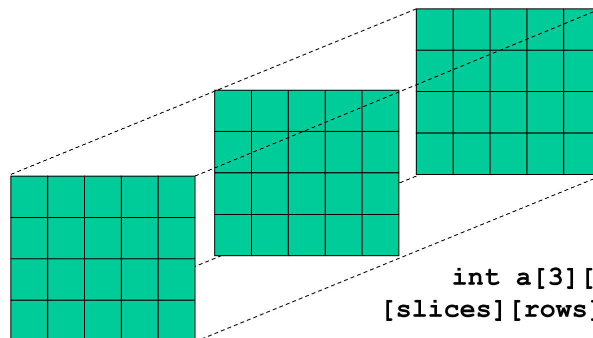
Offset to a[i][j][k]?

- A 3D array



```
int a[3][4][5]
[slices][rows][columns]
```

```
offset = (i * rows * columns) + (j * columns)
         + k
```

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Recall

- **One Dimensional Array**

  `int ia[6];`
- **Address of beginning of array:**

  `ia ≡ &ia[0]`

- **Two Dimensional Array**

  `int ia[3][6];`
- **Address of beginning of array:**

  `ia ≡ &ia[0][0]`
- **also**
- **Address of row 0:**

  `ia[0] ≡ &ia[0][0]`
- **Address of row 1:**

  `ia[1] ≡ &ia[1][0]`
- **Address of row 2:**

  `ia[2] ≡ &ia[2][0]`

Static vs. Dynamic Allocation

- There are two different ways that multidimensional arrays could be implemented in C.
- Static: When you know the size at compile time
  - A Static implementation which is more efficient in terms of space and probably more efficient in terms of time.
- Dynamic: what if you don't know the size at compile time?
  - More flexible in terms of run time definition but more complicated to understand and build
  - Dynamic data structures
- Need to allocate memory at run-time – malloc
  - Once you are done using this, then release this memory – free
- Next: Dynamic Memory Alloction