HIGH-LEVEL PROGRAMMING I

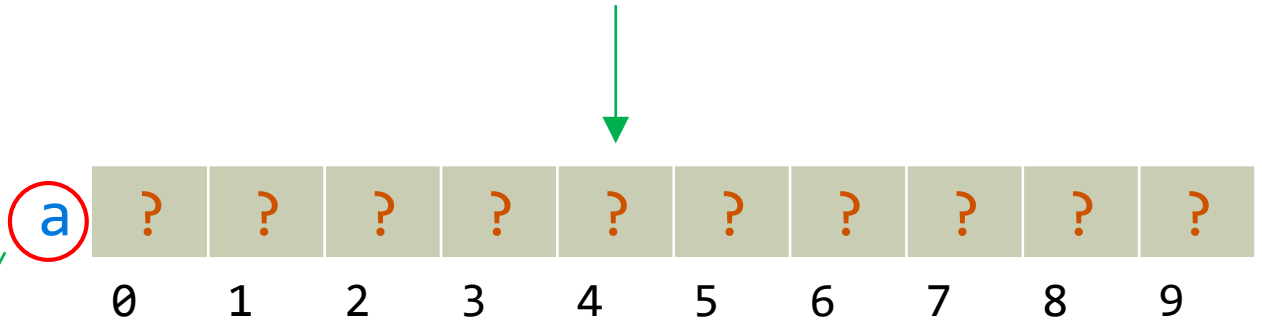
Arrays and pointers

by Prasanna Ghali

What do we know about arrays?


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

Using base type `int` and size `10`, compiler reserves 40 bytes of contiguous memory storage



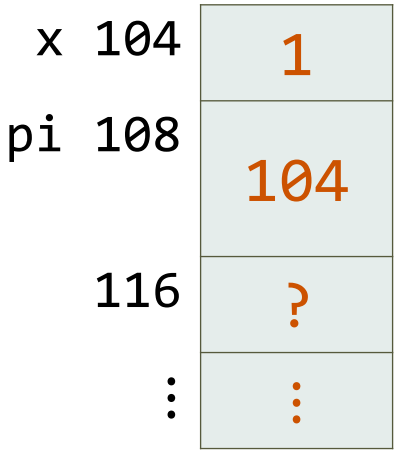
`a` is base address of array

`a[i]`: subscript operator is used to refer to anonymous array elements

What do we know about pointers? (1/2)


```
int x = 1, *pi = &x;
```

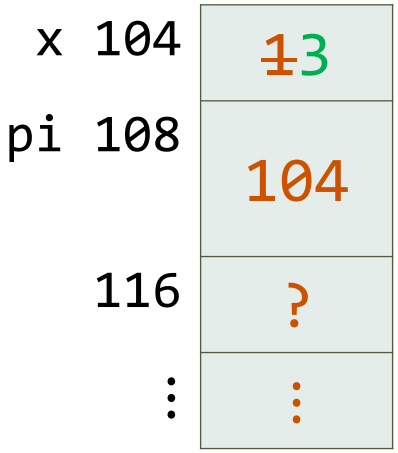
address of operator



What do we know about pointers? (2/2)


```
int x = 1, *pi = &x;
*pi = 3;
```

dereference or *indirection* operator



Pointers and arrays

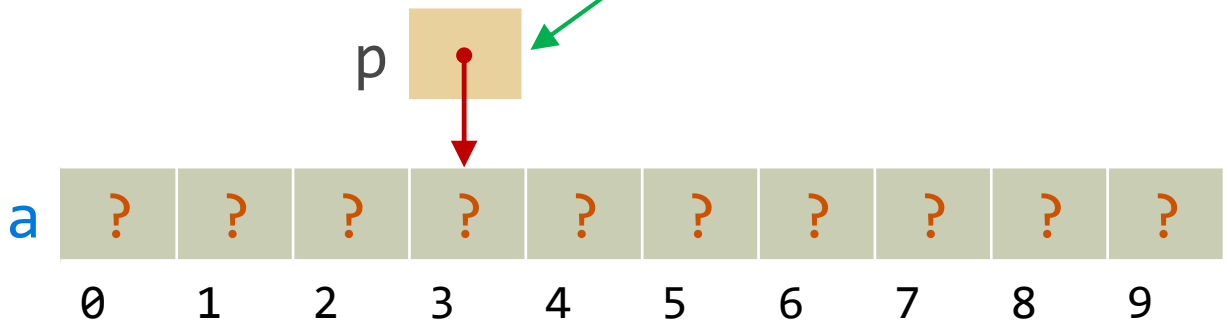
- Pointers and arrays have close relationship that provides alternative way of referencing array elements
  - Subscript operator can be replaced with pointer arithmetic and dereference operator
- Understanding this relationship critical for mastering C

Pointer arithmetic (1/4)

Array element `a[i]` is like any other `int` variable

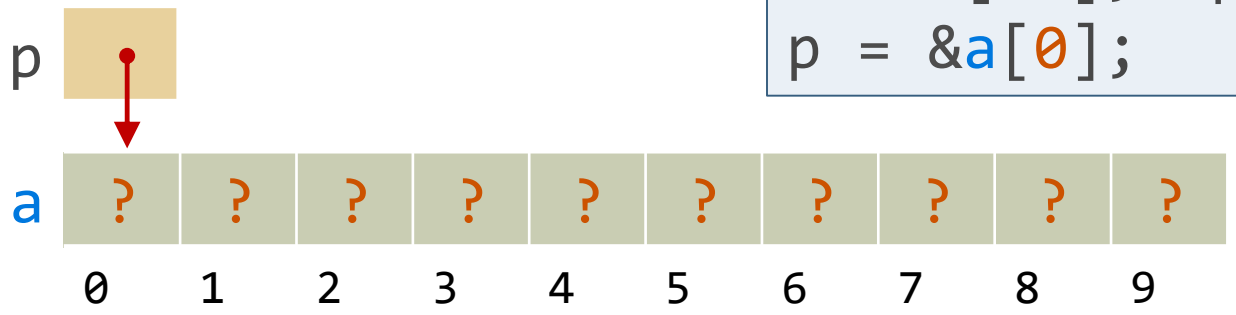
```
int a[10], *p;
p = &a[3];
```

Pointer `p` can therefore point to array element `a[i]`



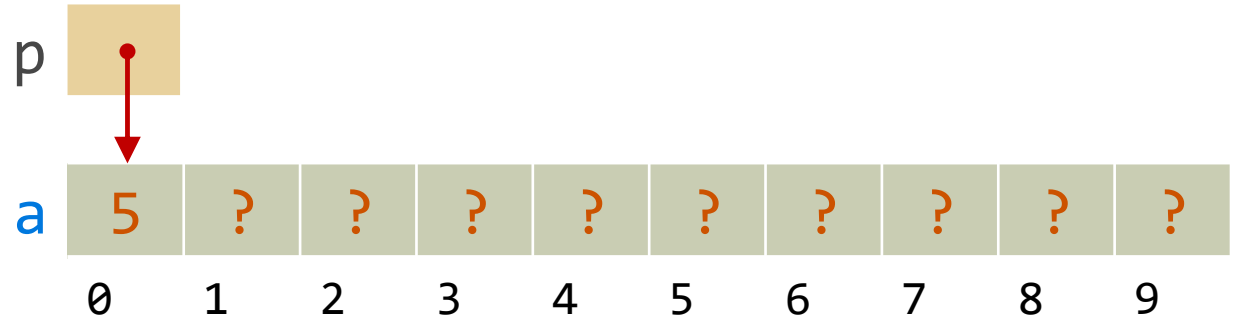
Pointer arithmetic (2/4)


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

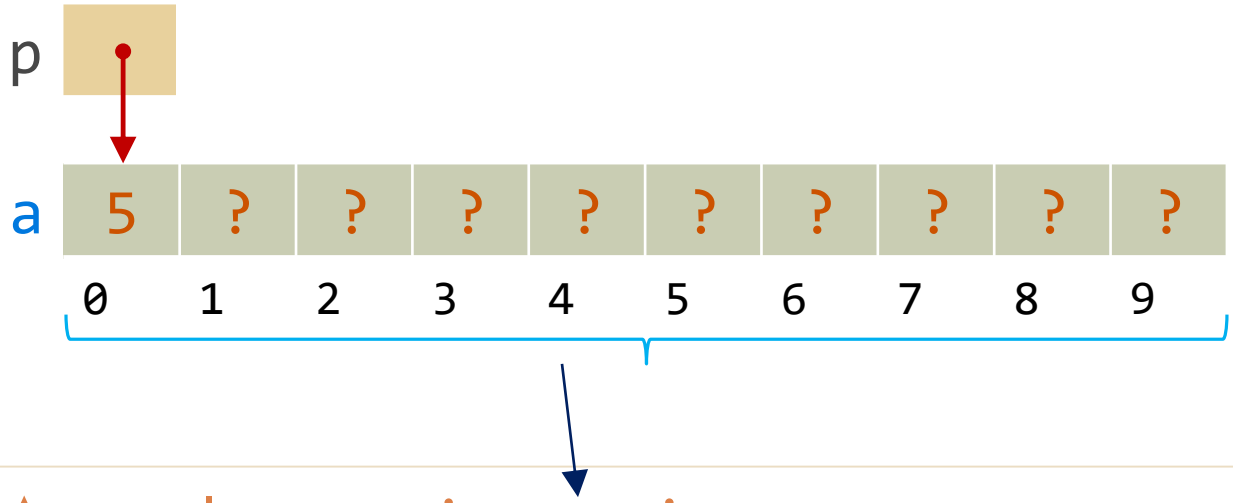


- Use p to indirectly update a[0]:

```
*p = 5;
```



Pointer arithmetic (3/4)




```
int a[10], *p;
p = &a[0];
*p = 5;
```

Array elements given contiguous memory storage.
Each element stored `sizeof(int)` bytes after previous element.

- If pointer p points to array element, other array elements can be referenced by performing pointer arithmetic on p

Pointer arithmetic (4/4)

- Four forms of pointer arithmetic supported:
  - Adding integer to pointer
  - Subtracting integer from pointer
  - Subtracting one pointer from another
  - Comparing pointers

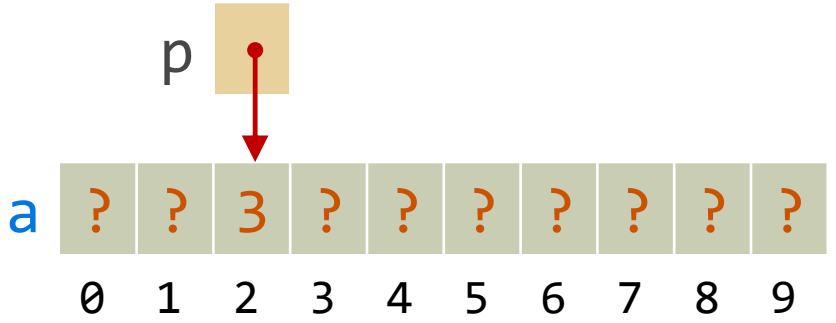
Adding integer to pointer

- Suppose `p` is pointing to array element `a[i]`
- Adding integer `j` to pointer `p` yields pointer to element `j` places *after* the one that `p` points to
  - More precisely: if `p` points to array element `a[i]`, then `p+j` points to `a[i+j]`

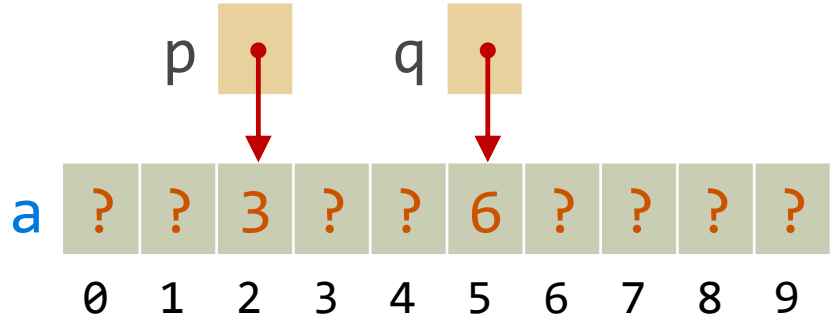
```
int a[5] = {6, 2, 7, 3, 8};
int *p = &a[1], *q = p+3;
printf("%p | %p | %p\n", p, p+3, q);
printf("%d | %d | %d\n", *p, *(p+3), *q);
```

Examples:
Adding integer to pointer

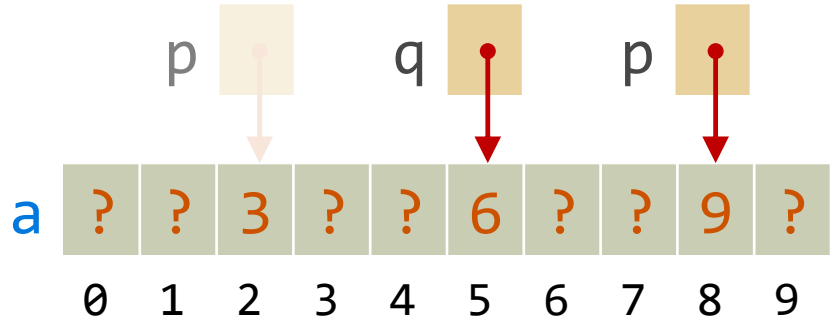

```
int a[10], *p, *q;
p = &a[2];
*p = 3;
```




```
q = p + 3;
*q = 6;
```

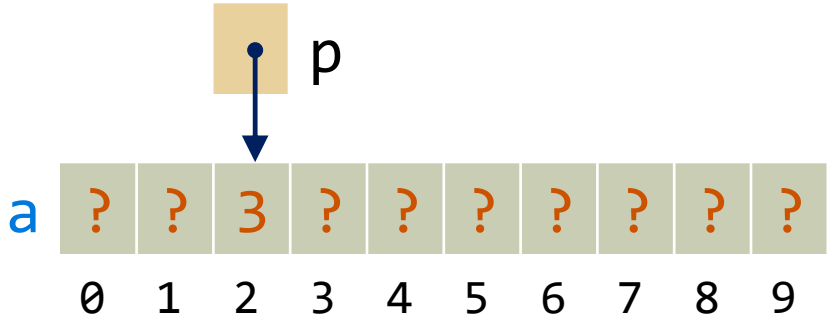



```
p += 6;
*p = 9;
```

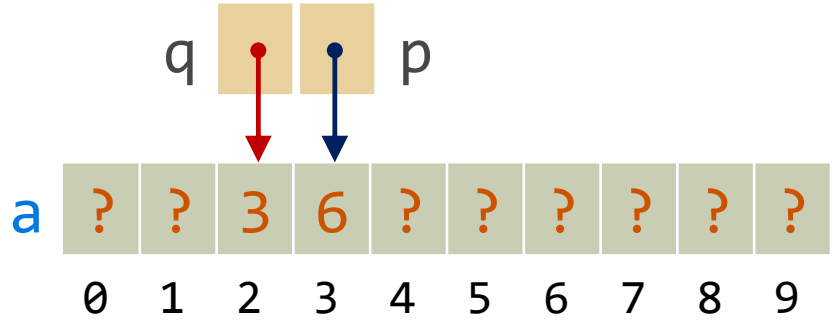


Postfix and prefix increment operators

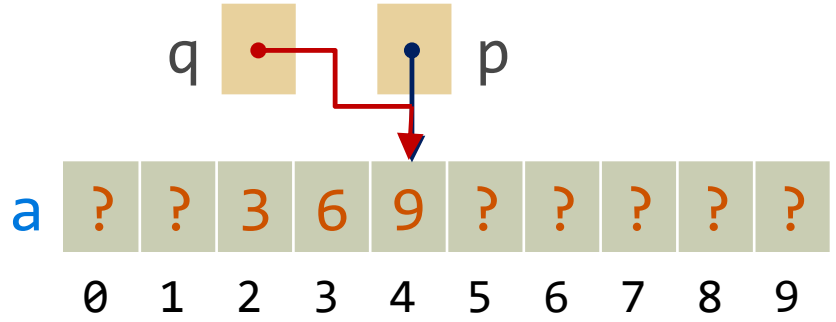

```
int a[10], *p, *q;
p = &a[2];
*p = 3;
```




```
q = p++;
*p = 6;
```




```
q = ++p;
*p = 9;
```



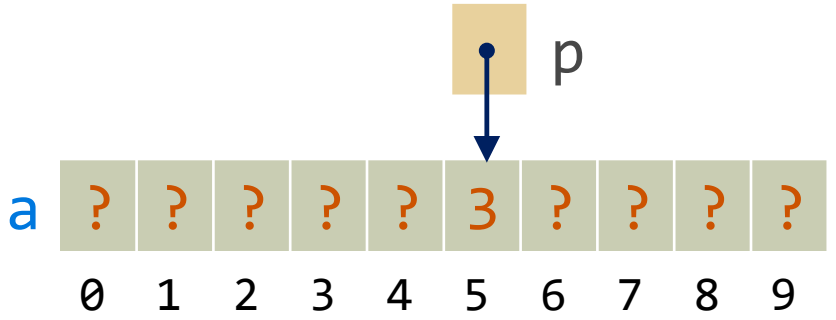
Subtracting integer from pointer

- Suppose `p` is pointing to array element `a[i]`
- Subtracting integer `j` from pointer `p` yields pointer to element `j` places *before* the one that `p` points to
  - More precisely: if `p` points to array element `a[i]`, then `p-j` points to `a[i-j]`

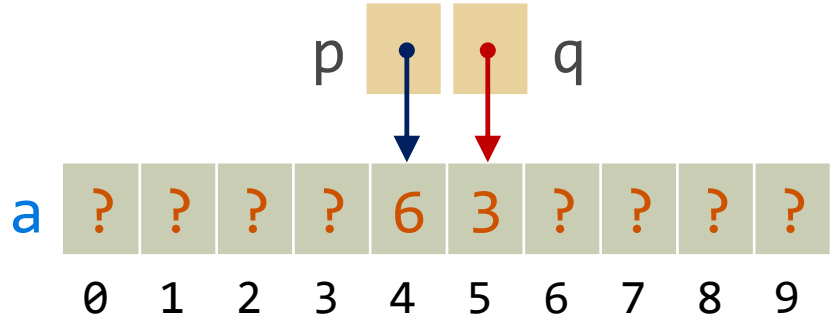
```
int a[5] = {6, 2, 7, 3, 8};
int *p = &a[4], *q = p-3;
printf("%p | %p | %p\n", p, p-3, q);
printf("%d | %d | %d\n", *p, *(p-3), *q);
```

Postfix and prefix decrement operators

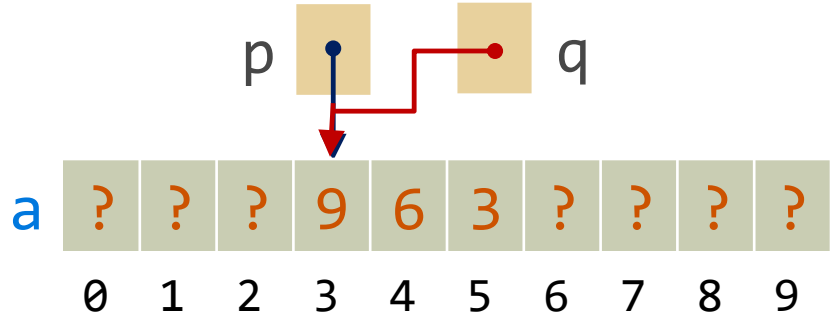

```
int a[10], *p, *q;
p = &a[5];
*p = 3;
```




```
q = p--;
*p = 6;
```



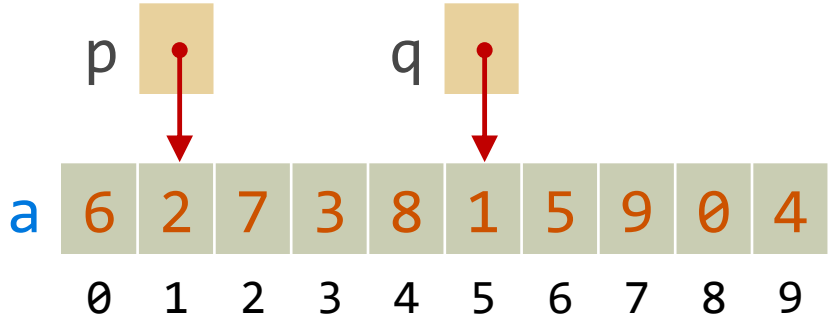

```
q = --p;
*p = 9;
```



Subtracting pointers

- When one pointer is subtracted from another, result is 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`

Subtracting pointers: Example




```
int a[10] = {6, 2, 7, 3, 8, 1, 5, 9, 0, 4};
int *p = &a[1];
int *q = &a[5];

int i = q - p; // q is 4 elements after p
printf("%d\n", i);

int j = p - q; // p is 4 elements ahead of q
printf("%d\n", j);
```

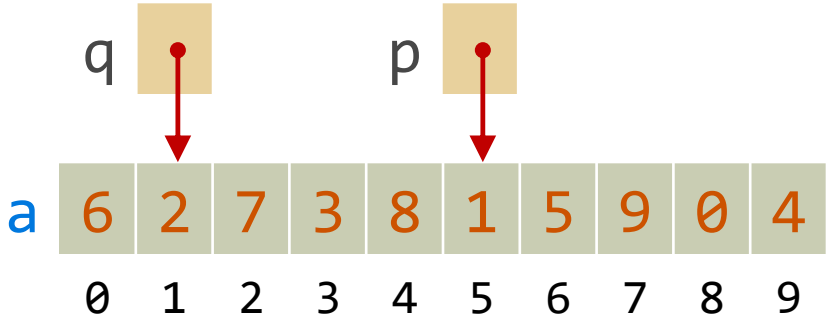
Subtracting pointers: Undefined behavior

- Undefined behavior caused when:
  - Arithmetic performed on pointer that doesn't point to array element
  - Subtracting pointers that both don't point to elements of same array

Comparing pointers (1/2)

- Pointers can be compared using relational operators (<, <=, >, >=) and equality operators (== and !=)
  - *Meaningful only for pointers to elements of same array*
  - Expression evaluation depends on relative positions of array elements that pointers are pointing to

Comparing pointers (2/2)




```
int a[10] = {6, 2, 7, 3, 8, 1, 5, 9, 0, 4};
int *p = &a[5], *q = &a[1];
printf("%d | %d\n",  p<q,    p>q);
printf("%d | %d\n", *p<*q,  *p>*q);
printf("%d | %d\n",  p<=q,   p>=q);
printf("%d | %d\n", *p<=*q, *p>=*q);
printf("%d | %d\n",  p==q,   p!=q);
printf("%d | %d\n", *p==*q, *p!=*q);
```

Processing arrays through pointers (1/4)

- Individual array elements visited using subscript operator

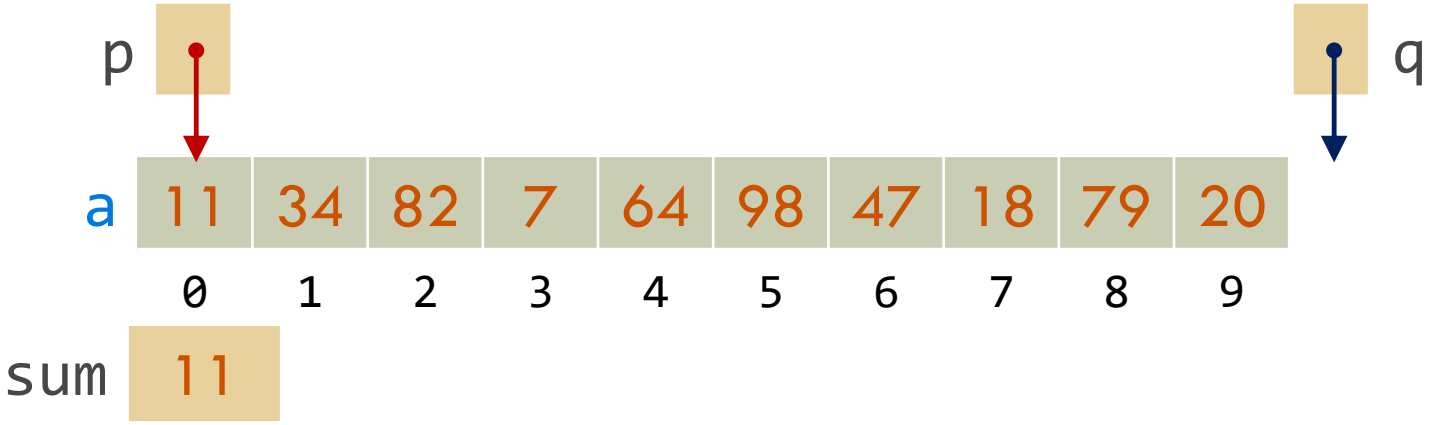
```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int sum = 0;
for (int i = 0; i < SIZE; ++i) {
  sum += a[i];
}
```

- Pointer arithmetic allows us to visit elements of array by repeatedly incrementing pointer variable

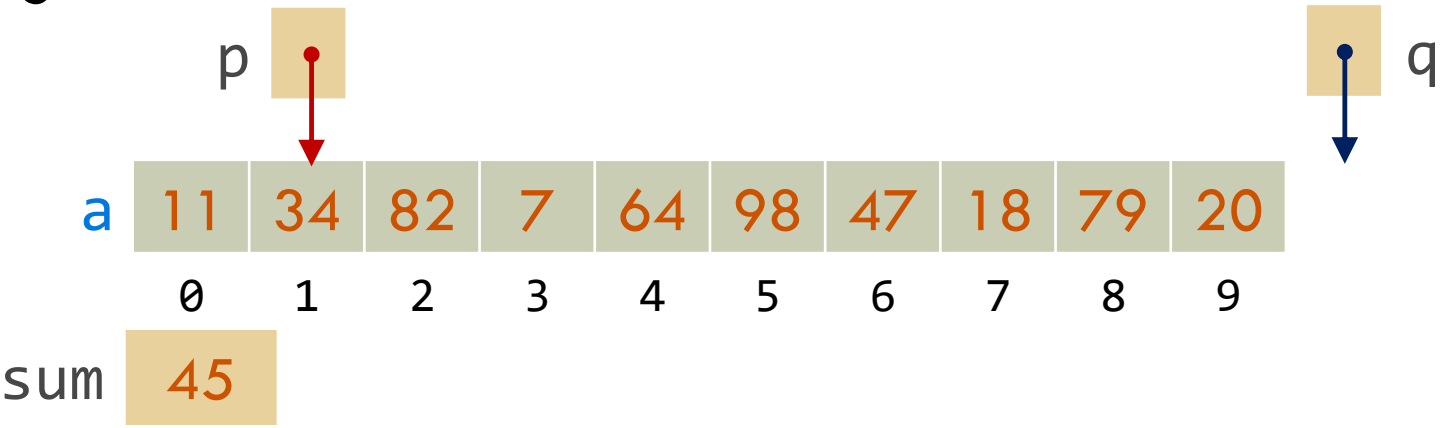
```
#define SIZE 10
int a[SIZE] = {11,34,82,7,64,98,47,18,79,20}, sum = 0;
for (int *p = &a[0], *q = &a[SIZE]; p < q; ++p) {
  sum += *p;
}
```

Processing arrays through pointers (2/4)

- During 1st iteration

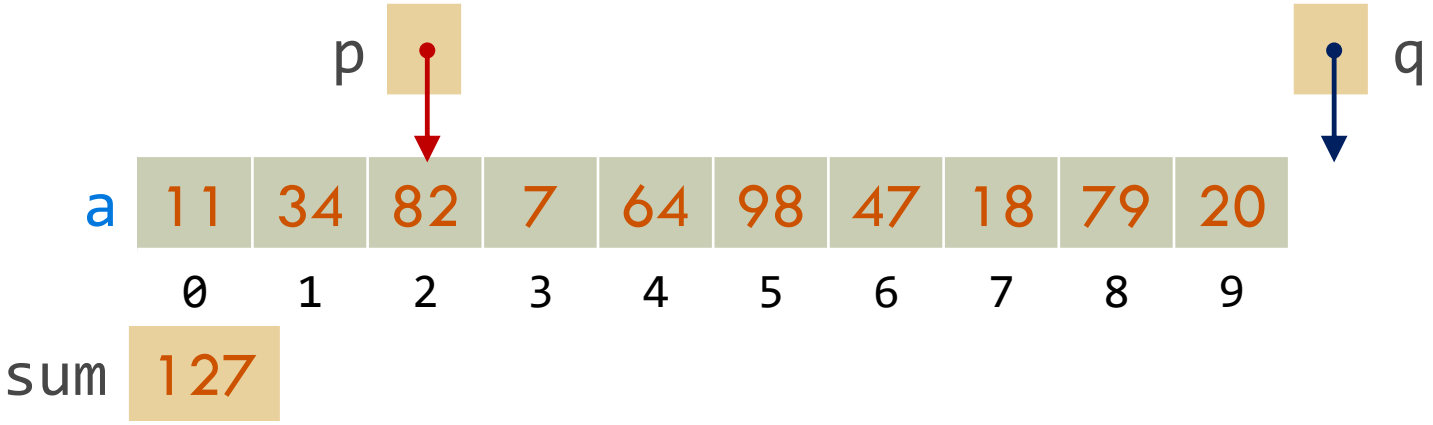


- During 2nd iteration

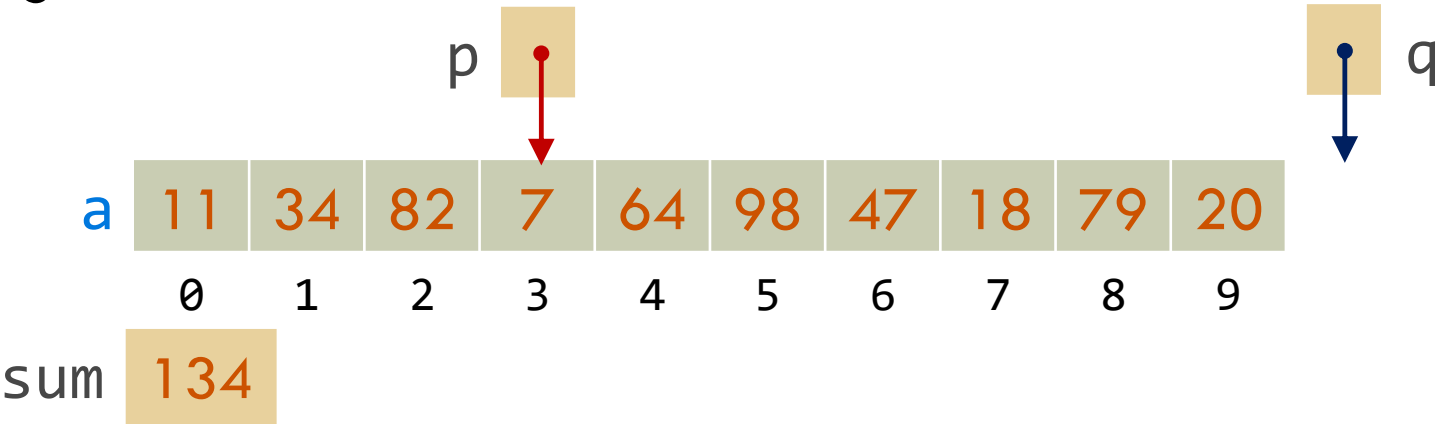


Processing arrays through pointers (3/4)

- During 3rd iteration

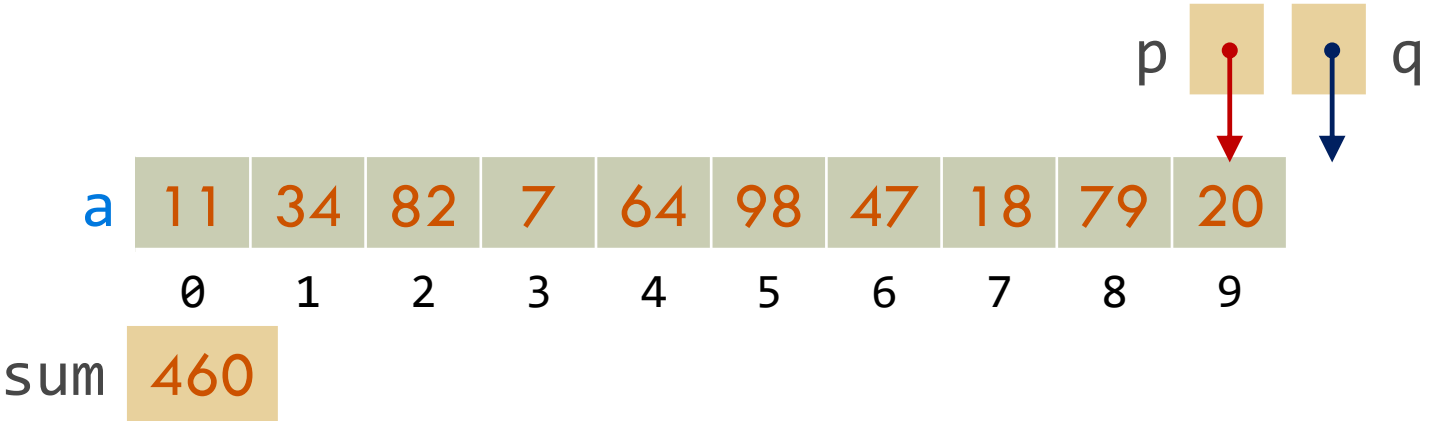


- During 4th iteration

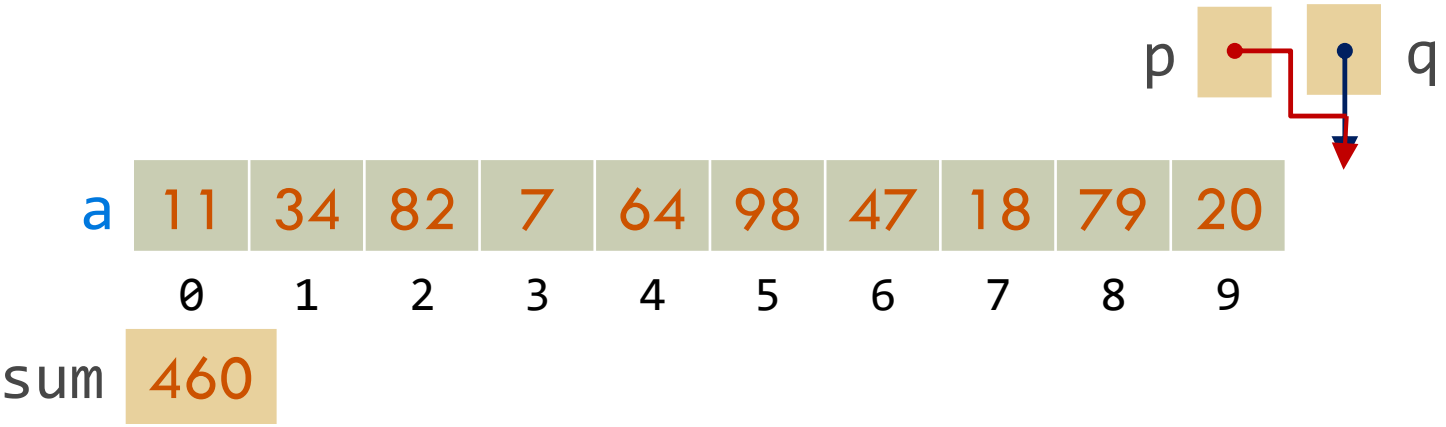


Processing arrays through pointers (4/4)

- During 10th iteration



- After 10th iteration



Compact pointer expressions (1/6)

- Combinations of indirection operator and pre/post-fix increment/decrement operators

high to low precedence order

Operator	Associativity
postfix ++	Left to right
postfix --	
prefix ++	Right to left
prefix --	
indirection *	
address &	

Compact pointer expressions (2/6)

- Where do compact expressions come in handy?

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int sum = 0;
for (int i = 0; i < SIZE; ++i) {
  sum += a[i];
}
```

- Can rewrite as:

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int i = 0, sum = 0;
while (i < SIZE) {
  sum += a[i];
  ++i;
}
```

Compact pointer expressions (3/6)

- Previously written as …

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int i = 0, sum = 0;
while (i < SIZE) {
  sum += a[i];
  ++i;
}
```

- Can further rewrite as:

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int i = 0, sum = 0;
while (i < SIZE) {
  sum += a[i++];
}
```

Compact pointer expressions (4/6)

- Previously written as …

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int i = 0, sum = 0;
while (i < SIZE) {
  sum += a[i++];
}
```

- Can further rewrite using pointers as:

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int *p = &a[0], *q = &a[SIZE], sum = 0;
while (p < q) {
  sum += *p;
  ++p;
}
```

Compact pointer expressions (5/6)

- Previously written using pointers as …

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int *p = &a[0], *q = &a[SIZE], sum = 0;
while (p < q) {
  sum += *p;
  ++p;
}
```

- Using compact pointer expression:

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int *p = &a[0], *q = &a[SIZE], sum = 0;
while (p < q) {
  sum += *p++;
}
```

Compact pointer expressions (6/6)

- If pointer p is pointing to array element, combinations of compact pointer expressions:

Expression	Operation	Affects	Read as
*p++	post increment	pointer	*(p++)
*p--	post decrement	pointer	*(p--)
*++p	pre increment	pointer	*(++p)
*--p	pre decrement	pointer	*(--p)
++*p	pre increment	pointee object	++(*p)
--*p	pre decrement	pointee object	--(*p)
(*p)++	post increment	pointee object	(*p)++
(*p)--	post decrement	pointee object	(*p)--

Compact pointer expressions: Example (1/3)

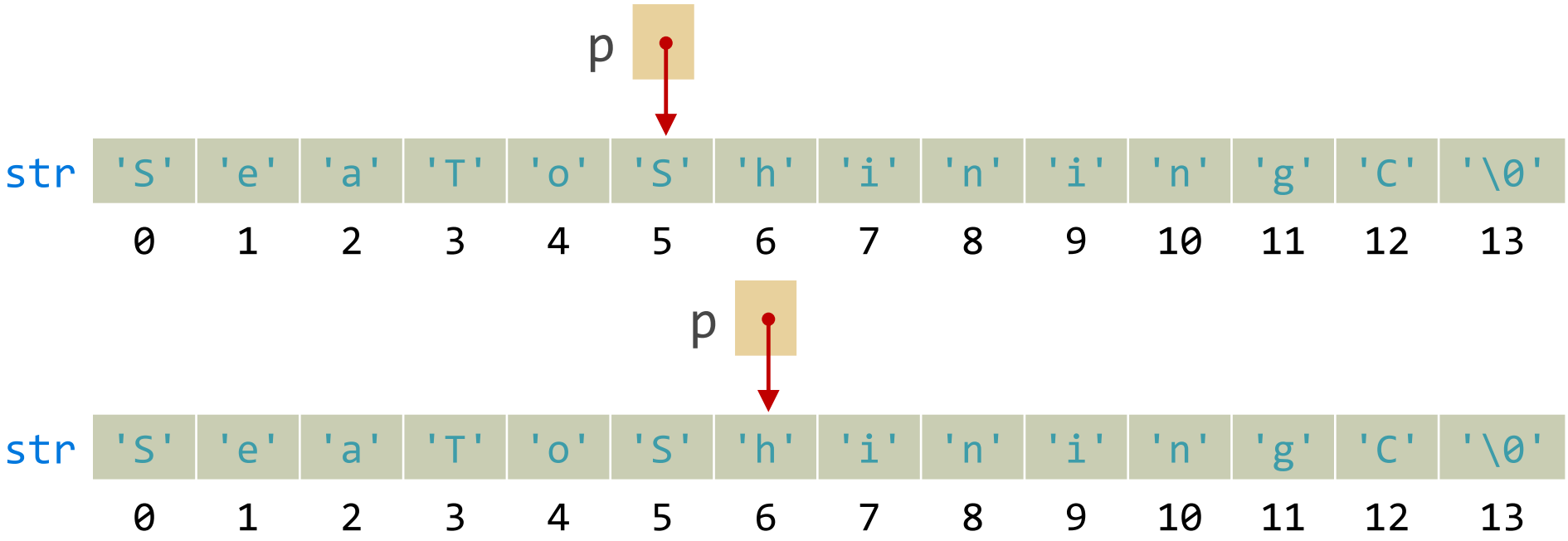
- Given

```
char str[] = "SeaToShiningC";
char *p= &str[5];
```

Expression	Result	Pointer pointing to	Resultant string
*p++	'S'	'h'	"SeaToShiningC"
*p--	'S'	'o'	"SeaToShiningC"
*++p	'h'	'h'	"SeaToShiningC"
*--p	'o'	'o'	"SeaToShiningC"
++*p	'T'	'T'	"SeaToThiningC"
--*p	'R'	'R'	"SeaToRhiningC"
(*p)++	'S'	'T'	"SeaToThiningC"
(*p)--	'S'	'R'	"SeaToRhiningC"

Compact pointer expressions: Example (2/3)

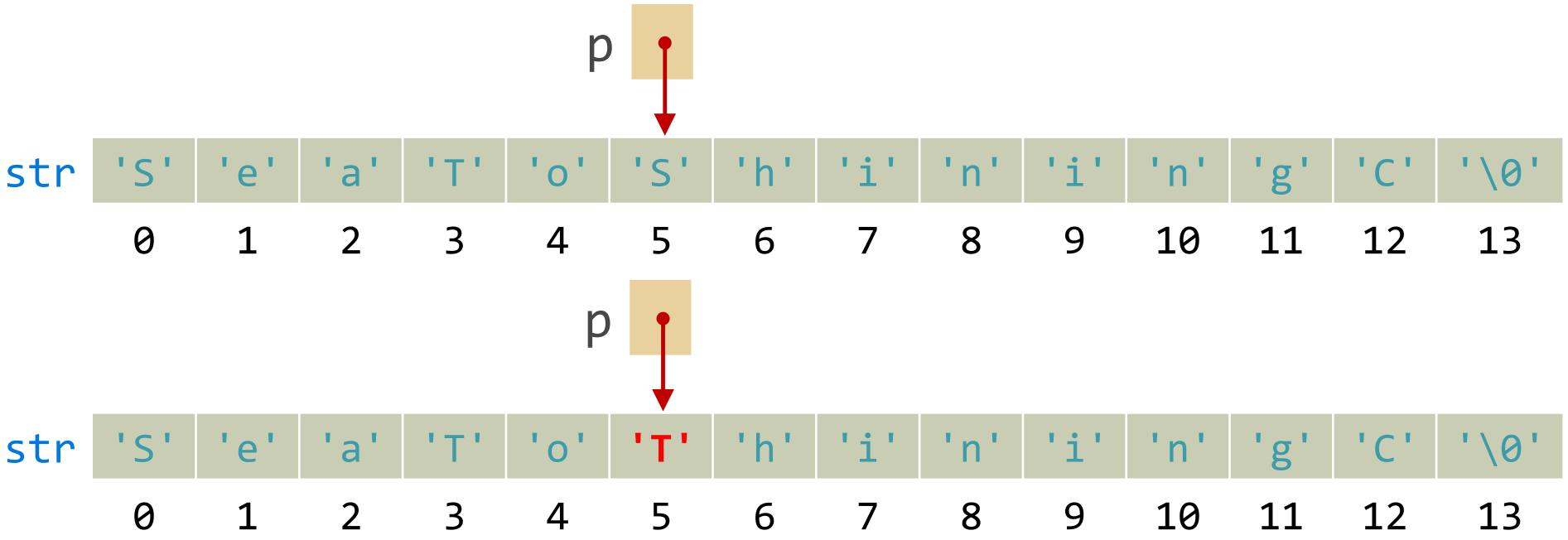

```
char str[] = "SeaToShiningC", *p = &str[5];
char ch = *p++;
```



Expression	Result	Pointer pointing to	Resultant string
*p++	'S'	'h'	"SeaToShiningC"

Compact pointer expressions: Example (3/3)


```
char str[] = "SeaToShiningC", *p = &str[5];
char ch = ++*p;
```



Expression	Result	Pointer pointing to	Resultant string
++*p	'T'	'T'	"SeaToThiningC"

Array name as pointer (1/7)

- Pointer arithmetic relates arrays and pointers:
  - *Pointer to array element can use pointer arithmetic to access other array elements*
- Another key relationship:
  - *Array name in expression evaluates to address of element with subscript 0*
  - Sole exception: when array name is operand to `sizeof` operator

Array name as pointer (2/7)


```
int a[5] = {3, 1, 5, 7, 9};
*a = 4;       // assign 4 to a[0]
*(a+3) = 23; // assign 23 to a[3]
++*a;         // increments a[0] not a!!!

int *p = a;  // p points to a[0]
printf("%lu\n", sizeof(a)); // print 20 to stdout
printf("%lu\n", sizeof(p)); // prints 8 to stdout

a++; // error - cannot relocate array
```

Array name as pointer (3/7)

- Actually, subscript operator is syntactic sugarcoating
- C always replaces subscript operator with expression involving pointer arithmetic and dereference operator

Array name as pointer (4/7)

- In general, `a[i]` is equivalent to `*(a+i)`
  - Both represent element with subscript `i`
- In general, `&a[i]` is equivalent to `&*(a+i)` which is equivalent to `(a+i)`
  - Both `&a[i]` and `(a+i)` represent address of element with subscript `i`

Array name as pointer (5/7)

- Using array name as pointer to 1st array element makes loops easier to write because address of & operator is not required!!!

```
int a[10] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20}, sum = 0;
int *p = &a[0], *q = &a[10];
while (p < q) {
  sum += *p++;
}
```

```
int a[10] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20}, sum = 0;
int *p = a, *q = a+10; // & and [] operators not required
while (p < q) {
  sum += *p++;
}
```

Array name as pointer (6/7)

- Array names are non-modifiable
- Compiler treats array name as `const` pointer to first element of array
- Meaning of `const` pointer:
  - Pointer value cannot be modified to reference another address
  - Pointer can be used to modify value at address it references

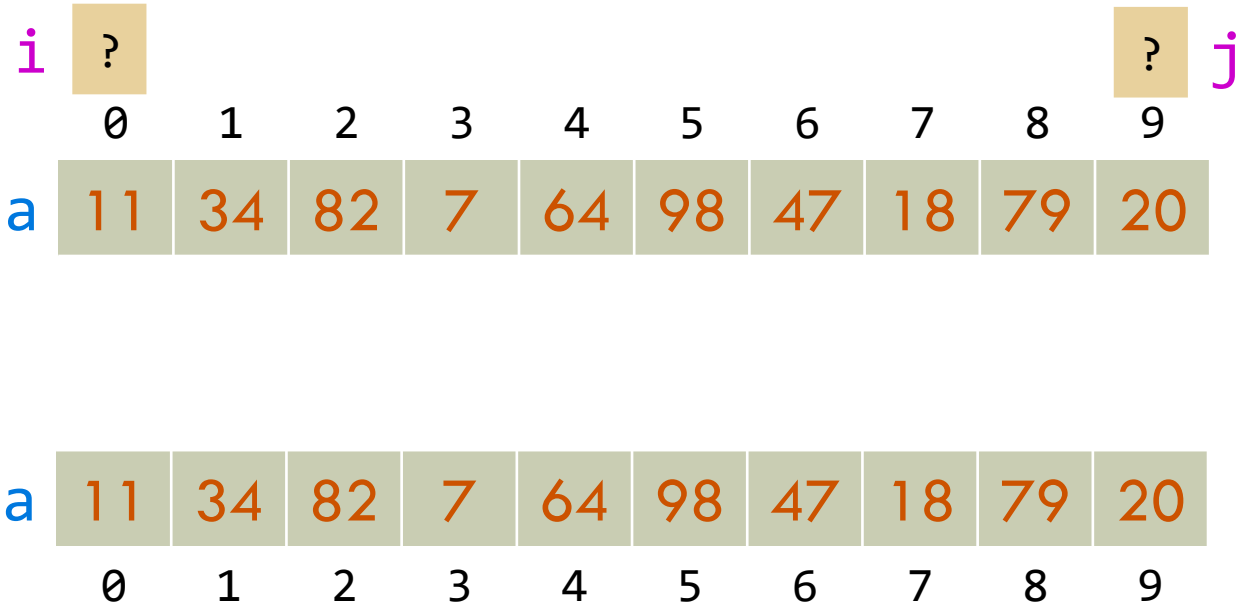
Array name as pointer (7/7)


```
int a[10] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
// find first array element with value 0
int *q = a+10;
while (*a != 0 && a < q) {
  ++a; // flagged as compile-time error
}
// if a == q, then no element with value 0 ...
```

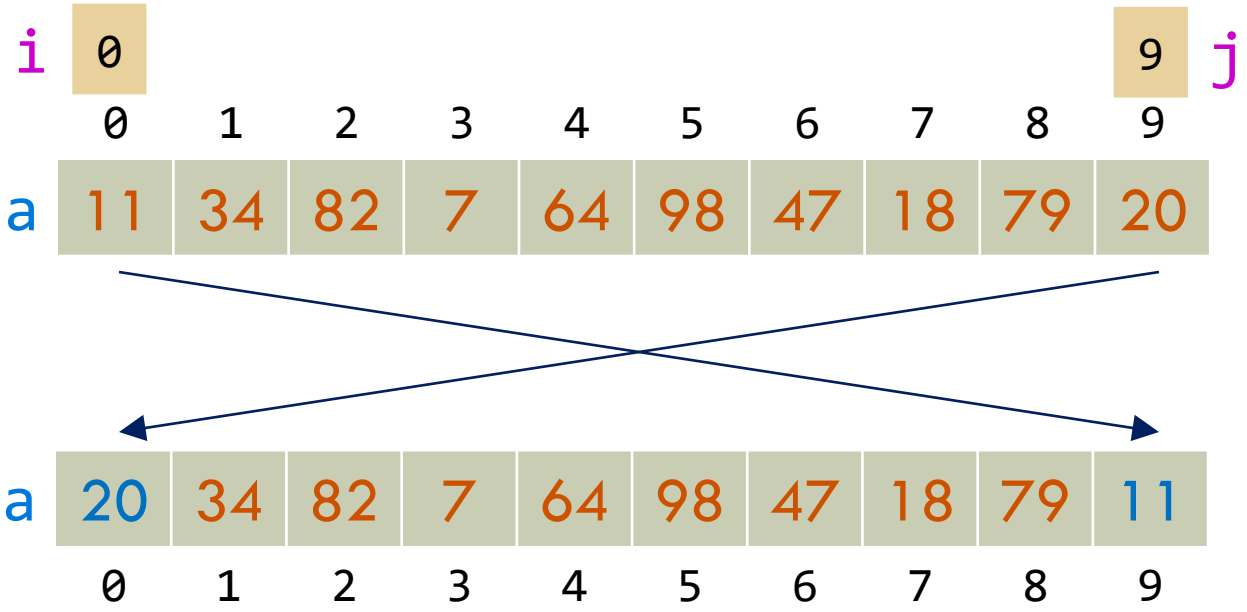
```
int a[10] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
// find first array element with value 0
// not a great loss that value of a cannot be changed
// we just copy value of a into variable p ...
int *p = a, *q = a+10;
while (*p != 0 && p < q) {
  ++p;
}
// if p == q, then no element with value 0 ...
```

Example: Array reversal using subscripts (1/8)

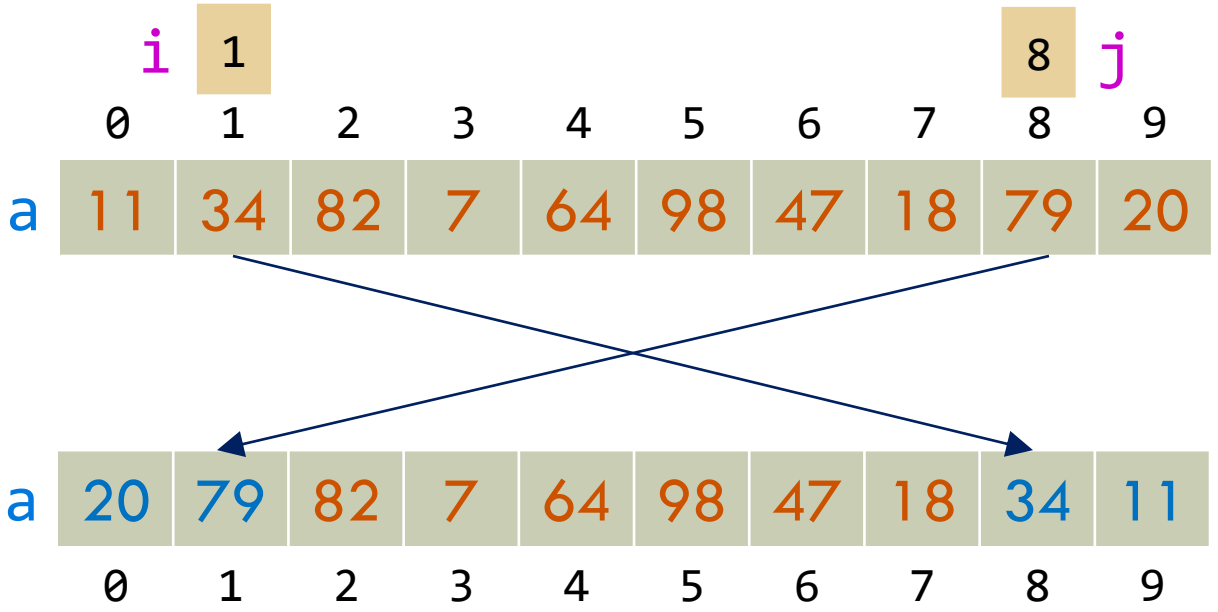
- We want to reverse elements of array `a` in-place using subscripts `i` and `j` and function `swap`



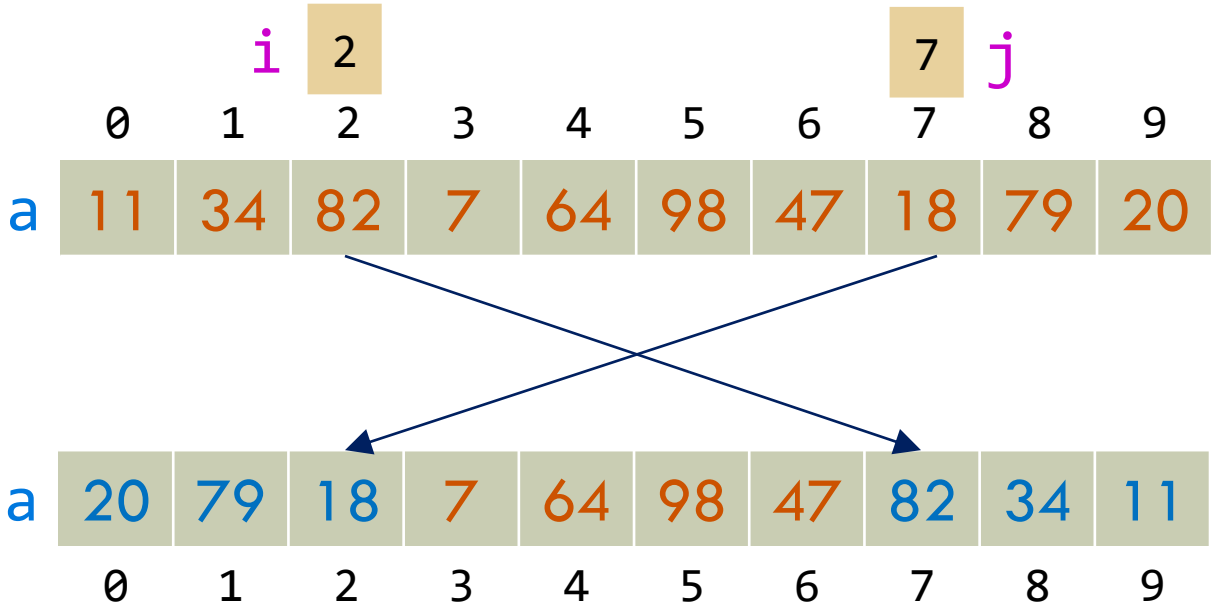
Example: Array reversal using subscripts (2/8)



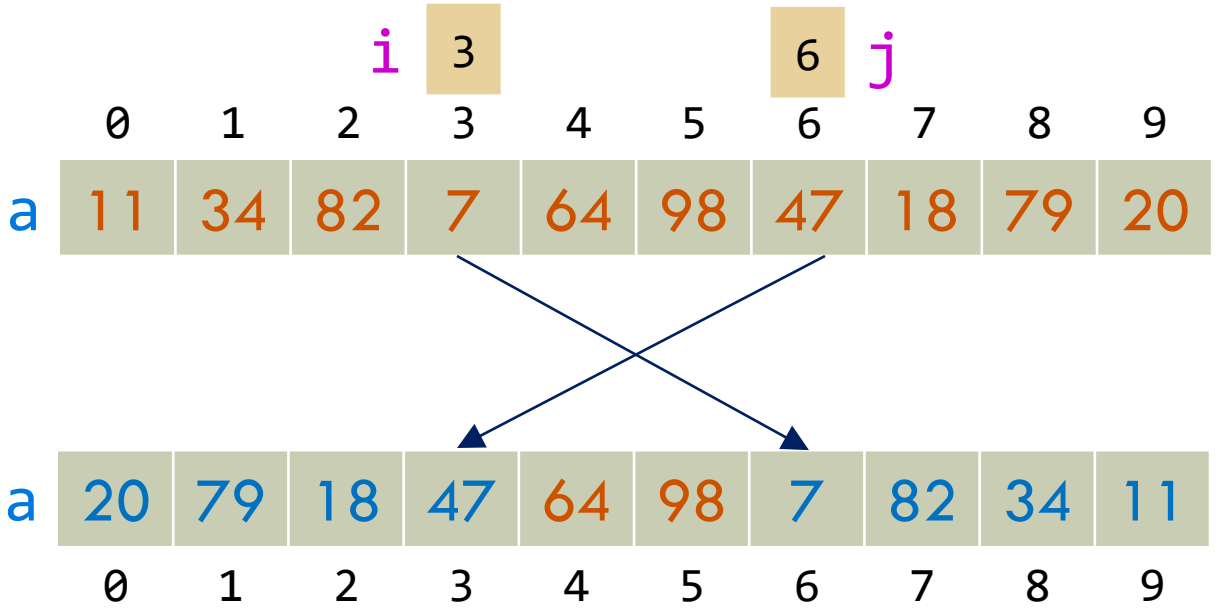
Example: Array reversal using subscripts (3/8)



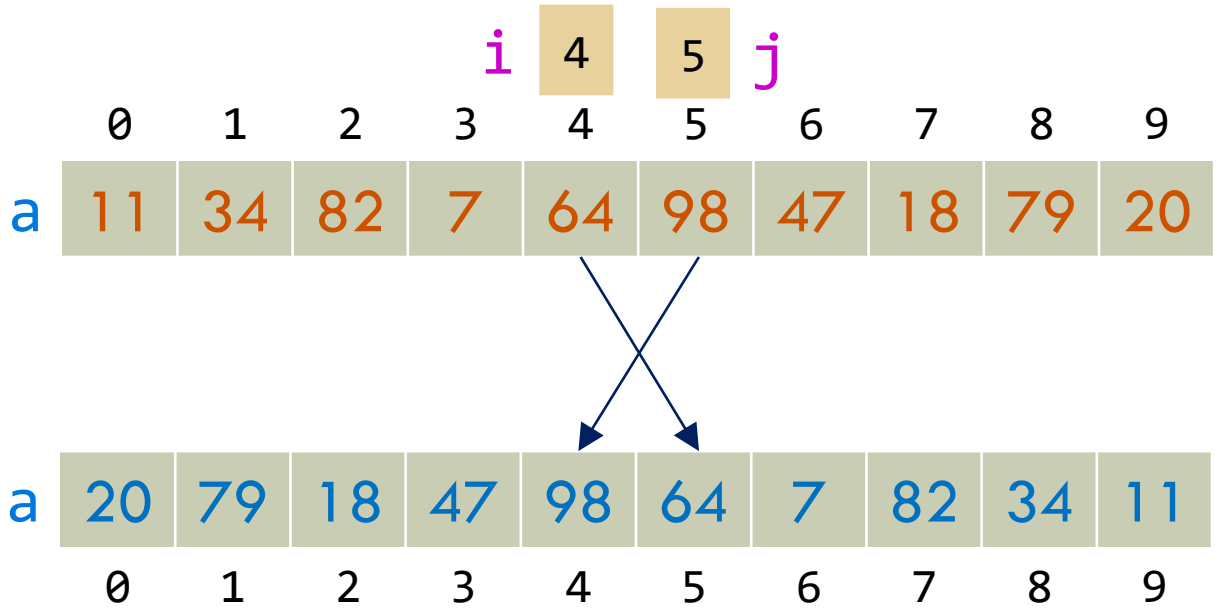
Example: Array reversal using subscripts (4/8)



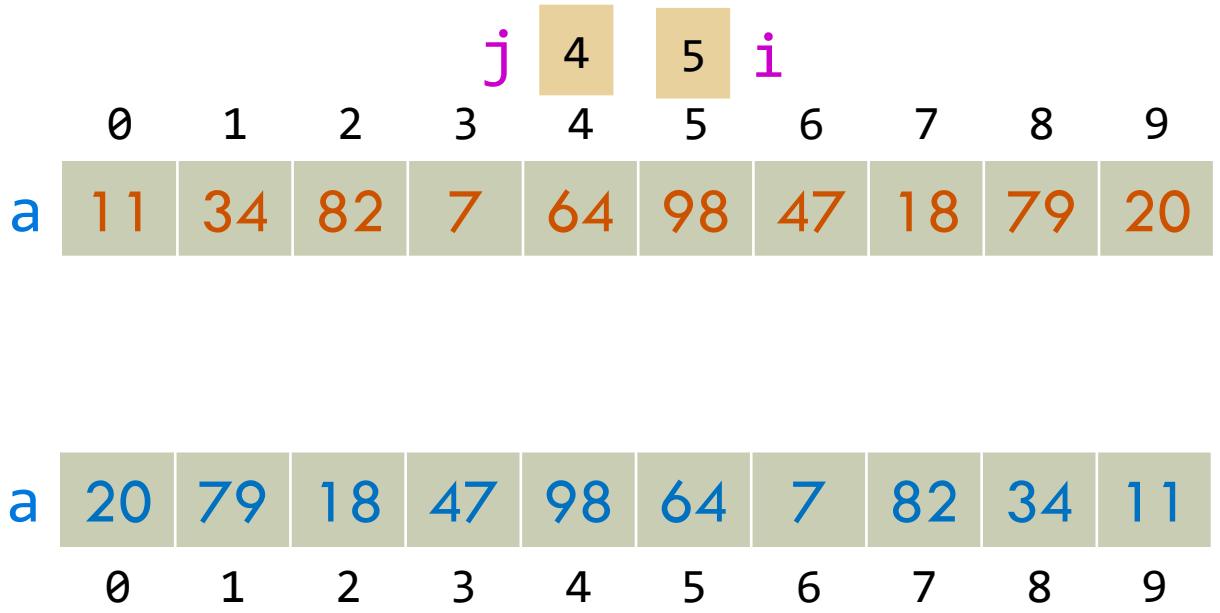
Example: Array reversal using subscripts (5/8)



Example: Array reversal using subscripts (6/8)



Example: Array reversal using subscripts (7/8)

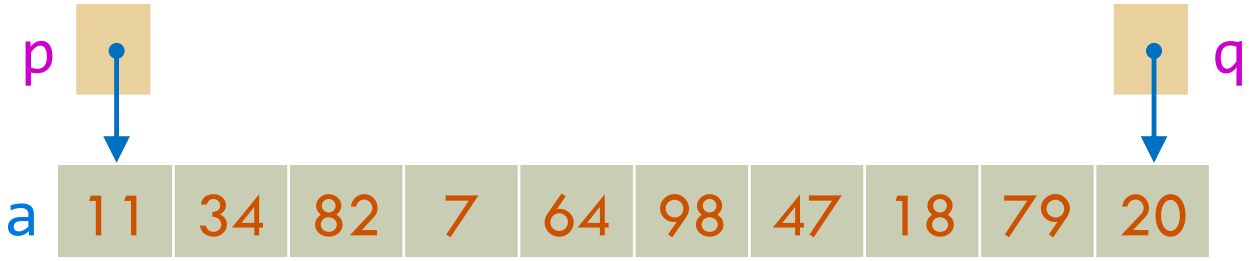


Example: Array reversal using subscripts (8/8)

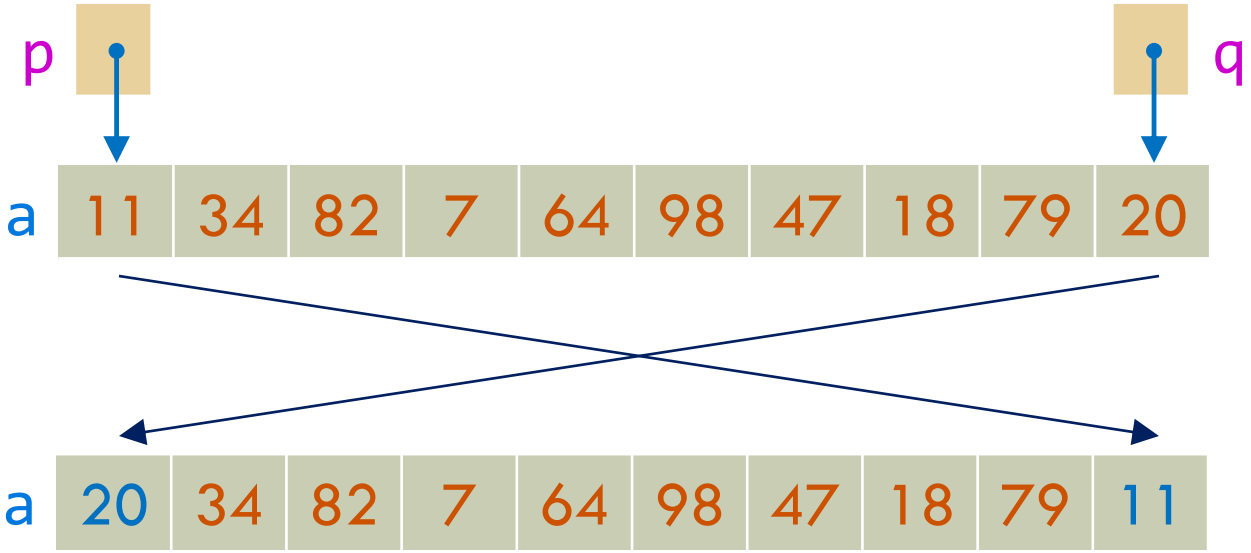

```c
void swap(int *p, int *q) {
  int tmp = *p;
  *p = *q;
  *q = tmp;
}

int main(void) {
#define SIZE 10
  int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
  for (int i = 0, j = SIZE-1; i < j; ++i, --j) {
    swap(&a[i], &a[j]);
  }
  for (int i = 0; i < SIZE; ++i) {
    printf("%d%c", a[i], i==SIZE-1 ? '\n' : ' ');
  }
  return 0;
}
```

Example: Array reversal using pointers (1/8)

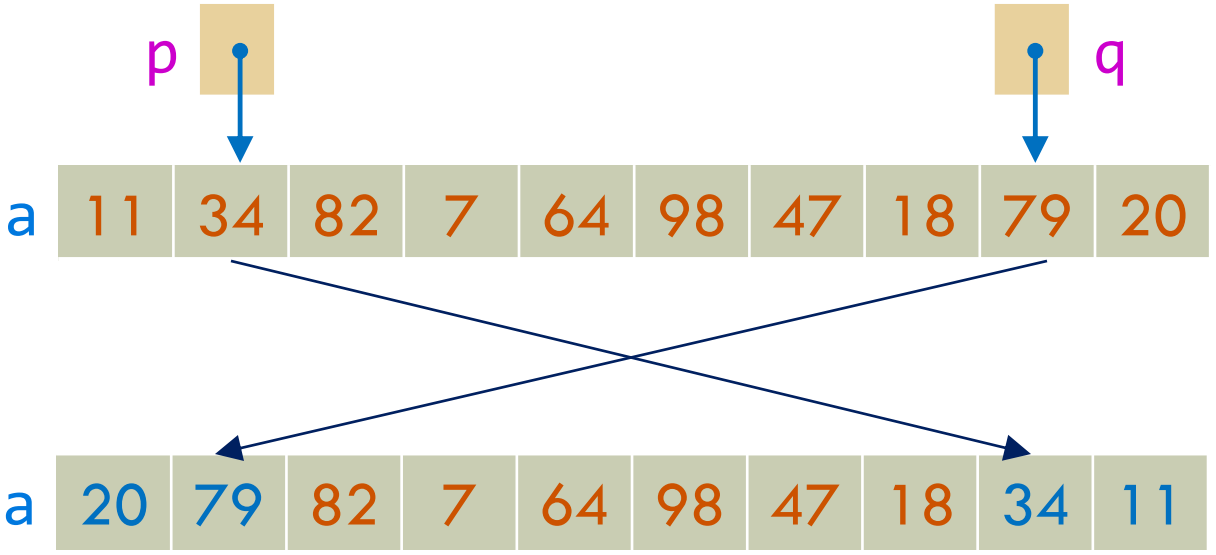
We want to reverse elements of array a in-place using pointers p and q and function swap



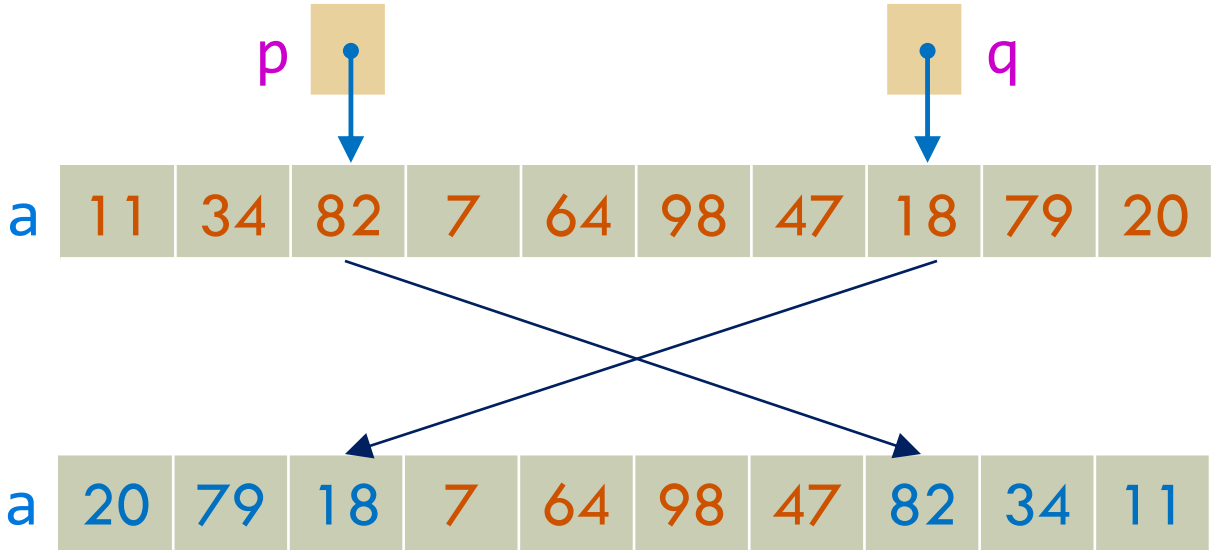
Example: Array reversal using pointers (2/8)



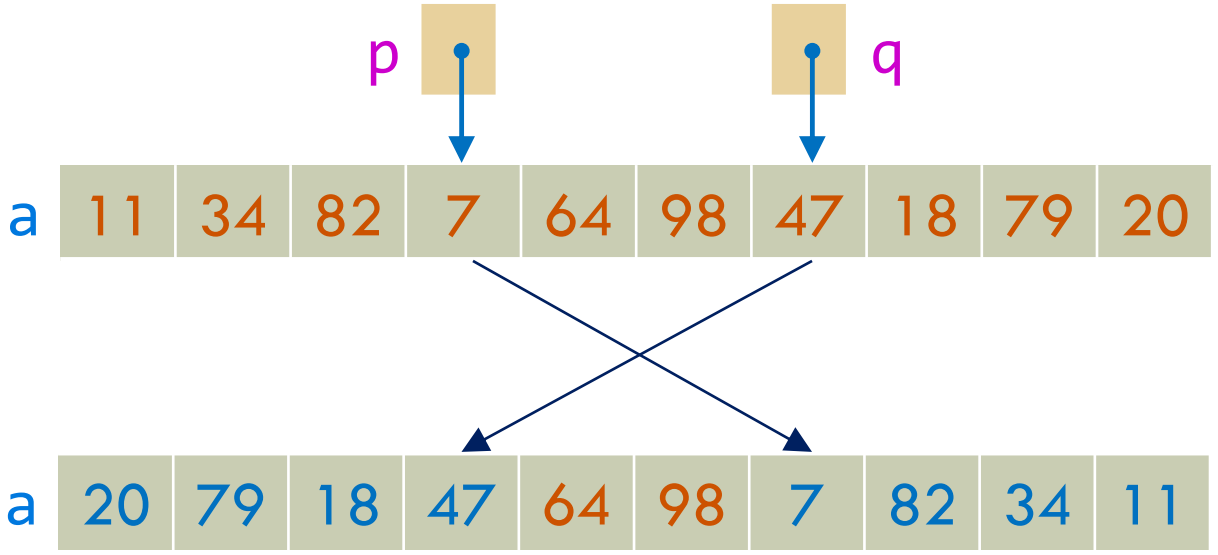
Example: Array reversal using pointers (3/8)



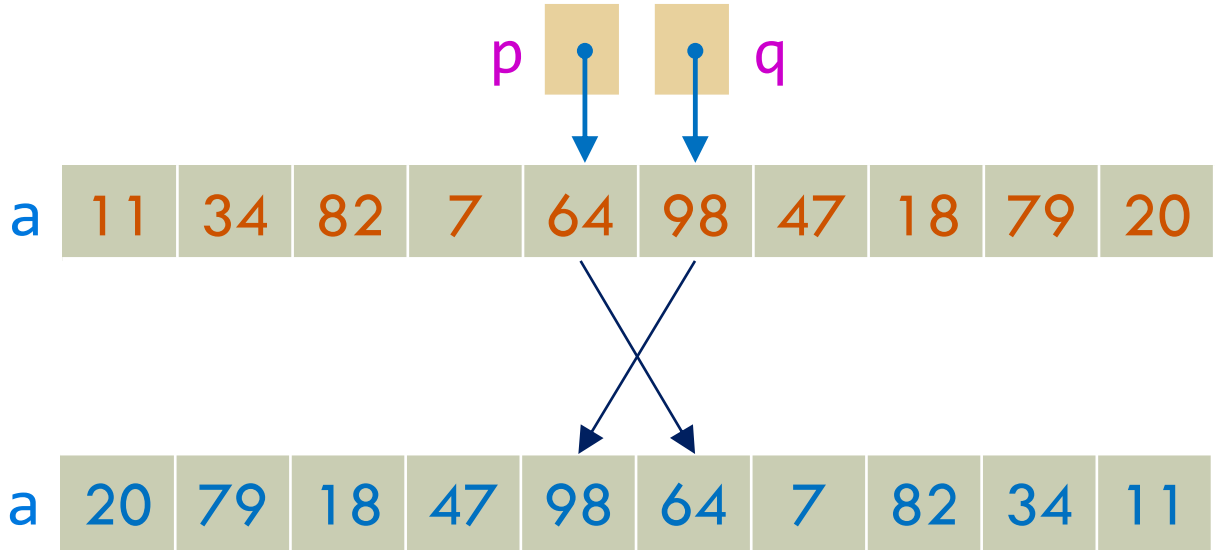
Example: Array reversal using pointers (4/8)



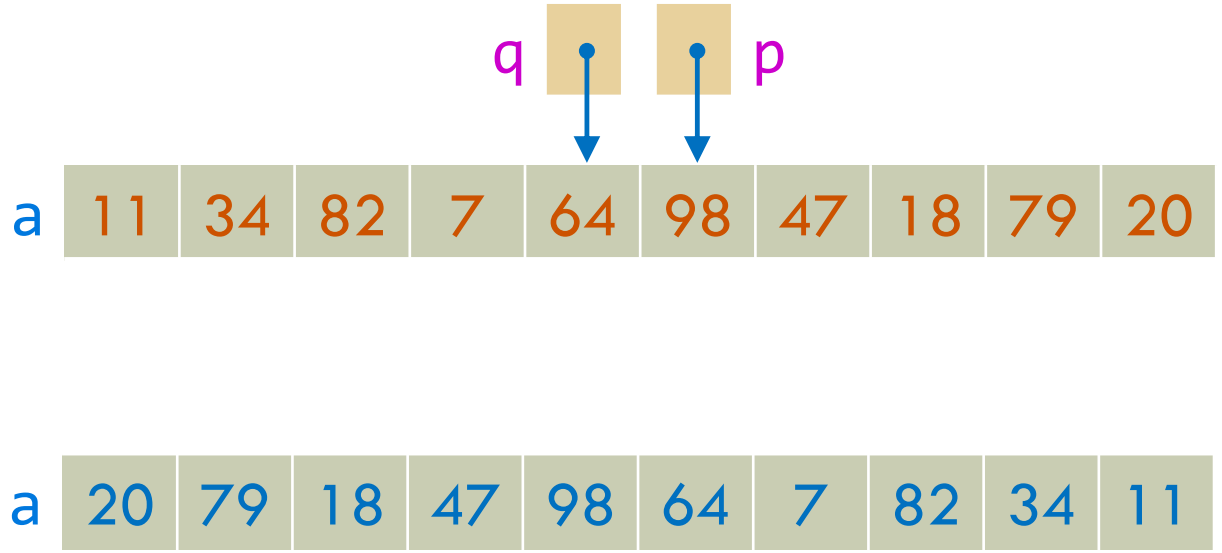
Example: Array reversal using pointers (5/8)



Example: Array reversal using pointers (6/8)



Example: Array reversal using pointers (7/8)



Example: Array reversal using pointers (8/8)


```c
void swap(int *p, int *q) {
  int tmp = *p;
  *p = *q;
  *q = tmp;
}

int main(void) {
#define SIZE 10
  int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
  for (int *p = a, *q = a+SIZE-1; p < q; ++p, --q) {
    swap(p, q);
  }
  for (int i = 0; i < SIZE; ++i) {
    printf("%d%c", a[i], i==SIZE-1 ? '\n' : ' ');
  }
  return 0;
}
```

Arrays as function arguments (1/2)

- We've previously seen arrays can be passed to functions

```
void zero_out_array(int p[], int size) {
  for (int i = 0; i < size; ++i) {
    p[i] = 0;
  }
}
```

```
// find subscript of element whose value is val
int find(int p[], int size, int val) {
  for (int i = 0; i < size; ++i) {
     if (val == p[i]) return i;
  }
  return -1;
}
```

Arrays as function arguments (2/2)

- Copy source array to destination array …

```
void copy(int dst[], int src[], int size) {
  int i = 0;
  while (i < size) {
    dst[i] = src[i];
    ++i;
  }
}
```

Arrays as function arguments: pointer parameter (1/3)

- When array is passed to function, what is actually passed is *array's base address* which is also *address of array's first element*

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int total = summation(a, SIZE);
```

```
int summation(int p[], int size) {
  int sum = 0;
  for (int i = 0; i < size; ++i) {
    sum += p[i];
  }
  return sum;
}
```

Arrays as function arguments: pointer parameter (2/3)

- Syntactic sugar coating can be discarded by replacing array parameter with pointer parameter

```
#define SIZE 10
int a[SIZE] = {11, 34, 82, 7, 64, 98, 47, 18, 79, 20};
int total = summation(a, SIZE);
```

```
int summation(int *p, int size) {
  int sum = 0;
  for (int i = 0; i < size; ++i) {
    sum += *p++;
  }
  return sum;
}
```

Arrays as function arguments: pointer parameter (3/3)

- Compiler treats array parameter and pointer parameter as identical declarations
- It is left to author to decide which declaration to use

```
void zero_out_array(int p[], int size) {
  for (int i = 0; i < size; ++i) {
    p[i] = 0;
  }
}
```

```
void zero_out_array(int *p, int size) {
  int *q = p + size;
  while (p < q) {
    *p++ = 0;
  }
}
```

Arrays as function arguments: const type specifier (1/3)

- When ordinary variable is passed to function, its value is copied; changes to corresponding parameter don't affect variable
- In contrast, when argument is array name, function has copy of array's base address and can therefore modify individual subscripted variables of array

Arrays as function arguments: const type specifier (2/3)

- This function can modify array by storing zero into each of its elements since array parameter p is pointer to first element of array in calling function …

```
void zero_out_array(int p[], int size) {
  for (int i = 0; i < size; ++i) {
    p[i] = 0;
  }
}
```

Arrays as function arguments: const type specifier (3/3)

- In contrast, this function *must not* modify its array parameter
  - Author can make compiler enforce this contract by adding type qualifier `const` to array declaration
  - In this case, parameter `p` is *pointer to read-only* `int`

```
int summation(int const p[], int size) {
  int sum = 0;
  for (int i = 0; i < size; ++i) {
    sum += p[i];
  }
  return sum;
}
```

Arrays as function arguments: cost of passing arrays

- Inexpensive to pass arrays between functions – only need to pass base address and number of elements
- Time required to pass arrays is same irrespective of their size

Arrays as function arguments: range-based functions (1/2)

- Can pass array slices to functions
- Example: zero out array elements in half-open range specified by element with address `start` and up to but not including element with address `end`

```
void zero_out_array(int *start, int *end) {
  while (start != end) {
    *start++ = 0;
  }
}
```

Arrays as function arguments: range-based functions (2/2)

- Example: return sum of array elements in half-open range specified by element having address `start` and up to but not including element having address `end`

```
int summation(int const *start, int const *end) {
  int sum = 0;
  while (start != end) {
    sum += *start++;
  }
  return sum;
}
```

Summary

- Pointer arithmetic allows adding and subtracting of integers to/from pointers
- Pointers used as arguments to functions that modify values
- When arrays are sent to functions as arguments, a pointer to first element is passed to function
- `const` type qualifier can protect data