Chapter 8

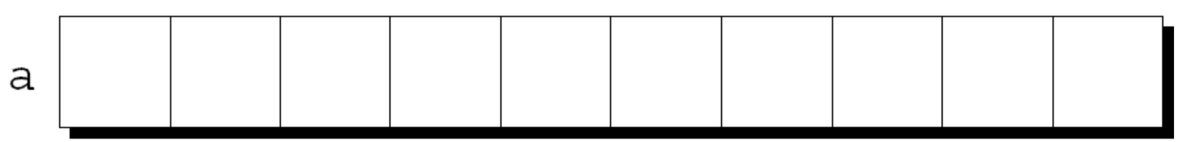
Arrays

Scalar Variables versus Aggregate Variables

- So far, the only variables we've seen are ***scalar (a single number):*** 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.
- The focus of the chapter is on one-dimensional arrays, which play a much bigger role in C than do multidimensional arrays.

One-Dimensional Arrays

- An ***array*** is a data structure containing a number of data values, all of which have the same type.
- These values, known as ***elements,*** can be individually selected by their position (***index***) 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:

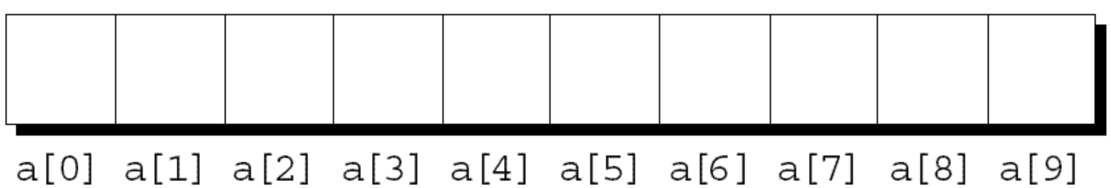
```
int a[10];
```

- 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 value 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

- Expressions of the form `a[i]` are lvalues, so they can be used in the same way as ordinary variables:

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

- In general, if an array contains elements of type *T*, then each element of the array is treated as if it were a variable of type *T*.

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 */

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

Array Subscripting

- C doesn't 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;
```

  With some compilers, this innocent-looking `for` statement causes an infinite loop.

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;
```

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;
}
```

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. (*warning: excess elements in array initializer*)

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.

Designated Initializers (C99)

- It's often the case that relatively few elements of an array need to be initialized explicitly; the other elements can be given default values.
- 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 (C99)

- Designated initializers are shorter and easier to read (at least for some arrays).
- Also, 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 deduce 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};
```

Designated Initializers (C99)

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

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

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 user enters a number, 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 doesn't.

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 twice 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 an array element, such as `a[0]`.
- Dividing the array size by the element size gives the length of the array:

```
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 doesn't 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's 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 different 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 ((int) (sizeof(value) / sizeof(value[0])))
#define INITIAL_BALANCE 100.00

int main(void)
{
  int i, low_rate, num_years, year;
  double value[5];

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

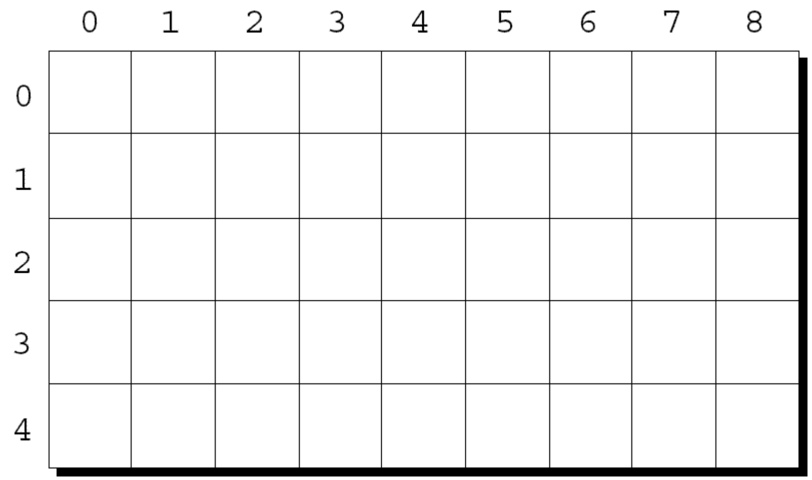
```
  printf("\nYears");
  for (i = 0; i < NUM_RATES; i++) {
    printf("%6d%%", low_rate + i);
    value[i] = INITIAL_BALANCE;
  }
  printf("\n");

  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:

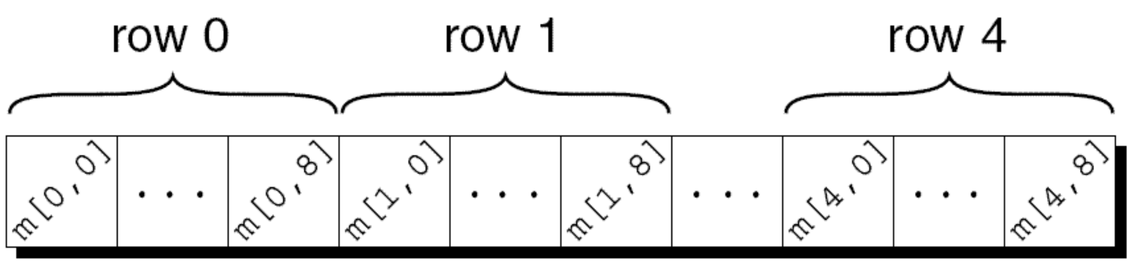


Multidimensional Arrays

- 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-major 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.
- C provides a variety of ways to abbreviate initializers for multidimensional arrays

Initializing a Multidimensional Array

- If an initializer isn't 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 isn't 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 even worse, a missing 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 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.

Constant Arrays

- Advantages of declaring an array to be `const`:
  - Documents that the program won't change the array.
  - Helps the compiler catch errors.
- `const` isn't limited to arrays, but it's particularly useful in array declarations.

Program: Dealing a Hand of Cards

- The `deal.c` program illustrates both two-dimensional arrays and constant arrays.
- The program deals a random hand from a standard deck of playing cards.
- Each card in a standard deck 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 pick cards randomly from the deck?
  - How do we avoid duplicated cards (i.e., 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 number.
  - `srand` (from `<stdlib.h>`) – initializes C's random number generator.
  - `rand` (from `<stdlib.h>`) – produces an apparently random number each time it's called.
- 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 deck.
- 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—and then use the numbers to subscript the arrays.
- These arrays won't change during program execution, so they are declared to be `const`.

deal.c

```
/* Deals 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 too short (causing the program to fail).

Variable-Length Arrays (C99)

- The length of a VLA doesn't 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't have static storage duration (discussed in Chapter 18).
  - Can't have an initializer.

Variable-Length Arrays (C99)

- If VLA fails, a STACK overflow occurs, which can not be checked beforehand. (However, ***dynamic memory allocation*** can.)
- have to keep track of how much stack you use with respect to your total stack size to avoid this situation.
- The main use of VLA is basically a zero-overhead malloc() for **small allocations**.

Variable-Length Arrays (C99)

- While VLA is bad/dangerous, pointer-to-VLA types are extremely useful. They make it possible to have dynamically-allocated (via malloc) multi-dimensional arrays without doing the dimension arithmetic manually, as in:

  size_t n;

  double (*matrix)[n] = malloc(n * sizeof *matrix);

  to get an n-by-n matrix addressable as matrix[i][j].