MANCHESTER 1824
The University of Manchester

COMP26120: Pointers in C (2019/20)

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Organisation

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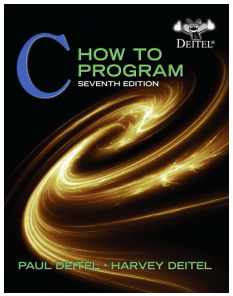
  - Office hours: 15-16 Tuesday, 14-15 Wednesday
- Textbook:
  - *C How to Program* (chapter 7)

These slides are based on the lectures notes of "C How to Program"



Intended learning outcomes

- To learn about **pointers** and **pointer operations**
- To use pointers to **pass arguments** to functions by **reference**
- To understand the close relationships among **pointers**, **arrays**, and **strings**
- To use **pointers** to **functions**
- To define and use **arrays of strings**

Introduction

- Pointers enable programs to
  - simulate **pass-by-reference**

```
int x=2;
void square(int *nPtr){
   *nPtr *=*nPtr;
}
int main(void) {
  square (&x);
  return 0;

}
```

What are the **advantages** and **disadvantages** to pass arguments to functions by reference?

Introduction

- Pointers enable programs to
  - simulate pass-by-reference
  - use **function pointers**

```
#include <stdio.h>
typedef void (*functiontype)(int x);
void dosomething(int x){
  printf("x: %d\n", x);
}
int main(void){
  functiontype func = &dosomething;
  func(2);
  return 0;
}
```

What is the common use of function pointers?

Introduction

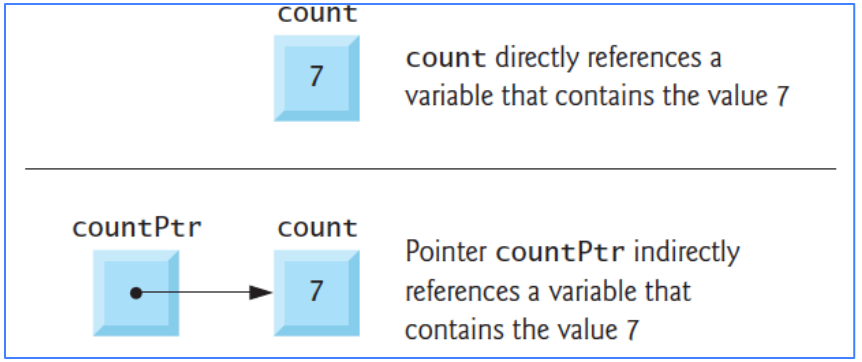
- Pointers enable programs to
  - simulate pass-by-reference
  - use function pointers
  - create and manipulate **dynamic data structures**

```
entry *allocate_entries(int num_entries){
 entry *entriesPtr = (entry*)malloc(sizeof(entry)
   * num_entries);
 for(int i=0; i<num_entries; i++)
  init_entry(&entriesPtr[i]);
 return entriesPtr;
}
```

- Next class: dynamic memory management

Pointer Variable Definitions and Initialization

- **Pointers** are variables whose values are ***memory addresses***
  - A **variable** directly contains a **specific value**
  - A **pointer** contains an **address of a variable** that contains a specific value
    - a variable name **directly** references a value, and a pointer **indirectly** references a value
- Referencing a value through a pointer is called **indirection**



Declaring Pointers

- Pointers, like all variables, must be defined before they can be used
- The definition
  - **int *countPtr, count;**
  - **void *speedPtr;**
  - *How can we interpret these definitions?*

- **Pointers** can be defined to **point to objects of any type**

Common Programming Error

- The asterisk (*) notation used to declare pointer variables does not distribute to all variable names in a declaration
  - Each pointer must be declared with the * prefixed to the name
    - *xPtr* and *yPtr* must be declared as **xPtr* and **yPtr*
- Include the letters ***ptr*** in pointer variable names
  - make it clear that these variables are pointers
  - need to be handled appropriately

Initialising and Assigning Values to Pointers

- Pointers should be initialised when they're defined
  - A pointer may be initialised to NULL, 0 or an address
    - A pointer with the value NULL points to *nothing*
    - Initializing a pointer to 0 is equivalent to initialising a pointer to NULL, but NULL is preferred
  - NULL is a *symbolic constant* defined in the **<stddef.h>** header (and other headers, **<stdio.h>**)

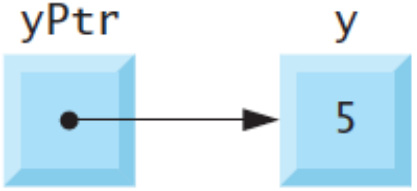
Initialise pointers to prevent unexpected results

Pointer Operators

- The &, or **address operator**, is a unary operator that returns the address of its operand
- For example, assuming the definitions
  - **int y = 5;**
    int *yPtr;

  the statement
  - yPtr = &y;

  assigns the *address* of the variable *y* to pointer variable *yPtr*



- Variable *yPtr* is then said to “point to” y

Pointer Representation in Memory

- Assume that integer variable *y* is stored at location 600000, and pointer variable *yPtr* is stored at location 500000

- The operand of the address operator **must be a variable**
  - the address operator *cannot* be applied to constants or expressions

The Indirection (*) Operator

- The unary * operator: **indirection operator** or **dereferencing operator**
  - returns the object *value* to which its operand points
- For example, the statement
    - printf("%d", ***yPtr);**

  prints the value of variable *y*, namely 5
  - Using * here is called **dereferencing a pointer**

Dereferencing a pointer that has not been initialised or that has not been assigned to point to a specific location in memory is an error

```c
// Fig. 7.4: fig07_04.c
// Using the & and * pointer operators.
#include <stdio.h>

int main(void)
{
   int a = 7;
   int *aPtr = &a; // set aPtr to the address of a

   printf("The address of a is %p"
          "\nThe value of aPtr is %p", &a, aPtr);

   printf("\n\nThe value of a is %d"
          "\nThe value of *aPtr is %d", a, *aPtr);

   printf("\n\nShowing that * and & are complements of "
          "each other\n&*aPtr = %p"
          "\n*&aPtr = %p\n", &*aPtr, *&aPtr);
}
```

Using the & and * pointer operators (Part 1 of 2)

%p outputs the memory location as a *hexadecimal* integer on most platforms

```
The address of a is 0028FEC0
The value of aPtr is 0028FEC0

The value of a is 7
The value of *aPtr is 7

Showing that * and & are complements of each other
&*aPtr = 0028FEC0
*&aPtr = 0028FEC0
```

the address of *a* is indeed assigned to the pointer variable *aPtr*

Using the & and * pointer operators (Part 2 of 2)

- The *&* and * operators are complements of one another—when they're both applied consecutively to *aPtr* in either order, the same result is printed

Operators	Associativity	Type
`()` `[]` `++` *(postfix)* `--` *(postfix)*	left to right	postfix
`+` `-` `++` `--` `!` `*` `&` (*type*)	right to left	unary
`*` `/` `%`	left to right	multiplicative
`+` `-`	left to right	additive
`<` `<=` `>` `s>=`	left to right	relational
`==` `!=`	left to right	equality
`&&`	left to right	logical AND
`||`	left to right	logical OR
`?:`	right to left	conditional
`=` `+=` `-=` `*=` `/=` `%=`	right to left	assignment
`,`	left to right	comma

Precedence and associativity
of the operators discussed so far

Exercise

Answer each of the following:

a) A pointer variable contains as its value the _____ of another variable?

b) The three values that can ne used to initialise a pointer are _____, _____ and _____.

c) The only integer that can be assigned to a pointer is _____.

d) The address operator can be applied only to _____.

Passing Arguments to Functions by Reference

- There are two ways to pass arguments to a function: **pass-by-value** and **pass-by-reference**
  - *All arguments in C are passed by value*
- Many functions require the capability to
  - modify variables in the **caller** or
  - pass a pointer to a large data object
    - To avoid the time and memory overheads
- In C, you use **pointers** and the **indirection** operator to *simulate* **pass-by-reference**

```c
// Fig. 7.6: fig07_06.c
// Cube a variable using pass-by-value.
#include <stdio.h>

int cubeByValue(int n); // prototype

int main(void)
{
   int number = 5; // initialize number

   printf("The original value of number is %d", number);

   // pass number by value to cubeByValue
   number = cubeByValue(number);

   printf("\nThe new value of number is %d\n", number);
}

// calculate and return cube of integer argument
int cubeByValue(int n)
{
   return n * n * n; // cube local variable n and return result
}
```

Cube a variable using pass-by-value (Part 1 of 2)

```
The original value of number is 5
The new value of number is 125
```

Cube a variable using pass-by-value (Part 2 of 2)

Use **call-by-value** to pass arguments to a function to prevent accidental modification of the caller's argument

```c
// Fig. 7.7: fig07_07.c
// Cube a variable using pass-by-reference with a pointer argument.

#include <stdio.h>

void cubeByReference(int *nPtr); // function prototype

int main(void)
{
   int number = 5; // initialize number

   printf("The original value of number is %d", number);

   // pass address of number to cubeByReference
   cubeByReference(&number);

   printf("\nThe new value of number is %d\n", number);
}

// calculate cube of *nPtr; actually modifies number in main
void cubeByReference(int *nPtr)
{
   *nPtr = *nPtr * *nPtr * *nPtr; // cube *nPtr
}
```

Cube a variable using pass-by-reference with a pointer argument (Part 1 of 2)

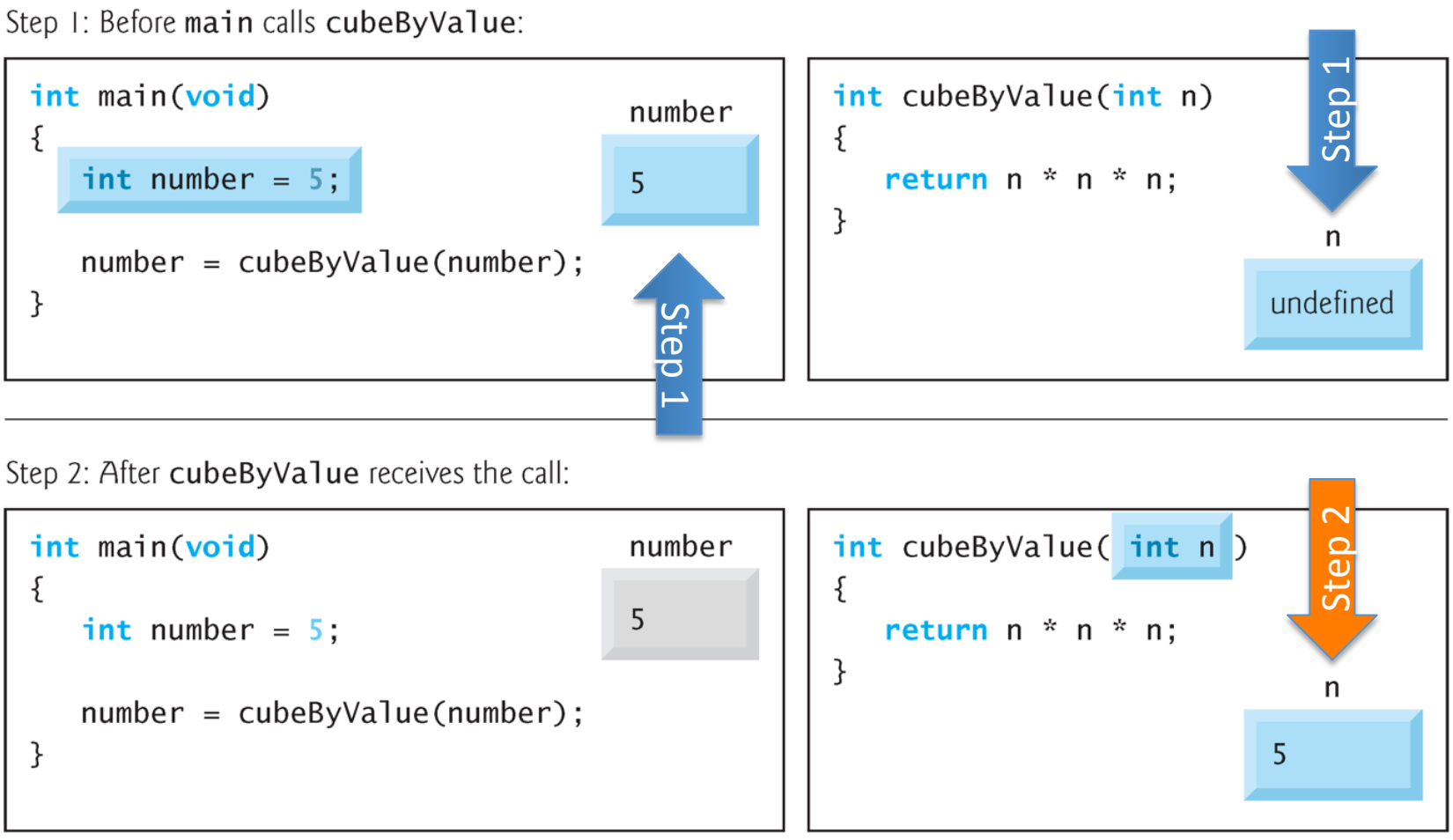
```
The original value of number is 5
The new value of number is 125
```

Cube a variable using pass-by-reference
with a pointer argument (Part 2 of 2)

Use **pass-by-reference** only if the caller explicitly requires the called function to modify the value of the argument variable in the caller's environment

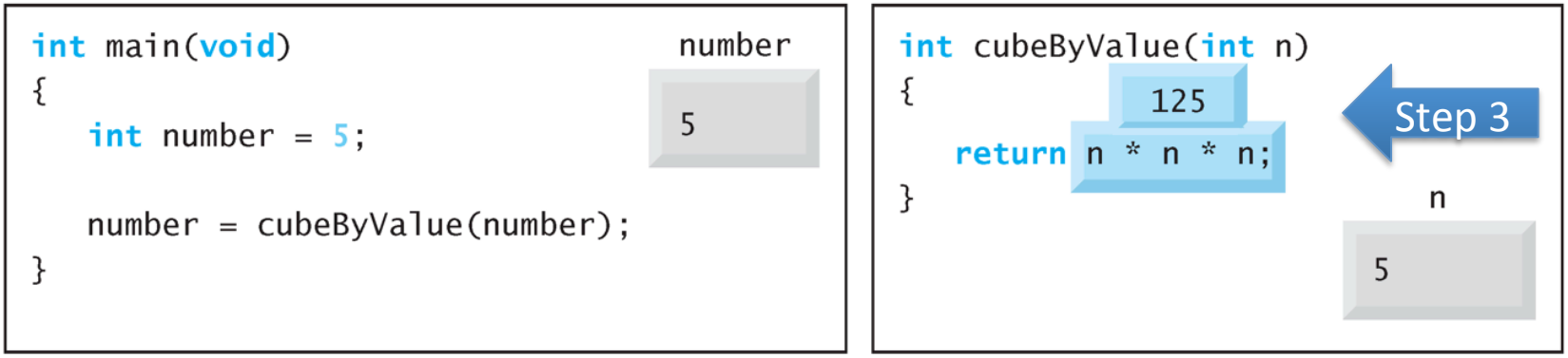
Passing Arguments to Functions by Reference (Cont.)

- For a function that expects **one-dimensional array**, its prototype and header can use **pointer notation**
  - No difference between a function that receives a pointer and one that receives a one-dimensional array
  - the function must “know” when it’s receiving an array or a single variable to perform pass-by-reference
- The compiler converts *int b[]* to the pointer notation *int *b*

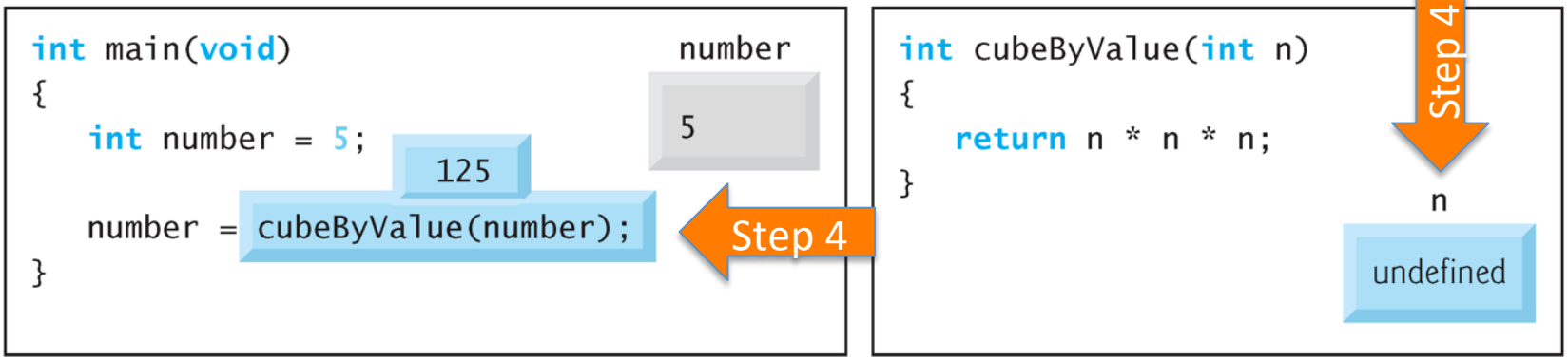


Analysis of a typical pass-by-value (Part 1 of 3)

Step 3: After `cubeByValue` cubes parameter `n` and before `cubeByValue` returns to `main`:

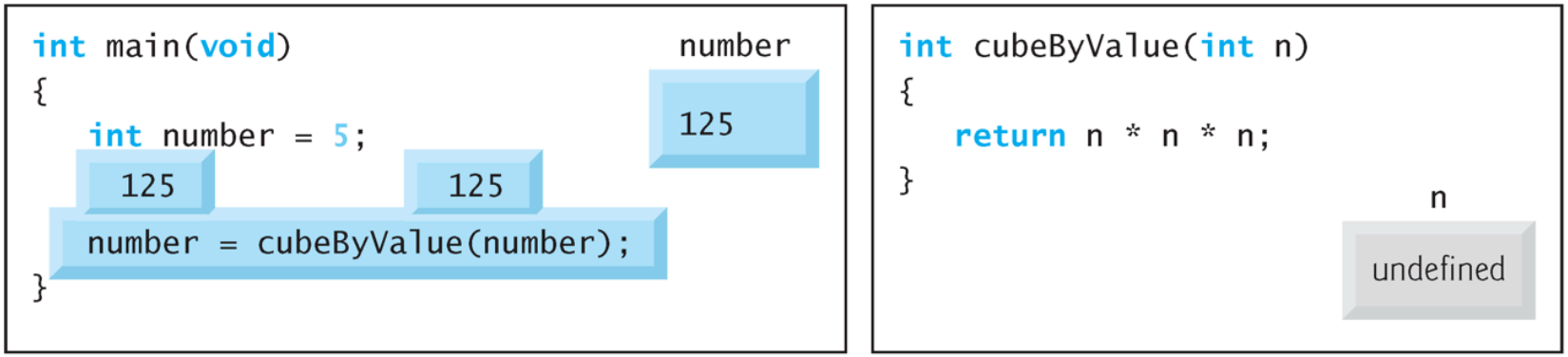


Step 4: After `cubeByValue` returns to `main` and before assigning the result to `number`:



Analysis of a typical pass-by-value (Part 2 of 3)

Step 5: After **main** completes the assignment to **number**:



Analysis of a typical pass-by-value (Part 3 of 3)

Step 1: Before `main` calls `cubeByReference`:

```
int main(void)
{
   int number = 5;

   cubeByReference(&number);
}
```

number: 5

```
void cubeByReference(int *nPtr)
{
   *nPtr = *nPtr * *nPtr * *nPtr;
}
```

nPtr: undefined

Step 2: After `cubeByReference` receives the call and before `*nPtr` is cubed:

```
int main(void)
{
   int number = 5;

   cubeByReference(&number);
}
```

number: 5

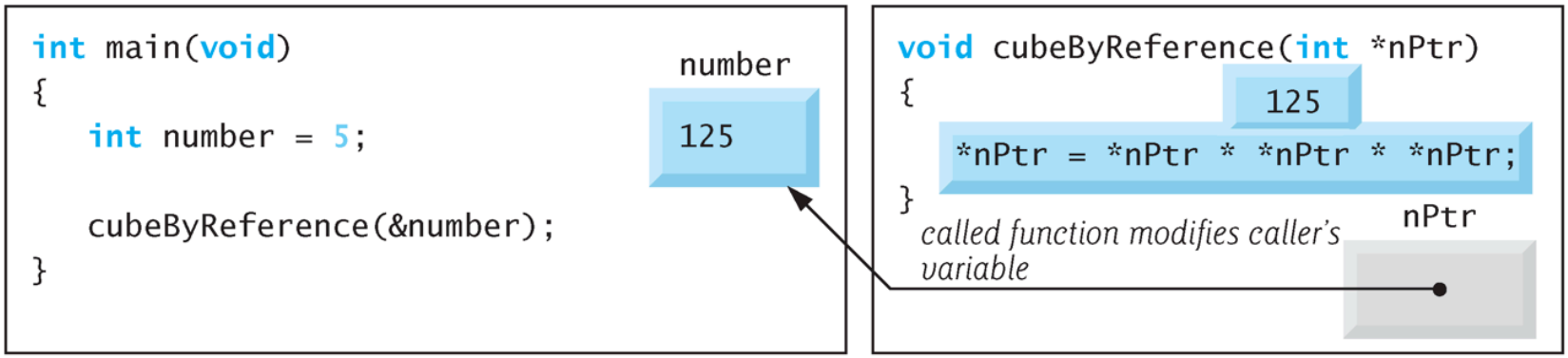
```
void cubeByReference( int *nPtr )
{
   *nPtr = *nPtr * *nPtr * *nPtr;
}
```

call establishes this pointer

nPtr

Analysis of a typical pass-by-reference with a pointer argument (Part 1 of 2)

Step 3: After *nPtr is cubed and before program control returns to main:



Analysis of a typical pass-by-reference with a pointer argument (Part 2 of 2)

`sizeof` Operator

- C provides the special unary operator **`sizeof`** to determine the size in bytes of an array (or any other data type)
- **`sizeof`** is a **compile-time operator**, so it does not incur any **execution-time overhead**

```c
// Fig. 7.16: fig07_16.c
// Applying sizeof to an array name returns
// the number of bytes in the array.
#include <stdio.h>
#define SIZE 20

size_t getSize(float *ptr); // prototype

int main(void)
{
   float array[SIZE]; // create array

   printf("The number of bytes in the array is %u"
          "\nThe number of bytes returned by getSize is %u\n",
          sizeof(array), getSize(array));
}

// return size of ptr
size_t getSize(float *ptr)
{
   return sizeof(ptr);
}
```

Applying `sizeof` to an array name returns the number of bytes in the array (Part 1 of 2)

```
The number of bytes in the array is 80
The number of bytes returned by getSize is 4
```

Applying `sizeof` to an array name returns the number of bytes in the array (Part 1 of 2)

- When applied to the name of an array, the **`sizeof`** operator returns the total number of bytes in the array as type **`size_t`**
- Variables of type **`float`** on this computer are stored in 4 bytes of memory, and array is defined to have 20 elements
- Therefore, there are a total of 80 bytes in array

```c
// Fig. 7.17: fig07_17.c
// Using operator sizeof to determine standard data type sizes.
#include <stdio.h>

int main(void)
{
   char c;
   short s;
   int i;
   long l;
   long long ll;
   float f;
   double d;
   long double ld;
   int array[20]; // create array of 20 int elements
   int *ptr = array; // create pointer to array

   printf("     sizeof c = %u\tsizeof(char)  = %u"
          "\n     sizeof s = %u\tsizeof(short) = %u"
          "\n     sizeof i = %u\tsizeof(int) = %u"
          "\n     sizeof l = %u\tsizeof(long) = %u"
          "\n    sizeof ll = %u\tsizeof(long long) = %u"
          "\n     sizeof f = %u\tsizeof(float) = %u"
```

Using operator **`sizeof`** to determine standard data type sizes (Part 1 of 2)

```
24              "\n     sizeof d = %u\tsizeof(double) = %u"
25              "\n    sizeof ld = %u\tsizeof(long double) = %u"
26              "\n sizeof array = %u"
27              "\n   sizeof ptr = %u\n",
28              sizeof c, sizeof(char), sizeof s, sizeof(short), sizeof i,
29              sizeof(int), sizeof l, sizeof(long), sizeof ll,
30              sizeof(long long), sizeof f, sizeof(float), sizeof d,
31              sizeof(double), sizeof ld, sizeof(long double),
32              sizeof array, sizeof ptr);
33   }
```

```
     sizeof c = 1       sizeof(char)  = 1
     sizeof s = 2       sizeof(short) = 2
     sizeof i = 4       sizeof(int) = 4
     sizeof l = 4       sizeof(long) = 4
    sizeof ll = 8       sizeof(long long) = 8
     sizeof f = 4       sizeof(float) = 4
     sizeof d = 8       sizeof(double) = 8
    sizeof ld = 8       sizeof(long double) = 8
sizeof array = 80
  sizeof ptr = 4
```

Using operator **`sizeof`** to determine standard data type sizes (Part 1 of 2)

Exercise

- Consider the following array definition:
  - **double real[22];**
- What is the total number of bytes?

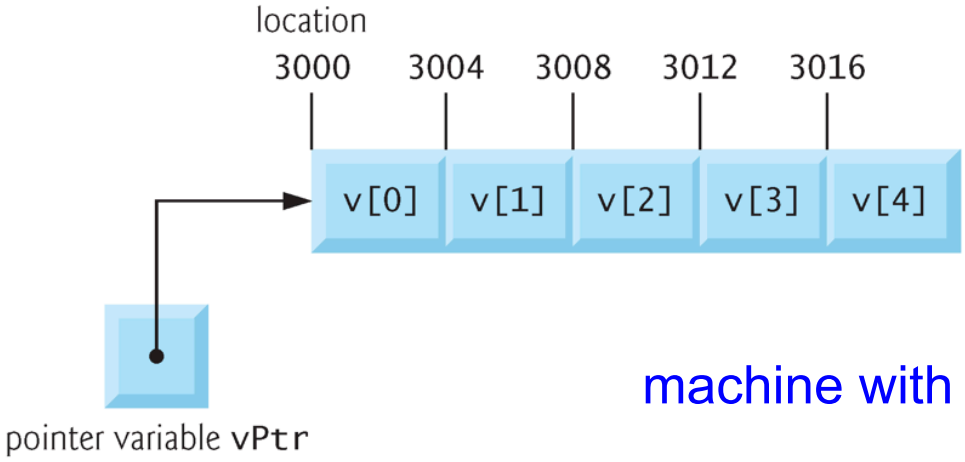
- How can you determine the total number of elements?

Pointer Expressions and Pointer Arithmetic

- **Pointers** are valid operands in **arithmetic** expressions, **assignment** expressions and **comparison** expressions
- A pointer may be
  - *incremented* (++) or *decremented* (--)
  - an integer may be *added* to a pointer (+ or +=)
  - an integer may be *subtracted* from a pointer (- or -=)
  - one pointer may be subtracted from another if *both* pointers point to elements of the *same* array

Pointer Arithmetic Example

```
int v[5];
int *vPtr;
vPtr = v;
```



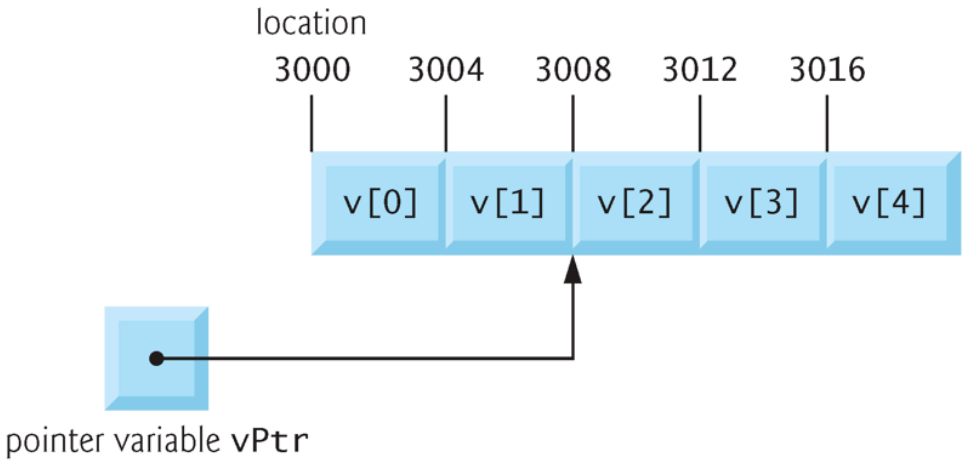
machine with 4-byte integers

Array *v* and a pointer variable *vPtr* that points to *v*

Since the results of pointer arithmetic depend on the size of the objects a pointer points to, **pointer arithmetic is machine dependent**

Pointer Arithmetic Example

- When an integer is added to or subtracted from a pointer, the pointer is *not* incremented or decremented simply by that integer,
  - By that integer times the size of the object to which the pointer refers
    - The number of bytes depends on the object's data type
- What this statement would produce?
    - vPtr += **2**;
  - it would produce 3008 (3000 + 2 * 4), assuming an integer is stored in 4 bytes of memory
  - In the array *v*, *vPtr* would now point to v[2]



The pointer *vPtr* after pointer airhtmetic

Using pointer arithmetic on a pointer that does not refer to an element in an array is a common programming error

Pointer Expressions and Pointer Arithmetic (Cont.)

- A pointer can be assigned to another pointer if both have the same type
  - The exception to this rule is the pointer to void (i.e., void *), which is a generic pointer that can represent *any* pointer type
- All pointer types can be assigned a pointer to *void*, and a pointer to *void* can be assigned a pointer of any type
  - In both cases, a cast operation is not required

A pointer to void *cannot* be dereferenced

Pointer Expressions and Pointer Arithmetic (Cont.)

- The compiler knows that a pointer to *int* refers to 4 bytes of memory on a machine with 4-byte integers
  - however, a pointer to void simply contains a memory location for an *unknown* data type
  - the precise number of bytes to which the pointer refers is not known by the compiler

The compiler *must* know the data type to determine the number of bytes to be dereferenced for a particular pointer

Pointer Expressions and Pointer Arithmetic (Cont.)

- Pointers can be compared using equality and relational operators, but such comparisons need to point to elements of the *same* array
  - Pointer comparisons compare the addresses stored in the pointers
- A comparison of two pointers pointing to elements in the same array could show that one pointer points to a higher-numbered element of the array than the other pointer does
- A common use of pointer comparison is determining whether a pointer is NULL

Relationship between Pointers and Arrays

- Arrays and pointers are intimately related in C and often may be used interchangeably
  - An *array name* can be thought of as a **constant pointer**
  - **Pointers** can be used to do any operation involving **array indexing**
- Assume that integer array *b[5]* and integer pointer variable have been defined
  - Attempting to modify an array name with pointer arithmetic is a compilation error (e.g., b+=3)

```
1  // Fig. 7.20: fig07_20.cpp
2  // Using indexing and pointer notations with arrays.
3  #include <stdio.h>
4  #define ARRAY_SIZE 4
5
6  int main(void)
7  {
8     int b[] = {10, 20, 30, 40}; // create and initialize array b
9     int *bPtr = b; // create bPtr and point it to array b
10
11    // output array b using array index notation
12    puts("Array b printed with:\nArray index notation");
13
14    // loop through array b
15    for (size_t i = 0; i < ARRAY_SIZE; ++i) {
16       printf("b[%u] = %d\n", i, b[i]);
17    }
18
19    // output array b using array name and pointer/offset notation
20    puts("\nPointer/offset notation where\n"
21          "the pointer is the array name");
22
```

Using indexing and pointer notations with arrays (Part 1 of 3)

```
23      // loop through array b
24      for (size_t offset = 0; offset < ARRAY_SIZE; ++offset) {
25         printf("*(b + %u) = %d\n", offset, *(b + offset));
26      }
27
28      // output array b using bPtr and array index notation
29      puts("\nPointer index notation");
30
31      // loop through array b
32      for (size_t i = 0; i < ARRAY_SIZE; ++i) {
33         printf("bPtr[%u] = %d\n", i, bPtr[i]);
34      }
35
36      // output array b using bPtr and pointer/offset notation
37      puts("\nPointer/offset notation");
38
39      // loop through array b
40      for (size_t offset = 0; offset < ARRAY_SIZE; ++offset) {
41         printf("*(bPtr + %u) = %d\n", offset, *(bPtr + offset));
42      }
43   }
```

Using indexing and pointer notations with arrays (Part 2 of 3)

```
Array b printed with:
Array index notation
b[0] = 10
b[1] = 20
b[2] = 30
b[3] = 40

Pointer/offset notation where
the pointer is the array name
*(b + 0) = 10
*(b + 1) = 20
*(b + 2) = 30
*(b + 3) = 40

Pointer index notation
bPtr[0] = 10
bPtr[1] = 20
bPtr[2] = 30
bPtr[3] = 40

Pointer/offset notation
*(bPtr + 0) = 10
*(bPtr + 1) = 20
*(bPtr + 2) = 30
*(bPtr + 3) = 40
```

Using indexing and pointer notations with arrays (Part 3 of 3)

Exercise

- Find the error in each of the following program segments:

```
int *zPtr;
int *aPtr = NULL;
void *sPtr = NULL;
int number, i;
int z[5] = {1, 2, 3, 4, 5};
sPtr = z;
```

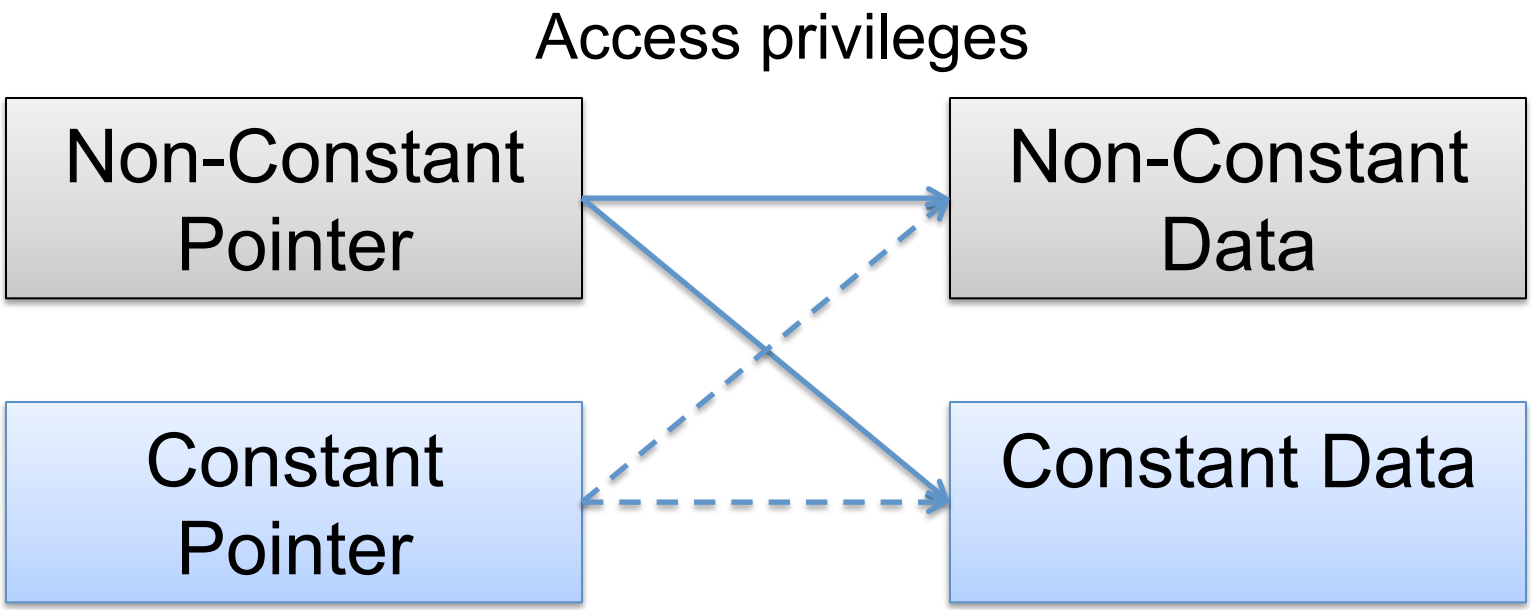
a) ++zPtr;
b) number = zPtr;
c) number = *zPtr[2];
d) number = *sPtr;
e) ++z;

Using the `const` Qualifier with Pointers

- The **`const` qualifier** indicates that the value of a particular variable should not be modified
  - Reduce debugging time and improper side effects
    - It also makes a program easier to modify and maintain
  - Ensure that data is **not accidentally modified**

If an attempt is made to modify a value that's declared **const**, the compiler catches it and issues either a **warning** or an **error**

Using the `const` Qualifier with Pointers (Cont.)



Which combination provides the **highest level of data access**?

```c
// Fig. 7.10: fig07_10.c
// Converting a string to uppercase using a
// non-constant pointer to non-constant data.
#include <stdio.h>
#include <ctype.h>

void convertToUppercase(char *sPtr); // prototype

int main(void)
{
   char string[] = "cHaRaCters and $32.98"; // initialize char array

   printf("The string before conversion is: %s", string);
   convertToUppercase(string);
   printf("\nThe string after conversion is: %s\n", string);
}
```

Converting a string to uppercase using a non-constant pointer to non-constant data (Part 1 of 2)

```
18  // convert string to uppercase letters
19  void convertToUppercase(char *sPtr)
20  {
21     while (*sPtr != '\0') { // current character is not '\0'
22        *sPtr = toupper(*sPtr); // convert to uppercase
23        ++sPtr; // make sPtr point to the next character
24     }
25  }
```

```
The string before conversion is: cHaRaCters and $32.98
The string after conversion is: CHARACTERS AND $32.98
```

Converting a string to uppercase using a non-constant pointer to non-constant data (Part 2 of 2)

Example of Non-Constant Pointer to Constant Data

- A **non-constant pointer to constant data** *can be modified* to point to any data item of the appropriate type, but the *data* to which it points *cannot be modified*

```c
// Fig. 7.11: fig07_11.c
// Printing a string one character at a time using
// a non-constant pointer to constant data.

#include <stdio.h>

void printCharacters(const char *sPtr);

int main(void)
{
   // initialize char array
   char string[] = "print characters of a string";

   puts("The string is:");
   printCharacters(string);
   puts("");
}

```

Printing a string one character at a time using a non-constant pointer to constant data (Part 1 of 2)

```
19  // sPtr cannot be used to modify the character to which it points,
20  // i.e., sPtr is a "read-only" pointer
21  void printCharacters(const char *sPtr)
22  {
23     // loop through entire string
24     for (; *sPtr != '\0'; ++sPtr) { // no initialization
25        printf("%c", *sPtr);
26     }
27  }
```

```
The string is:
print characters of a string
```

Printing a string one character at a time using a non-constant pointer to constant data (Part 2 of 2)

Attempt to Modify Data via a Non-Constant Pointer to Constant Data

- The next example illustrates the attempt to compile a function that receives a non-constant pointer (xPtr) to constant data
- This function attempts to modify the data pointed to by xPtr—which results in a compilation error

```c
// Fig. 7.12: fig07_12.c
// Attempting to modify data through a
// non-constant pointer to constant data.
#include <stdio.h>
void f(const int *xPtr); // prototype

int main(void)
{
   int y; // define y

   f(&y); // f attempts illegal modification
}

// xPtr cannot be used to modify the
// value of the variable to which it points
void f(const int *xPtr)
{
   *xPtr = 100; // error: cannot modify a const object
}
```

```
error C2166: l-value specifies const object
```

Attempting to modify data through a non-constant pointer to constant data

Trade-off Memory and Execution Efficiency

- If **memory** is low and **execution** efficiency is a concern, use **pointers**
- If memory is in abundance and efficiency is not a major concern, **pass data by value** to enforce the principle of **least privilege**
- Remember that some systems do not enforce **`const`** well, so **pass-by-value** is still the best way to prevent data from being modified

Attempting to Modify a Constant Pointer to Non-Constant Data

- A **constant pointer** to **non-constant data** always points to the same memory location
  - the data at that location *can be modified* through the pointer
  - This is the default for an array name (constant pointer)
    - All data in the array can be accessed and changed by using the array name and array indexing

```
int a[5];
```


```
for(int i=0; i<5; i++)
  a[i] = 2*i;
```

a+=2

invalid operands to binary expression ('const int [5]' and 'int')

```c
// Fig. 7.13: fig07_13.c
// Attempting to modify a constant pointer to non-constant data.
#include <stdio.h>

int main(void)
{
   int x; // define x
   int y; // define y

   // ptr is a constant pointer to an integer that can be modified
   // through ptr, but ptr always points to the same memory location
   int * const ptr = &x;

   *ptr = 7; // allowed: *ptr is not const
   ptr = &y; // error: ptr is const; cannot assign new address
}
```

```
c:\examples\ch07\fig07_13.c(15) : error C2166: l-value specifies const object
```

Attempting to modify a constant pointer to non-constant data

Attempting to Modify a Constant Pointer to Constant Data

- The *least* access privilege is granted by a **constant pointer** to **constant data**
- Such a pointer always points to the *same* memory location, and the data at that memory location *cannot be modified*

```
const int a[5];
```


```
for(int i=0; i<5; i++)
  printf("a[%i]: %i\n", i, a[i]);
```

```
a[1]=2
```

read-only variable is not assignable

```c
// Fig. 7.14: fig07_14.c
// Attempting to modify a constant pointer to constant data.
#include <stdio.h>

int main(void)
{
   int x = 5; // initialize x
   int y; // define y

   // ptr is a constant pointer to a constant integer. ptr always
   // points to the same location; the integer at that location
   // cannot be modified
   const int *const ptr = &x; // initialization is OK

   printf("%d\n", *ptr);
   *ptr = 7; // error: *ptr is const; cannot assign new value
   ptr = &y; // error: ptr is const; cannot assign new address
}
```

```
c:\examples\ch07\fig07_14.c(16) : error C2166: l-value specifies const object
c:\examples\ch07\fig07_14.c(17) : error C2166: l-value specifies const object
```

Attempting to modify a constant pointer to constant data

Summary

- Pointer variable definition and initialization
- Pointer operators
- Passing arguments to functions by reference
- Using the `const` qualifier with pointers
- `sizeof` operator
- Pointer expression and pointer arithmetic
- Relationship between pointers and arrays