Chapter 12

Pointers and Arrays

Introduction

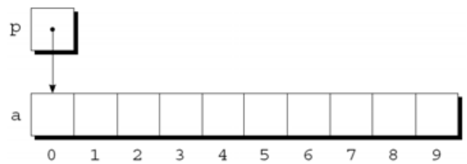
- C allows us to perform
  - arithmetic—addition and subtraction—
  - on pointers to array elements.
- This leads to an alternative way of processing arrays in which pointers
  - take the place (代替) of array subscripts.
- The relationship between pointers and arrays in C is a close one.
- Understanding this relationship is critical for mastering C.

Pointer Arithmetic

- Chapter 11 showed that pointers can point to array elements:

```
int a[10], *p;
p = &a[0];
```

- A graphical representation:

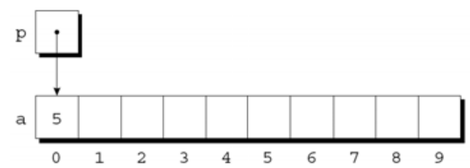


Pointer Arithmetic

- We can now access `a[0]` through `p`; for example, we can store the value 5 in `a[0]` by writing

```
*p = 5;
```

- An updated picture:



Pointer Arithmetic

- If `p` points to an element of an array `a`,
  - the other elements of `a` can be accessed
  - by performing ***pointer arithmetic*** (or ***address arithmetic***) on `p`.
- C supports three (and only three) forms of pointer arithmetic:
  - Adding an integer to a pointer
  - Subtracting an integer from a pointer
  - Subtracting one pointer from another

Adding an Integer to a Pointer

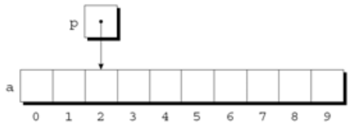
- Adding an integer `j` to a pointer `p`
  - yields a pointer to the element `j` places after the one that `p` points to.
- More precisely,
  - if `p` points to the array element `a[i]`,
  - then `p + j` points to `a[i+j]`.
- Assume that the following declarations are in effect:

```
int a[10], *p, *q, i;
```

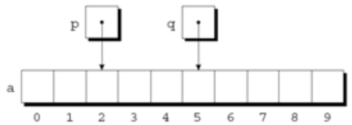

Adding an Integer to a Pointer

- Example of pointer addition:

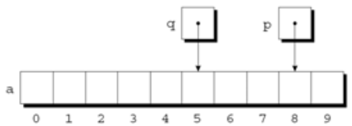
```
p = &a[2];
```




```
q = p + 3;
```



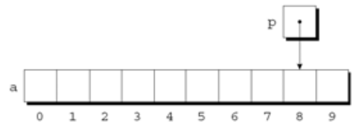

```
p += 6;
```



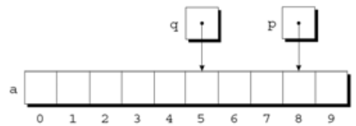
Subtracting an Integer from a Pointer

- If `p` points to `a[i]`, then `p - j` points to `a[i-j]`.
- Example:

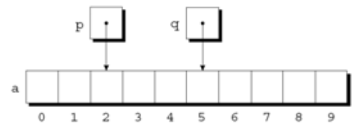
```
p = &a[8];
```




```
q = p - 3;
```



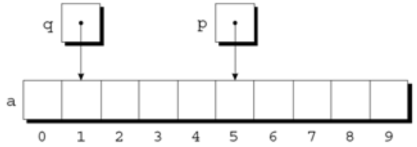

```
p -= 6;
```



Subtracting One Pointer from Another

- When one pointer is subtracted from another, the result is the distance (measured in array elements) between the pointers.
- If `p` points to `a[i]` and `q` points to `a[j]`, then `p - q` is equal to `i - j`.
- Example:

```
p = &a[5];
q = &a[1];
```




```
i = p - q;   /* i is 4 */
i = q - p;   /* i is -4 */
```


Subtracting One Pointer from Another

- Operations that cause undefined behavior:
  - Performing arithmetic on a pointer that doesn't point to an array element

```
int i, *ip = &i;
ip += 3;                /* wrong */
```

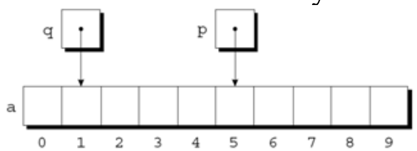
  - Subtracting pointers unless both point to elements of the same array

```
int a[10], *ap = a[0];
int b[10], *bp = b[0];
int dis = bp - ap;            /* wrong */
```


Comparing Pointers

- Pointers can be compared using
  - the relational operators (<, <=, >, >=) and
  - the equality operators (== and !=).
  - Using relational operators is meaningful only for pointers to elements of the same array.
- The outcome of the comparison depends on the relative positions of the two elements in the array.
- After the assignments

```
p = &a[5];
q = &a[1];
```



the value of `p <= q` is 0 and the value of `p >= q` is 1.

Pointers to Compound Literals (C99)

- It's legal for a pointer to point to an element within an array created by a compound literal:

```
int *p = (int []){3, 0, 3, 4, 1};
```

- Using a compound literal saves us the trouble of
  - first declaring an array variable and then
  - making `p` point to the first element of that array:

```
int a[] = {3, 0, 3, 4, 1};
int *p = &a[0];
```

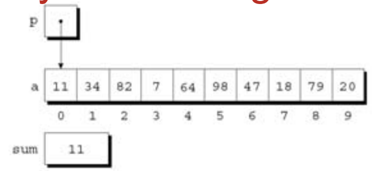
Using Pointers for Array Processing

- Pointer arithmetic
  - allows us to visit the elements of an array
  - by repeatedly incrementing a pointer variable.
- A loop that sums the elements of an array a:

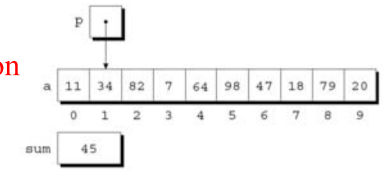
```
#define N 10
…
int a[N], sum, *p;
…
sum = 0;
for (p = &a[0]; p < &a[N]; p++)
  sum += *p;
```


Using Pointers for Array Processing

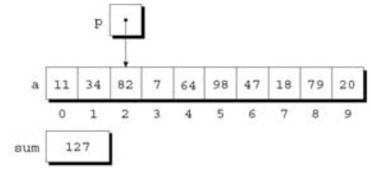
At the end of the first iteration:



At the end of the second iteration



At the end of the third iteration:



Using Pointers for Array Processing

```
for (p = &a[0]; p < &a[N]; p++)
  sum += *p;
```

- The condition `p < &a[N]` in the `for` statement deserves special mention.
- It's legal to apply the address operator to `a[N]`, even though this element doesn't exist.
- Pointer arithmetic may save execution time.
- However, some C compilers produce better code for loops that rely on subscripting.

Combining the * and ++ Operators

- C programmers often combine the `*` (indirection) and `++` operators.
- A statement that modifies an array element and then advances to the next element:

  `a[i++] = j;`
- The corresponding pointer version:

先

後

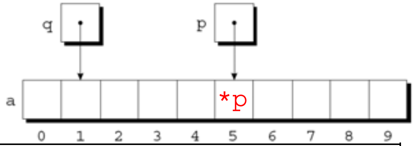
```
*p++ = j;
```

- Because the postfix version of `++` takes precedence over `*`, the compiler sees this as

  `*(p++) = j;`

Combining the * and ++ Operators

- Possible combinations of * and ++:



Expression	*Meaning*
`*p++` or `*(p++)`	Value of expression is `*p` before increment; increment `p` later 後指標往右移
`(*p)++`	Value of expression is `*p` before increment; increment `*p` later 後內容加一
`*++p` or `*(++p)`	Increment `p` first; 先指標往右移 value of expression is `*p` after increment
`++*p` or `++(*p)`	Increment `*p` first; 先內容加一 value of expression is `*p` after increment

Combining the * and ++ Operators

- The most common combination of * and ++ is `*p++`, which is handy in loops.
- Instead of writing

```
for (p = &a[0]; p < &a[N]; p++)
  sum += *p;
```

to sum the elements of the array a, we could write

```
p = &a[0];
while (p < &a[N])
  sum += *p++;
```


Combining the * and ++ Operators

- The * and -- operators mix in the same way as * and ++.
- For an application that combines * and --, let's return to the stack example of Chapter 10.
- The original version of the stack relied on an integer variable named `top` to keep track of the "top-of-stack" position in the contents array.
- Let's replace `top` by a pointer variable that points initially to element 0 of the `contents` array:

```
int *top_ptr = &contents[0];
```


Combining the * and ++ Operators

- The new `push` and `pop` functions:

```
void push(int i)
{
  if (is_full())
    stack_overflow();
  else
    *top_ptr++ = i;
}

int pop(void)
{
  if (is_empty())
    stack_underflow();
  else
    return *--top_ptr;
}
```

Using an Array Name as a Pointer

- Pointer arithmetic
  - is one way in which arrays and pointers are related.
- Another key relationship:

  The name of an array can be used as a pointer to the first element in the array.

```
int a[N];
a; &a[0];
```

- This relationship simplifies pointer arithmetic and makes both arrays and pointers more versatile 多樣.

Using an Array Name as a Pointer

- Suppose that `a` is declared as follows:

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

- Examples of using `a` as a pointer:

```
*a = 7;          /* stores  7 in a[0] */
*(a+1) = 12;     /* stores 12 in a[1] */
```

- In general, `a + i` is the same as `&a[i]`.
  - Both represent a pointer to element `i` of `a`.
- Also, `*(a+i)` is equivalent to `a[i]`.
  - Both represent element `i` itself.

Using an Array Name as a Pointer

- The fact that an array name
  - can serve as a pointer
  - makes it easier to write loops that step through an array.
- Original loop:

```
for (p = &a[0]; p < &a[N]; p++)
  sum += *p;
```

- Simplified version:

```
for (p = a; p < a + N; p++)
  sum += *p;
```


Using an Array Name as a Pointer

- Although an array name can be used as a pointer, it's not possible to assign it a new value.
- Attempting to make it point elsewhere is an error:

```
while (*a != 0)
  a++;            /*** WRONG ***/
```

- This is no great loss; we can always copy `a` into a pointer variable, then change the pointer variable:

```
p = a;
while (*p != 0)
  p++;
```

Program: Reversing a Series of Numbers (Revisited)

- The `reverse.c` program of Chapter 8
  - reads 10 numbers,
  - then writes the numbers in reverse order.
- The original program s
  - tores the numbers in an array,
  - with subscripting used to access elements of the array.
- `reverse3.c`
  - is a new version of the program
  - in which subscripting has been replaced with pointer arithmetic.

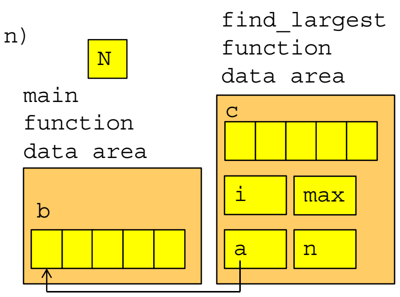
reverse3.c

```
/* Reverses a series of numbers (pointer version) */

#include <stdio.h>

#define N 10

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

  printf("Enter %d numbers: ", N);
  for (p = a; p < a + N; p++)
    scanf("%d", p);

  printf("In reverse order:");
  for (p = a + N - 1; p >= a; p--)
    printf(" %d", *p);
  printf("\n");

  return 0;
}
```


Array Arguments (Revisited)

- When passed to a function, an array name is treated as a pointer.
- Example:

```
int find_largest(int a[], int n)
{
  int i, max;
  int c[10]; /* local */
  max = a[0];
  for (i = 1; i < n; i++)
    if (a[i] > max)
      max = a[i];
  return max;
}
```



- A call of `find_largest`:

```
int b[10];
largest = find_largest(b, N);
```

This call causes a pointer to the first element of `b` to be assigned to `a`; the array itself isn't copied.

Array Arguments (Revisited)

- The fact that
  - an array argument is treated as a pointer
  - has some important consequences.
- *Consequence 1:*
- When an ordinary variable is passed to a function, its value is copied; any changes to the corresponding parameter don't affect the variable.
- In contrast, an array used as an argument isn't protected against change.

Array Arguments (Revisited)

- For example, the following function modifies an array by storing zero into each of its elements:

```
void store_zeros(int a[], int n)
{
  int i;

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


Array Arguments (Revisited)

- To indicate that an array parameter won't be changed, we can include the word `const` in its declaration:

```
int find_largest(const int a[], int n)
{
  …
}
```

- If `const` is present,
  - the compiler will check that no assignment to an element of `a` appears in the body of `find_largest`.

Array Arguments (Revisited)

- *Consequence 2:*
- The time required to pass an array to a function doesn't depend on the size of the array.
- There's no penalty for passing a large array, since no copy of the array is made.

Array Arguments (Revisited)

- *Consequence 3:*
- An array parameter can be declared as a pointer if desired.
- `find_largest` could be defined as follows:

```
int find_largest(int *a, int n)
{
  …
}
```

- Declaring `a` to be a pointer
  - is equivalent to declaring it to be an array; the compiler treats the declarations as though they were identical.

Array Arguments (Revisited)

- Although declaring a *parameter* to be an array
  - is the same as declaring it to be a pointer,
  - the same isn't true for a *variable*.
- The following declaration causes the compiler to set aside (留出) space for 10 integers:

```
int a[10];          /* 40 bytes */
```

- The following declaration causes the compiler to allocate space for a pointer variable:

```
int *a;              /* 8 bytes */
```


Array Arguments (Revisited)

- In the latter case, a is not an array; attempting to use it as an array can have disastrous results.
- For example, the assignment

```
*a = 0;    /*** WRONG ***/
```

will store 0 where a is pointing.

- Since we don't know where a is pointing, the effect on the program is undefined.

Array Arguments (Revisited)

- *Consequence 4:*
- A function with an array parameter
  - can be passed an array "slice"
  - —a sequence of consecutive elements.
- An example that applies `find_largest` to elements 5 through 14 of an array b:

```
largest = find_largest(&b[5], 10);
```


Using a Pointer as an Array Name

- C allows us to subscript a pointer as though it were an array name:

```
#define N 10
…
int a[N], i, sum = 0, *p = a;
…
for (i = 0; i < N; i++)
  sum += p[i];
```

The compiler treats `p[i]` as `*(p+i)`.

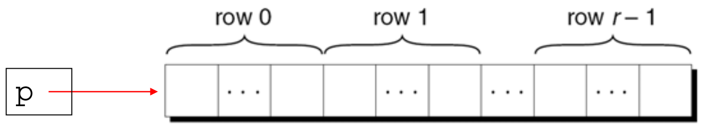
Pointers and Multidimensional Arrays

- Just as pointers can point to
  - elements of one-dimensional arrays,
- they can also point to
  - elements of multidimensional arrays.

- This section explores common techniques for using pointers
  - to process the elements of multidimensional arrays.

Processing the Elements of a Multidimensional Array

- Chapter 8 showed that C stores two-dimensional arrays in row-major order.
- Layout of an array with *r* rows:



- If `p` initially points to the element in row 0, column 0,
  - we can visit every element in the array
  - by incrementing `p` repeatedly.

Processing the Elements of a Multidimensional Array

- Consider the problem of initializing all elements of the following array to zero:

```
int a[NUM_ROWS][NUM_COLS];
```

- The obvious technique would be to use nested `for` loops:

```
int row, col;
…
for (row = 0; row < NUM_ROWS; row++)
  for (col = 0; col < NUM_COLS; col++)
    a[row][col] = 0;
```

- If we view `a` as a one-dimensional array of integers, a single loop is sufficient:

```
int *p;
…
for (p = &a[0][0]; p <= &a[NUM_ROWS-1][NUM_COLS-1]; p++)
  *p = 0;
```


Processing the Elements of a Multidimensional Array

- Although treating a two-dimensional array as one-dimensional
  - may seem like cheating,
  - it works with most C compilers.
- Techniques like this one
  - definitely hurt program readability,
  - but—at least with some older compilers—produce a compensating (補償性質的) increase in efficiency.
- With many modern compilers, though, there's often little or no speed advantage.

Processing the Rows of a Multidimensional Array

- A pointer variable `p`
  - can also be used for processing the elements in just one *row* of a two-dimensional array.
- To visit the elements of row `i`, we'd initialize `p` to point to element 0 in row `i` in the array `a`:

```
int a[NUM_ROWS][NUM_COLS];
p = &a[i][0];
```

or we could simply write

```
p = a[i];
```


Processing the Rows of a Multidimensional Array

- For any two-dimensional array `a`,
  - the expression `a[i]`
  - is a pointer to the first element in row `i`.
- To see why this works, recall that `a[i]` is equivalent to `*(a + i)`. `/* int a[10]; */`
- Thus, `&a[i][0]` is the same as `&(*(a[i] + 0))`, which is equivalent to `&*a[i]`.
- This is the same as `a[i]`, since the `&` and `*` operators cancel.

Processing the Rows of a Multidimensional Array

- A loop that clears row `i` of the array `a`:

```
int a[NUM_ROWS][NUM_COLS], *p, i;
…
for (p = a[i]; p < a[i] + NUM_COLS; p++)
  *p = 0;
```

- Since `a[i]`
  - is a pointer to row `i` of the array `a`,
  - we can pass `a[i]` to a function that's expecting a one-dimensional array as its argument.
- In other words, a function that's designed to
  - work with one-dimensional arrays will also
  - work with a row belonging to a two-dimensional array.

Processing the Rows of a Multidimensional Array

- Consider `find_largest`, which was originally designed to find the largest element of a one-dimensional array.
- We can just as easily use `find_largest` to determine the largest element in row `i` of the two-dimensional array `a`:

```
largest = find_largest(a[i], NUM_COLS);
```

Processing the Columns of a Multidimensional Array

- Processing the elements in a *column* of a two-dimensional array
  - isn't as easy,
  - because arrays are stored by row, not by column.
- A loop that clears column `i` of the array `a`:

```
int a[NUM_ROWS][NUM_COLS], (*p)[NUM_COLS], i;
…
for (p = &a[0]; p < &a[NUM_ROWS]; p++)
  (*p)[i] = 0;
```


Using the Name of a Multidimensional Array as a Pointer

- The name of *any* array
  - can be used as a pointer,
  - regardless of how many dimensions it has, but some care is required.
- Example:

  ```
  int a[NUM_ROWS][NUM_COLS];
  ```

  `a` is *not* a pointer to `a[0][0]`; instead, it's a pointer to `a[0]`.
- C regards `a`
  - as a one-dimensional array
  - whose elements are one-dimensional arrays.
- When used as a pointer, `a` has type `int (*)[NUM_COLS]` (pointer to an integer array of length `NUM_COLS`).

Using the Name of a Multidimensional Array as a Pointer

- Knowing that `a` points to `a[0]` is useful for simplifying loops that process the elements of a two-dimensional array.
- Instead of writing

  ```
  for (p = &a[0]; p < &a[NUM_ROWS]; p++)
    (*p)[i] = 0;
  ```

  to clear column `i` of the array `a`, we can write

  ```
  for (p = a; p < a + NUM_ROWS; p++)
    (*p)[i] = 0;
  ```


Using the Name of a Multidimensional Array as a Pointer

- We can "trick" a function into thinking that a multidimensional array is really one-dimensional.
- A first attempt at using using `find_largest` to find the largest element in `a`:

  ```
  largest = find_largest(a, NUM_ROWS * NUM_COLS);
    /* WRONG */
  ```

  This an error, because the type of `a` is `int (*)[NUM_COLS]` but `find_largest` is expecting an argument of type `int *`.
- The correct call:

  ```
  largest = find_largest(a[0], NUM_ROWS * NUM_COLS);
  ```

  `a[0]` points to element 0 in row 0, and it has type `int *` (after conversion by the compiler).

Pointers and Variable-Length Arrays (C99)

- Pointers are allowed to point to elements of variable-length arrays (VLAs).
- An ordinary pointer variable would be used to point to an element of a one-dimensional VLA:

```
void f(int n)
{
  int a[n], *p;
  p = a;
  …
}
```


Pointers and Variable-Length Arrays (C99)

- When the VLA has more than one dimension,
  - the type of the pointer depends on the length of each dimension except for the first.
- A two-dimensional example:

```
void f(int m, int n)
{
  int a[m][n], (*p)[n];
  p = a;
  …
}
```

  Since the type of `p` depends on `n`, which isn't constant, `p` is said to have a ***variably modified type.***

Pointers and Variable-Length Arrays (C99)

- The validity of an assignment such as `p = a` can't always be determined by the compiler.
- The following code will compile but is correct only if `m` and `n` are equal:

```
int a[m][n], (*p)[m];
p = a;
```

- If `m` is not equal to `n`, any subsequent use of `p` will cause undefined behavior.

Pointers and Variable-Length Arrays (C99)

- Variably modified types are subject to certain restrictions.
- The most important restriction:
  - the declaration of a variably modified type
  - must be inside the body of a function or in a function prototype.

Pointers and Variable-Length Arrays (C99)

- Pointer arithmetic works with VLAs.
- A two-dimensional VLA:

```
int a[m][n];
```

- A pointer capable of pointing to a row of `a`:

```
int (*p)[n];
```

- A loop that clears column `i` of `a`:

```
for (p = a; p < a + m; p++)
  (*p)[i] = 0;
```