Chapter 8

Arrays

Scalar Variables versus Aggregate Variables

- So far, the only variables we've seen are ***scalar:*** capable of holding a single data item
- C also supports ***aggregate*** variables, which can store collections of values
- There are two kinds of aggregates in C:
  - arrays and
  - structures

One-Dimensional Arrays

- An ***array*** is a data structure that can hold a number of data values ***(elements)***, all of which have the same type
- ***Elements*** can be individually accessed by their position within the array
- The simplest kind of array has just one dimension
- The elements of a one-dimensional array `a` are conceptually arranged one after another in a single row (or column):

One-Dimensional Arrays

- To *declare* an array, we must specify
  - the *type* of the array's elements and
  - the *number* of elements:

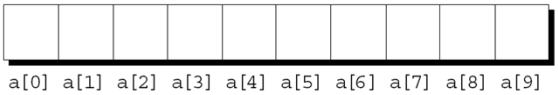
```
int a[10];  /* Note that it is [ ] not ( ) */
```

- The elements may be of *any type*
- The length of the array can be any *integer constant expression*
- Using a macro to define the length of an array is an excellent practice:

```
#define N 10
…
int a[N];
```

Array Subscripting

- To access an array element, write the array name followed by an *integer expression* in *square brackets*
- This is referred to as ***subscripting*** or ***indexing*** the array
- The elements of an array of length *n* are indexed from *0* to *n – 1*
- If `a` is an array of length `10`, its elements are designated by `a[0]`, `a[1]`, ..., `a[9]`:



Array Subscripting

- Array element `a[i]` can be used in the same way as ordinary variables:

```
a[0] = 1;
printf("%d\n", a[5]);
++a[i];
```

Array Subscripting

- Many programs contain `for` loops whose job is to perform some operation on every element in an array
- Examples of typical operations on an array `a` of length `N`:

```
for (i = 0; i < N; i++)
  a[i] = 0;              /* clears a */

for (i = 0; i < N; i++)
  scanf("%d", &a[i]);    /* reads data into a */

sum = 0;
for (i = 0; i < N; i++)
  sum += a[i];           /* sums the elements of a */
```


Array Subscripting

- C does not require that subscript bounds be checked
- If a subscript goes out of range, the program's behavior is undefined
- *A common mistake*: forgetting that an array with *n* elements is indexed from 0 to *n* – 1, not 1 to *n*:

```
int a[10], i;

for (i = 1; i <= 10; i++)
  a[i] = 0;
```

Array Subscripting

- An array subscript may be any *integer* expression:

```
a[i+j*10] = 0;
```

- The expression can even have side effects:

```
i = 0;
while (i < N)
  a[i++] = 0;
```

It is equivalent to

```
for (i = 0; i < N; i++)
  a[i] = 0;
```


Array Subscripting

- Be careful when an array subscript has a side effect:

```
i = 0;
while (i < N)
  a[i] = b[i++];
```

- The expression `a[i] = b[i++]` accesses the value of `i` and also modifies `i`, causing undefined behavior
- The problem can be avoided by removing the increment from the subscript:

```
for (i = 0; i < N; i++)
  a[i] = b[i];
```

Program: Reversing a Series of Numbers

- The `reverse.c` program prompts the user to enter a series of numbers, then writes the numbers in reverse order:

```
Enter 10 numbers: 34 82 49 102 7 94 23 11 50 31
In reverse order: 31 50 11 23 94 7 102 49 82 34
```

- The program stores the numbers in an array as they're read, then goes through the array backwards, printing the elements one by one

reverse.c

```
/* Reverses a series of numbers */

#include <stdio.h>

#define N 10

int main(void)
{
  int a[N], i;

  printf("Enter %d numbers: ", N);
  for (i = 0; i < N; i++)
    scanf("%d", &a[i]);

  printf("In reverse order:");
  for (i = N - 1; i >= 0; i--)
    printf(" %d", a[i]);
  printf("\n");

  return 0;
}
```

reverse.c

```
/* Reverses a series of numbers */

#include <stdio.h>

#define N 10

int main(void)
{
  int a[N], i;

  printf("Enter %d numbers: ", N);
  for (i = 0; i < N; i++)
    scanf("%d", &a[i]);

  printf("In reverse order:");
  for (i = 0; i < N; i++)
    printf(" %d", a[N-1-i]);
  printf("\n");

  return 0;
}
```


reverse.c

```
/* Reverses a series of numbers */

#include <stdio.h>

#define N 10

int main(void)
{
  int a[N], i;

  printf("Enter %d numbers: ", N);
  for (i = 0; i < N; i++)
    scanf("%d", &a[i]);

  printf("In reverse order:");
  for (i = 1; i <= N; i++)
    printf(" %d", a[N-i]);
  printf("\n");

  return 0;
}
```

Array Initialization

- An array, like any other variable, can be given an initial value at the time it's declared
- The most common form of ***array initializer*** is a list of constant expressions enclosed in *braces* and *separated by commas*:

```
int a[10] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
```


Array Initialization

- If the initializer is shorter than the array, the remaining elements of the array are given the value 0:

```
int a[10] = {1, 2, 3, 4, 5, 6};
/* initial value of a is {1,2,3,4,5,6,0,0,0,0} */
```

- Using this feature, we can easily initialize an array to all zeros:

```
int a[10] = {0};
/* initial value of a is {0,0,0,0,0,0,0,0,0,0} */
```

- There's a single 0 inside the braces because it's *illegal* for an initializer to be *completely empty*
- It's also *illegal* for an initializer to be *longer than the array* it initializes

Array Initialization

- If an initializer is present, the length of the array *may be* omitted:

```
int a[] = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
```

- The compiler uses the length of the initializer to determine how long the array is

Array Initialization

- It's often the case that relatively few elements of an array need to be explicitly initialized; the other elements can be given a default value
- An example:

```
int a[15] =
  {0, 0, 29, 0, 0, 0, 0, 0, 0, 7, 0, 0, 0, 0, 48};
```

- For a large array, writing an initializer in this fashion is tedious and error-prone

Designated Initializers (C99)

- C99's ***designated initializers*** can be used to solve this problem
- Here's how we could redo the previous example using a designated initializer:

```
int a[15] = {[2] = 29, [9] = 7, [14] = 48};
```

- Each number in brackets is said to be a ***designator***
- Designated initializers are shorter and easier to read

- The *order* in which the elements are listed *no longer matters*
- Another way to write the previous example:

```
int a[15] = {[14] = 48, [9] = 7, [2] = 29};
```


Designated Initializers (C99)

- *Designators* must be *integer constant expressions*
- If the array being initialized has length *n*, each designator must be between 0 and *n* – 1
- If the length of the array is omitted, a designator can be any nonnegative integer
  - The compiler will assume the length of the array from the largest designator
- The following array will have 24 elements:

```
int b[] = {[5] = 10, [23] = 13, [11] = 36, [15] = 29};
```

- An initializer may use both the *older (element-by-element) technique* and/or the *newer (designated) technique*:

```
int c[10] = {5, 1, 9, [4] = 3, 7, 2, [8] = 6};
/* initial value of a is {5, 1, 9, 0, 3, 7, 2, 0, 6, 0} */
```

Program: Checking a Number for Repeated Digits

- The `repdigit.c` program checks whether any of the *digits* in a *number* appear more than once
- After the user enters a number, the program prints either
  - `Repeated digit` or
  - `No repeated digit:`

```
Enter a number: 28212
Repeated digit
```

  - The number 28212 has a repeated digit (2)
  - a number like 9357 does not

Program: Checking a Number for Repeated Digits

- The program uses an array of 10 Boolean values to keep track of which digits appear in a number
- Initially, every element of the `digit_seen` array is `false`
- When given a number `n`, the program examines `n`'s digits one at a time, storing the current digit in a variable named `digit`
  - If `digit_seen[digit]` is `true`, then `digit` appears at least once in `n`
  - If `digit_seen[digit]` is `false`, then `digit` has not been seen before, so the program sets `digit_seen[digit]` to `true` and keeps going

repdigit.c

```
/* Checks numbers for repeated digits */

#include <stdbool.h>   /* C99 only */
#include <stdio.h>

int main(void)
{
  bool digit_seen[10] = {false};
  int digit;
  long n;

  printf("Enter a number: ");
  scanf("%ld", &n);
  while (n > 0) {
    digit = n % 10;
    if (digit_seen[digit])
      break;
    digit_seen[digit] = true;
    n /= 10;
  }
```



```
  if (n > 0)
    printf("Repeated digit\n");
  else
    printf("No repeated digit\n");

  return 0;
}
```

Using the `sizeof` Operator with Arrays

- The `sizeof` operator can determine the size of an array (in bytes)
- If `a` is an array of 10 integers, then `sizeof(a)` is typically 40 (assuming that each integer requires four bytes)
- We can also use `sizeof` to measure the size of a single array element, such as `a[0]` or `a[7]`
- Dividing the *array size* by the *element size* gives the length of the array (in elements):

```
sizeof(a) / sizeof(a[0])
```


Using the `sizeof` Operator with Arrays

- Some programmers use this expression when the length of the array is needed
- A loop that clears the array `a`:

```
for (i = 0; i < sizeof(a) / sizeof(a[0]); i++)
  a[i] = 0;
```

Note that the loop does not have to be modified if the array length should change at a later date

Using the `sizeof` Operator with Arrays

- Some compilers produce a warning message for the expression `i < sizeof(a) / sizeof(a[0])`
- The variable `i` probably has type `int` (a signed type), whereas `sizeof` produces a value of type `size_t` (an unsigned type)
- Comparing a signed integer with an unsigned integer can be dangerous, but in this case it is safe

Using the `sizeof` Operator with Arrays

- To avoid a warning, we can add a cast that converts `sizeof(a) / sizeof(a[0])` to a signed integer:

```
for (i = 0; i < (int) (sizeof(a) / sizeof(a[0])); i++)
  a[i] = 0;
```

- Defining a macro for the size calculation is often helpful:

```
#define SIZE ((int) (sizeof(a) / sizeof(a[0])))

for (i = 0; i < SIZE; i++)
  a[i] = 0;
```

Program: Computing Interest

- The `interest.c` program prints a table showing the value of $100 invested at various rates of interest over a period of years
- The user will enter an interest rate and the number of years the money will be invested
- The table will show the value of the money at one-year intervals—at that interest rate and the next four higher rates—assuming that *interest* is *compounded* once a year

Program: Computing Interest

- Here's what a session with the program will look like:

```
Enter interest rate: 6
Enter number of years: 5

Years     6%      7%      8%      9%     10%
  1     106.00  107.00  108.00  109.00  110.00
  2     112.36  114.49  116.64  118.81  121.00
  3     119.10  122.50  125.97  129.50  133.10
  4     126.25  131.08  136.05  141.16  146.41
  5     133.82  140.26  146.93  153.86  161.05
```

Program: Computing Interest

- The numbers in the second row depend on the numbers in the first row, so it makes sense to store the first row in an array
  - The values in the array are then used to compute the second row
  - This process can be repeated for the third and later rows
- The program uses nested `for` statements
  - The outer loop counts from 1 to the number of years requested by the user
  - The inner loop increments the interest rate from its lowest value to its highest value

interest.c

```
/* Prints a table of compound interest */

#include <stdio.h>

#define NUM_RATES 5
#define INITIAL_BALANCE 100.00

int main(void)
{
  int i, low_rate, num_years, year;
  double value[NUM_RATES];

  printf("Enter interest rate: ");
  scanf("%d", &low_rate);
  printf("Enter number of years: ");
  scanf("%d", &num_years);
```

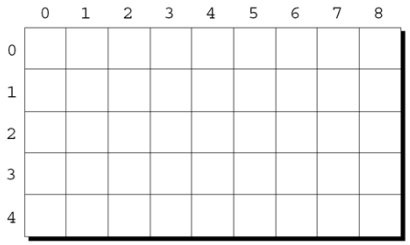
```
  printf("\nYears");
  for (i = 0; i < NUM_RATES; i++)
  { printf("%6d%%", low_rate + i);
    value[i] = INITIAL_BALANCE;
  }
  printf("\n");

  for (year = 1; year <= num_years; year++) {
    printf("%3d    ", year);
    for (i = 0; i < NUM_RATES; i++) {
      value[i] += (low_rate + i) / 100.0 * value[i];
      printf("%7.2f", value[i]);
    }
    printf("\n");
  }

  return 0;
}
```


Multidimensional Arrays

- An array may have any number of dimensions
- The following declaration creates a two-dimensional array (a *matrix*, in mathematical terminology):

```
int m[5][9];
```

- `m` has 5 rows and 9 columns
- Both rows and columns are indexed from 0:

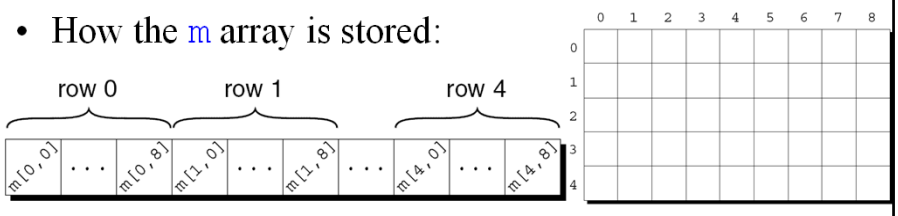


Multidimensional Arrays

- To access the element of `m` in row `i`, column `j`, we must write `m[i][j]`
- The expression `m[i]` designates row `i` of `m`, and `m[i][j]` then selects element `j` in this row
- *Resist the temptation* to write `m[i,j]` instead of `m[i][j]`
- C treats the comma as an operator in this context, so `m[i,j]` is the same as `m[j]`

Multidimensional Arrays

- Although we visualize two-dimensional arrays as tables, that's not the way they're actually stored in computer memory
- C stores arrays in ***row-wise order***, with row 0 first, then row 1, and so forth
- How the `m` array is stored:



Multidimensional Arrays

- Nested `for` loops are ideal for processing multidimensional arrays
- Consider the problem of initializing an array for use as an *identity matrix*
  - A pair of nested `for` loops is perfect:

```
#define N 10

double ident[N][N];
int row, col;

for (row = 0; row < N; row++)
  for (col = 0; col < N; col++)
    if (row == col)
      ident[row][col] = 1.0;
    else
      ident[row][col] = 0.0;
```


Initializing a Multidimensional Array

- We can create an initializer for a two-dimensional array by nesting one-dimensional initializers:

```
int m[5][9] = {{1, 1, 1, 1, 1, 0, 1, 1, 1},
               {0, 1, 0, 1, 0, 1, 0, 1, 0},
               {0, 1, 0, 1, 1, 0, 0, 1, 0},
               {1, 1, 0, 1, 0, 0, 0, 1, 0},
               {1, 1, 0, 1, 0, 0, 1, 1, 1}};
```

- Initializers for higher-dimensional arrays are constructed in a similar fashion

Initializing a Multidimensional Array

- If an initializer is not large enough to fill a multidimensional array, the remaining elements are given the value 0
- The following initializer fills only the first three rows of m; the last two rows will contain zeros:

```
int m[5][9] = {{1, 1, 1, 1, 1, 0, 1, 1, 1},
               {0, 1, 0, 1, 0, 1, 0, 1, 0},
               {0, 1, 0, 1, 1, 0, 0, 1, 0}};
```


Initializing a Multidimensional Array

- If an inner list is not long enough to fill a row, the remaining elements in the row are initialized to 0:

```
int m[5][9] = {{1, 1, 1, 1, 1, 0, 1, 1, 1},
               {0, 1, 0, 1, 0, 1, 0, 1},
               {0, 1, 0, 1, 1, 0, 0, 1},
               {1, 1, 0, 1, 0, 0, 0, 1},
               {1, 1, 0, 1, 0, 0, 1, 1, 1}};
```

Initializing a Multidimensional Array

- We can even omit the inner braces:

```
int m[5][9] = {1, 1, 1, 1, 1, 0, 1, 1, 1,
               0, 1, 0, 1, 0, 1, 0, 1, 0,
               0, 1, 0, 1, 1, 0, 0, 1, 0,
               1, 1, 0, 1, 0, 0, 0, 1, 0,
               1, 1, 0, 1, 0, 0, 1, 1, 1};
```

  Once the compiler has seen enough values to fill one row, it begins filling the next

- Omitting the inner braces can be *risky*, since an extra element (or missing an element) will affect the rest of the initializer

Initializing a Multidimensional Array

- C99's designated initializers work with multidimensional arrays
- How to create 2 × 2 identity matrix:

```
double ident[2][2] = {[0][0] = 1.0, [1][1] = 1.0};
```

  As usual, all elements for which no value is specified will default to zero

Constant Arrays

- An array can be made "constant" by starting its declaration with the word `const`:

```
const unsigned char hex_chars[] =
  {'0', '1', '2', '3', '4', '5', '6', '7', '8', '9',
   'A', 'B', 'C', 'D', 'E', 'F'};
```

- An array that's been declared `const` should not be modified by the program
- Advantages of declaring an array to be `const`:
  - Documents that the program will not change the array
  - Helps the compiler catch errors
- `const` is not limited to arrays

Program: Dealing a Hand of Cards

- The `deal.c` program illustrates both two-dimensional arrays and constant arrays
- The program deals with a random hand from a standard playing cards
- Each card has
  - a *suit* (clubs ♣, diamonds ♦, hearts ♥, or spades ♠) and
  - a *rank* (two, three, four, five, six, seven, eight, nine, ten, jack, queen, king, or ace)

Program: Dealing a Hand of Cards

- The user will specify how many cards should be in the hand:

```
Enter number of cards in hand: 5
Your hand: 7c 2s 5d as 2h
```

- Problems to be solved:
  - How do we randomly pick cards from the playing cards?
  - How do we avoid picking the same card twice?

Program: Dealing a Hand of Cards

- To pick cards randomly, we'll use several **C** library functions:
  - `time()` — from **`<time.h>`**
    returns the current time, encoded in a single *signed integer* value representing the number of seconds elapsed since 00:00 hours, Jan 1, 1970
  - `rand()` — from **`<stdlib.h>`**
    produces an *apparently* random integer number between 0 and `RAND_MAX` each time it's called
  - `srand()` — from **`<stdlib.h>`**
    initializes **C**'s random number generator for a new sequence of *pseudo-random* integers to be returned by `rand()`
- By using the `%` operator, we can scale the return value from `rand` so that it falls between 0 and 3 (for suits) or between 0 and 12 (for ranks)

Program: Dealing a Hand of Cards

- The `in_hand` array is used to keep track of which cards have already been chosen
- The array has 4 rows and 13 columns; each element corresponds to one of the 52 cards in the playing cards
- All elements of the array will be false to start with
- Each time we pick a card *at random*, we'll check whether the element of `in_hand` corresponding to that card is `true` or `false`
  - If it's `true`, we'll have to pick another card
  - If it's `false`, we'll store `true` in that element to remind us later that this card has already been picked

Program: Dealing a Hand of Cards

- Once we've verified that a card is *new*, we'll need to translate its numerical rank and suit into characters and then display the card
- To translate the rank and suit to character form, we'll
  - set up two arrays of characters:
    - one for the rank and
    - one for the suit
  - use the numbers to subscript the arrays
- These arrays will not change during program execution, so they are declared to be `const`

deal.c

```
/* Deals with a random hand of cards */

#include <stdbool.h>   /* C99 only */
#include <stdio.h>
#include <stdlib.h>
#include <time.h>

#define NUM_SUITS 4
#define NUM_RANKS 13

int main(void)
{
  bool in_hand[NUM_SUITS][NUM_RANKS] = {false};
  int num_cards, rank, suit;
  const char rank_code[] = {'2','3','4','5','6','7','8',
                            '9','t','j','q','k','a'};
  const char suit_code[] = {'c','d','h','s'};
```



```
  srand((unsigned) time(NULL));

  printf("Enter number of cards in hand: ");
  scanf("%d", &num_cards);

  printf("Your hand:");
  while (num_cards > 0)
  { suit = rand() % NUM_SUITS;     /* picks a random suit */
    rank = rand() % NUM_RANKS;     /* picks a random rank */
    if (!in_hand[suit][rank])
    { in_hand[suit][rank] = true;
      num_cards--;
      printf(" %c%c", rank_code[rank], suit_code[suit]);
    }
  }
  printf("\n");

  return 0;
}
```

Variable-Length Arrays (C99)

- In C89, the length of an array variable must be specified by a constant expression
- In C99, however, it's sometimes possible to use an expression that's *not* constant
- The `reverse2.c` program—a modification of `reverse.c`—illustrates this ability

reverse2.c

```
/* Reverses a series of numbers using a variable-length
   array - C99 only */

#include <stdio.h>

int main(void)
{
  int i, n;

  printf("How many numbers do you want to reverse? ");
  scanf("%d", &n);

  int a[n];   /* C99 only - length of array depends on n */

  printf("Enter %d numbers: ", n);
  for (i = 0; i < n; i++)
    scanf("%d", &a[i]);
```

```
  printf("In reverse order:");
  for (i = n - 1; i >= 0; i--)
    printf(" %d", a[i]);
  printf("\n");

  return 0;
}
```


Variable-Length Arrays (C99)

- The array `a` in the `reverse2.c` program is an example of a ***variable-length array*** (or ***VLA***)
- The length of a VLA is computed when the program is executed
- The chief advantage of a VLA is that a program can calculate exactly how many elements are needed
- If the programmer makes the choice, it's likely that the array will
  - be too long (wasting memory) or
  - Be too short (causing the program to fail)

Variable-Length Arrays (C99)

- The length of a VLA does not have to be specified by a single variable. Arbitrary expressions are legal:

```
int a[3*i+5];
int b[j+k];
```

- Like other arrays, VLAs can be multidimensional:

```
int c[m][n];
```

- **Restrictions on VLAs:**
  - Can not have an initializer
  - Can not have *static storage duration* (to be discussed in Chapter 18)