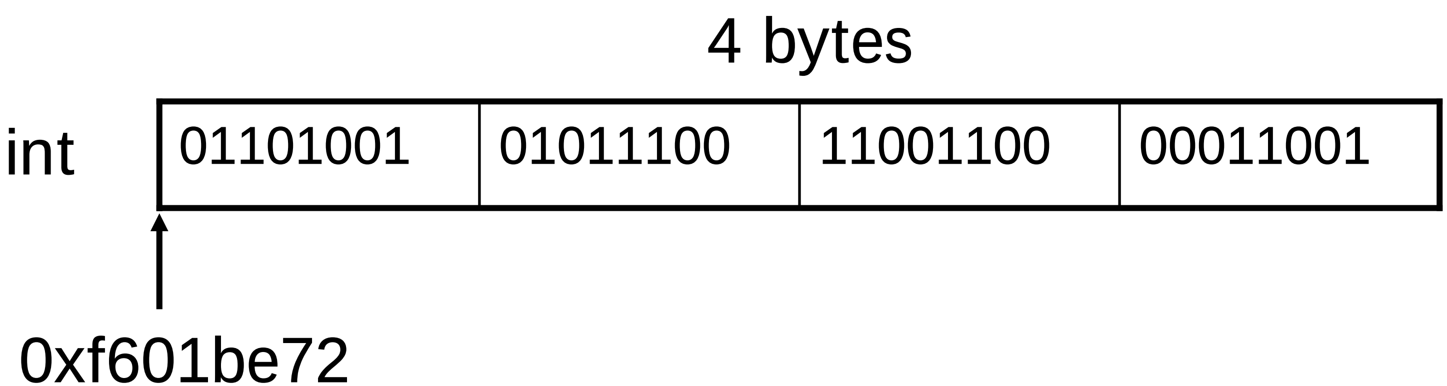
Pointers and the C++ Memory Model

Variables and Memory

- Each variable in a program is stored in a block of memory
- The block of memory that stores a variable's value has three attributes
  - 1. Size - how big is it?
  - 2. Address - where is it?
  - 3. Value - what does it contain?



sizeof Operator - How big is it?

- The sizeof operator tells you how many bytes of memory are needed to store a particular variable or data type

```
struct Student {
   long id;
   string name;
};

Student s;
Student t[10];

int longSize = sizeof(long);
int stringSize = sizeof(string);
int studentSize = sizeof(Student);

int idSize = sizeof(s.id);
int nameSize = sizeof(s.name);
int sSize = sizeof(s);
int tSize = sizeof(t);
```

& Operator - Where is it?

- The & operator returns the memory address at which the operand is stored
- In C++, address values are called "pointers"

```
struct Student {
   long id;
   string name;
};

Student s;
Student t[10];

Student * sAddr = &s;
cout << "s is at address " << sAddr << endl;

Student * elemAddr = &t[4];
cout << "t[4] is at address " << elemAddr << endl;

long * idAddr = &s.id;
cout << "s.id is at address " << idAddr << endl;
```

* Operator - What does it contain?

- The * operator returns the value pointed to by a pointer
- This is called "dereferencing" the pointer
- Result of * can be used as an l-value or r-value

```
// simple integer copy
int x = 100;
int y = x;
x = 212;

// do the same thing with pointers
int x = 100;
int * xAddr = &x;
int y = *xAddr;
*xAddr = 212;
```

* Operator - What does it contain?

- A structure example

```
struct Student { long id; string name; };

// simple structure operations
Student s = {12345, "fred"};
Student t = s;
string n = s.name;
s.name = "barney";

// do the same thing with pointers
Student s = {12345, "fred"};
Student * sAddr = &s;
Student t = *sAddr;
string n = (*sAddr).name;
(*sAddr).name = "barney";
```

The -> Operator

- When you have a pointer to a structure, the syntax for referencing a member of the structure is (*p).member
- The -> operator provides a more compact syntax for doing the same thing

```
// ugly syntax
Student s = {12345, "fred"};
Student * p = &s;
string n = (*p).name;
(*p).name = "barney";

// nicer syntax
Student s = {12345, "fred"};
Student * p = &s;
string n = p->name;
p->name = "barney";
```

Arrays and Pointers

- The name of an array (without a subscript) evaluates to the address of the array
- The address of an array is the same as the address of its first element
- Any pointer can be indexed like an array (even if it doesn’t point to an array)

```
short data[100];

short * p1 = data;
short * p2 = &data[0];
// (p1 == p2)

short s = p1[32];
p1[32] = -50;
```

Pointer Arithmetic

- Pointer values can be compared using relational operators: ==, !=, <, <=, >, >=

  ```
  if (p1 < p2) {…}
  ```

- The ++ operator can be used to move a pointer forward one position in memory
  - If p has type X *, ++p adds sizeof(X) to p, not 1
- The -- operator can be used to move a pointer backward one position in memory
  - If p has type X *, --p subtracts sizeof(X) from p, not 1

Pointer Arithmetic

- The + and += operators can be used to move a pointer forward n positions in memory
  - (p + n) adds n*sizeof(X) to p, not n
- The - and -= operators can be used to move a pointer backward n positions in memory
  - (p - n) subtracts n*sizeof(X) from p, not n
- The - operator can be used to subtract one pointer from another
  - (p - q) returns the number of array elements (not bytes) between q and p

Pointer Arithmetic

- Let's rewrite this code using pointer arithmetic

```
short data[5] = {12, 4, 22, 43, 9};
long sum = 0;
int i = 0;
while (i < 5) {
   sum += data[i];
   ++i;
}
```

Pointer Arithmetic

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short data[5] = {12, 4, 22, 43, 9};
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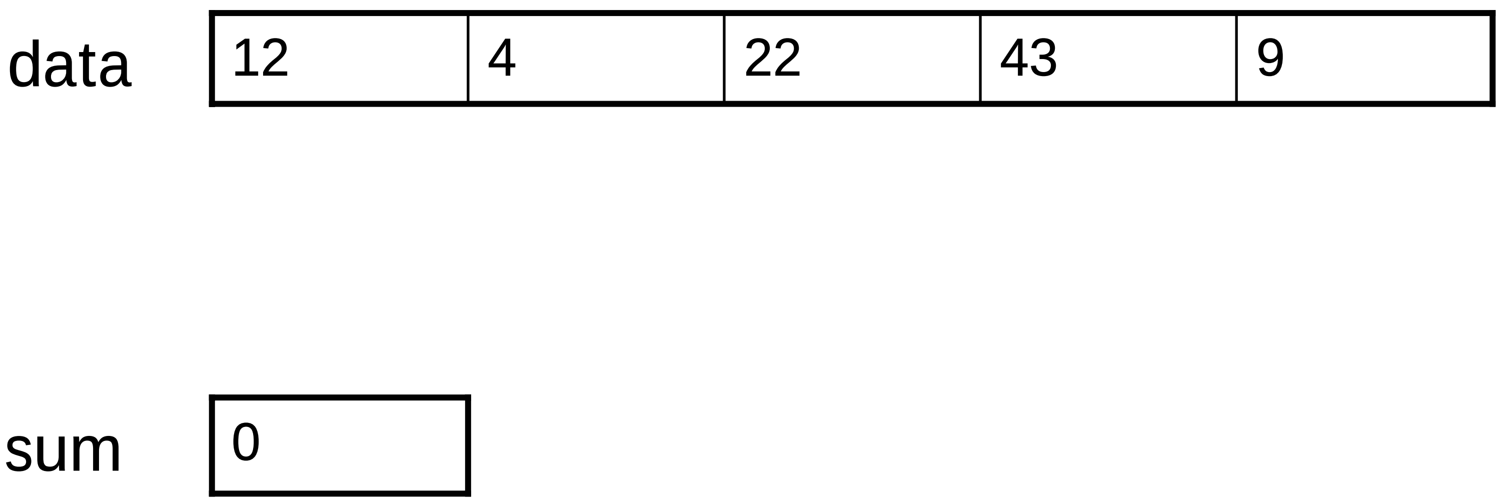

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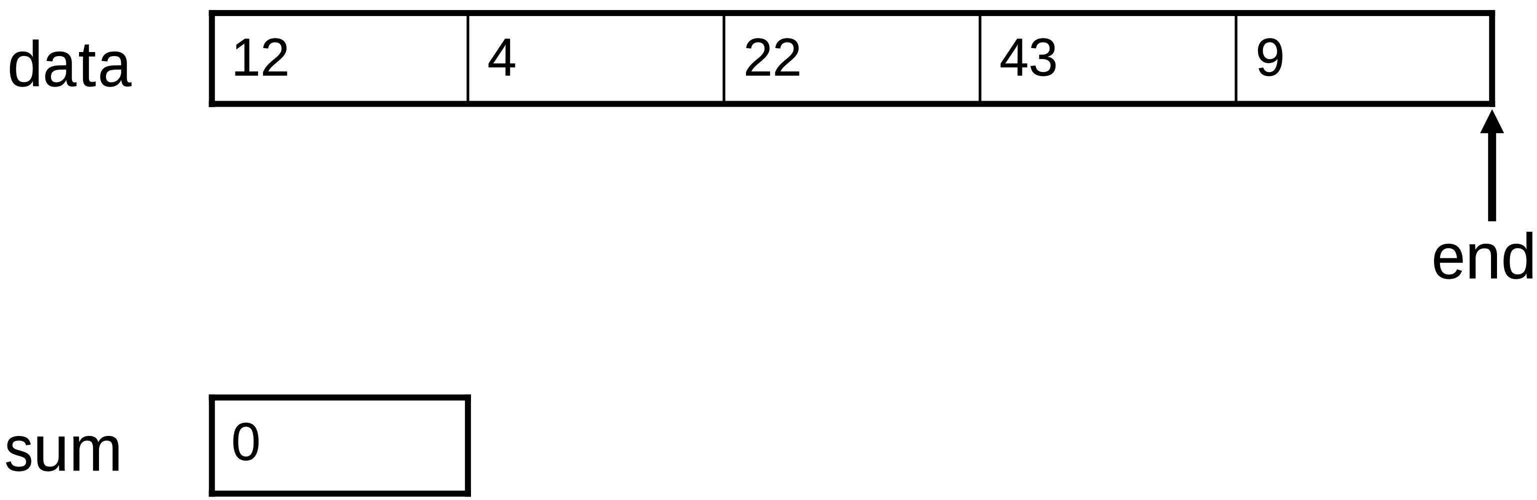

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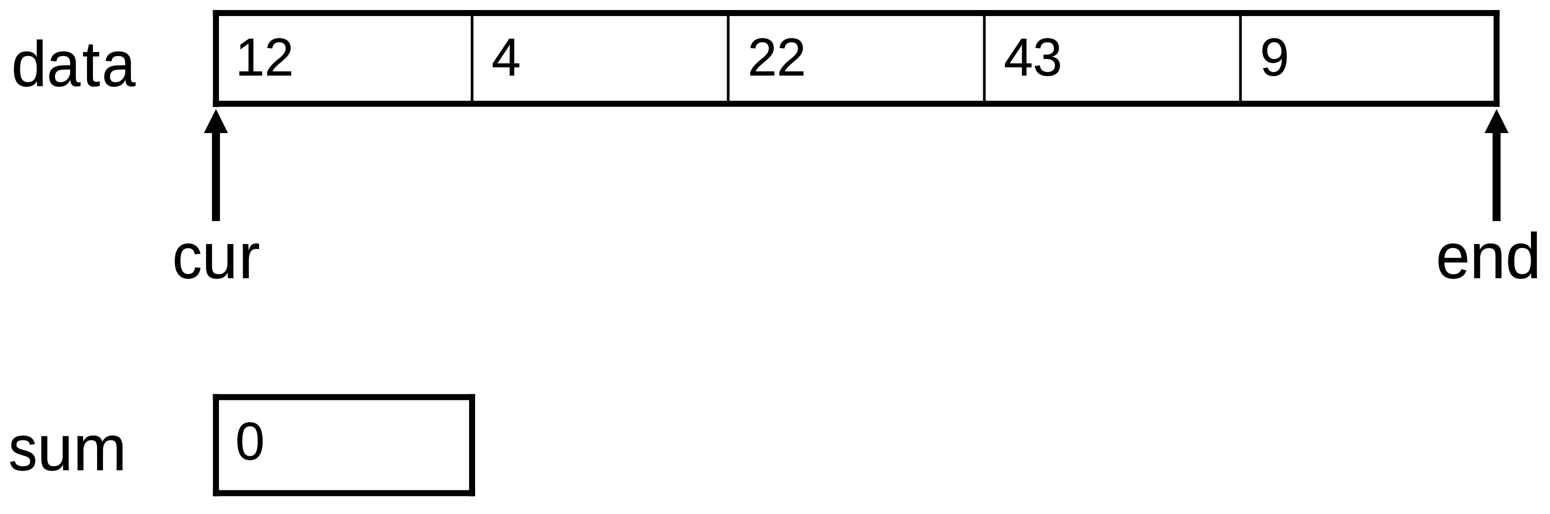

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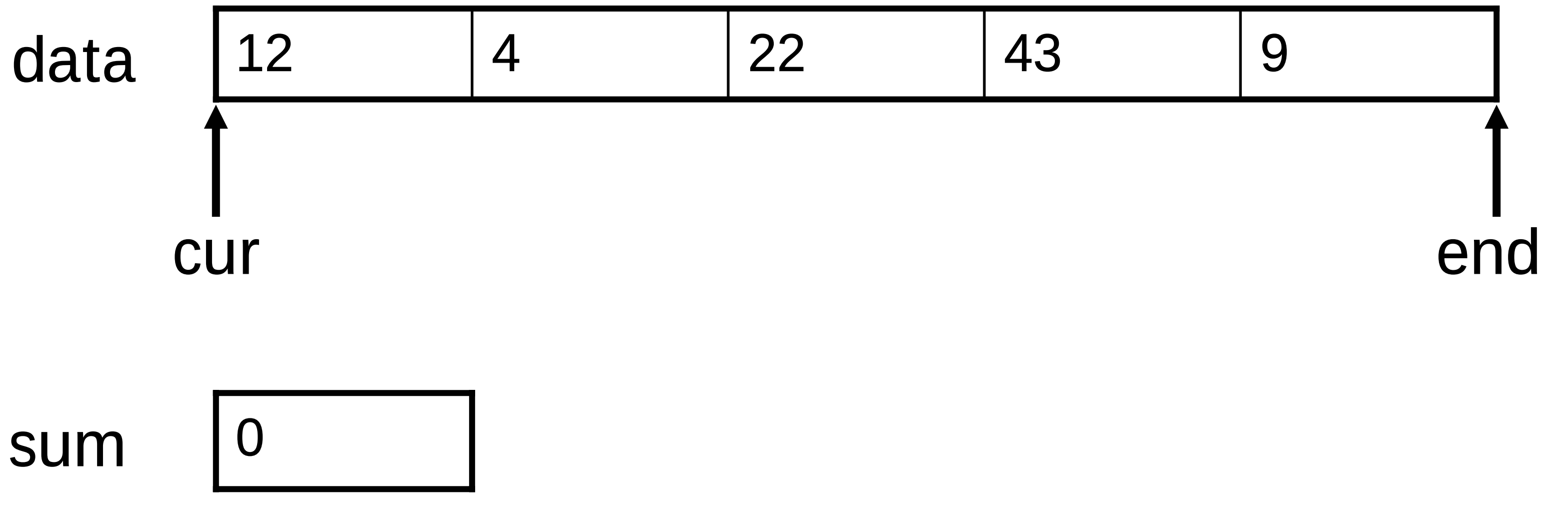

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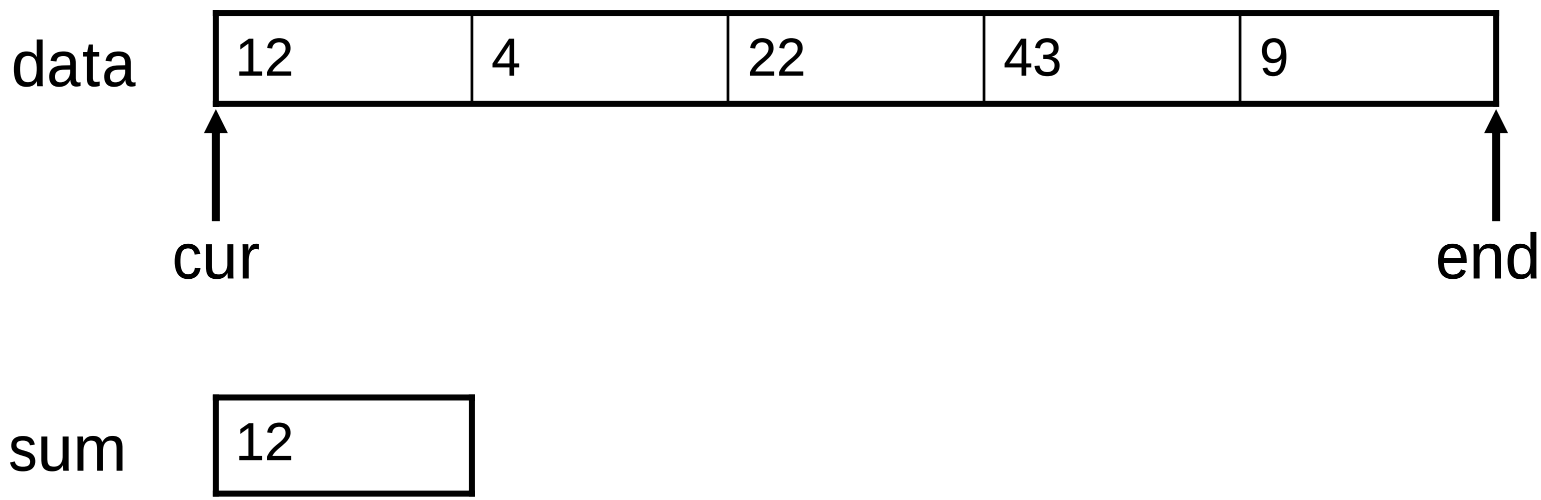

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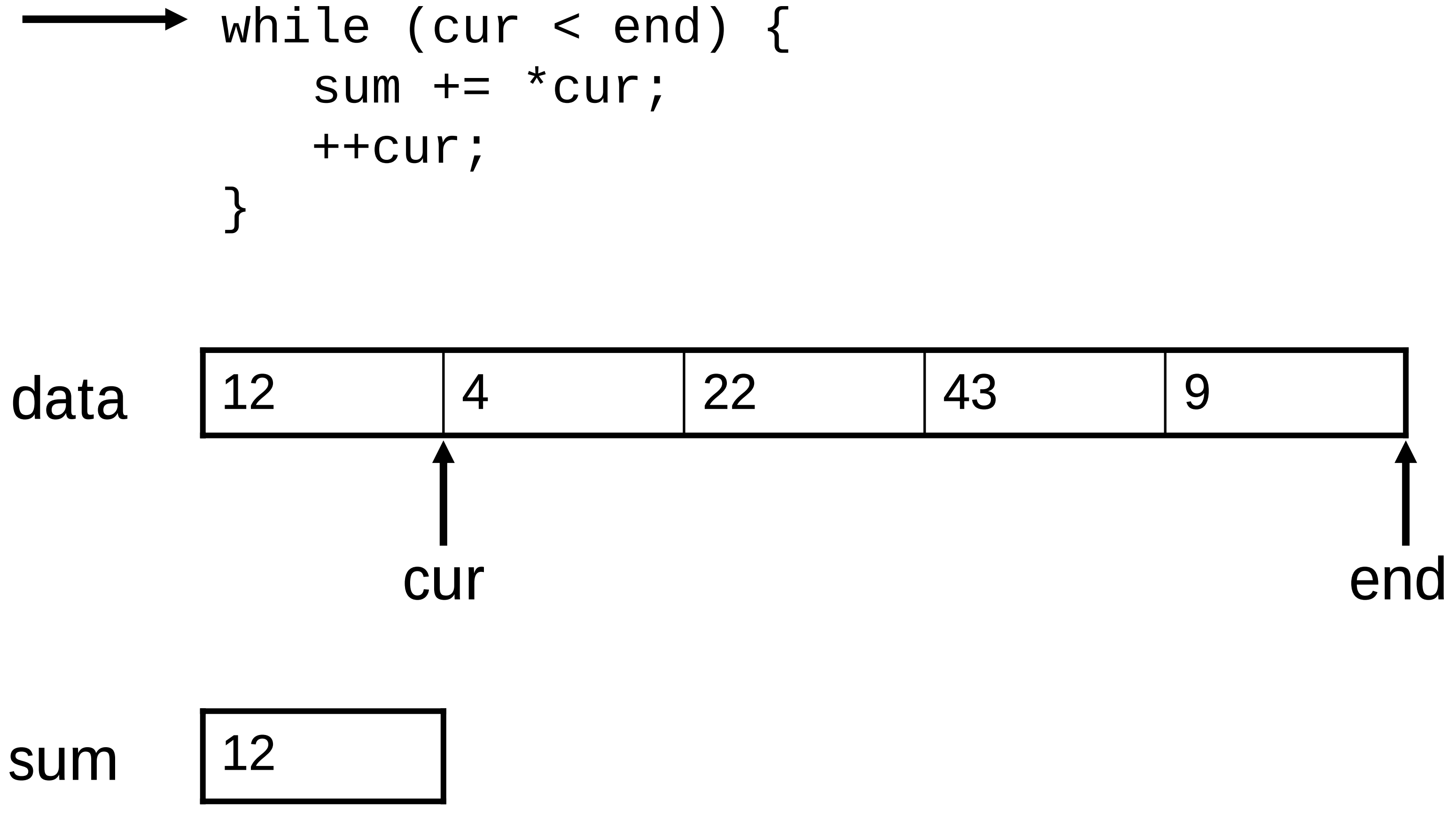

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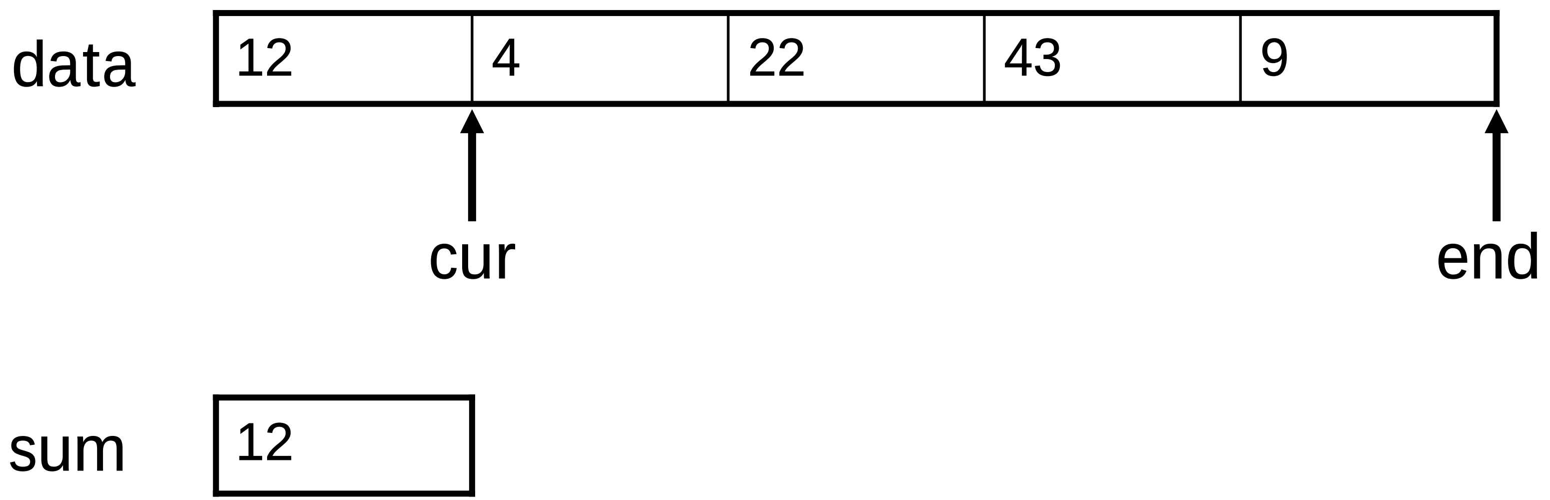

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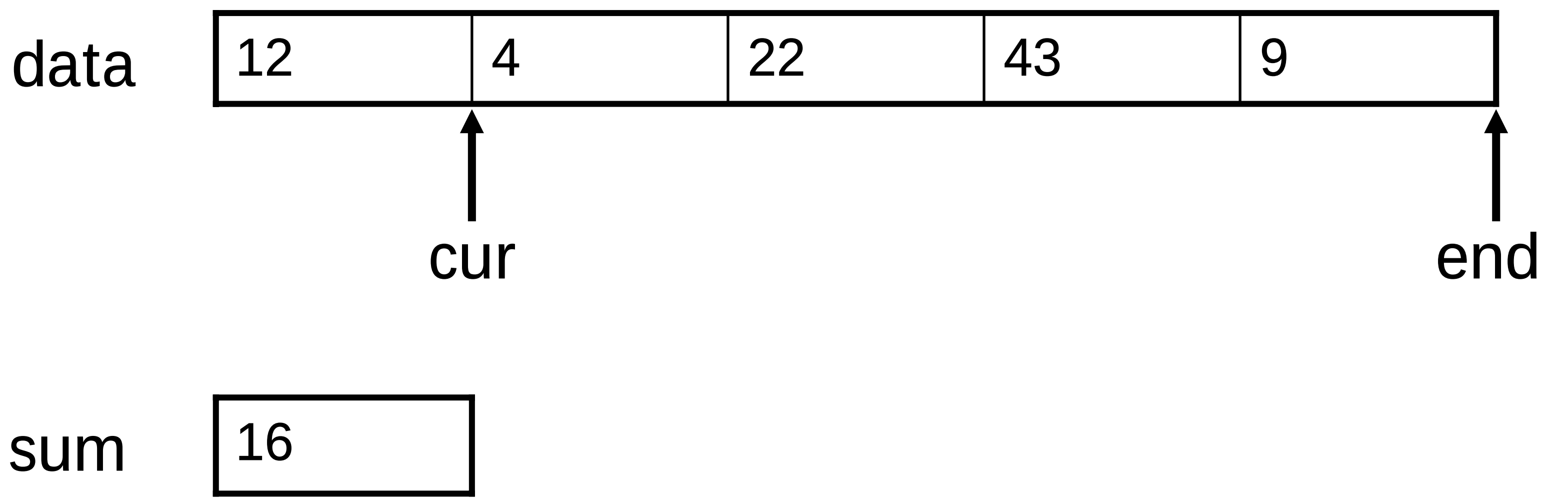

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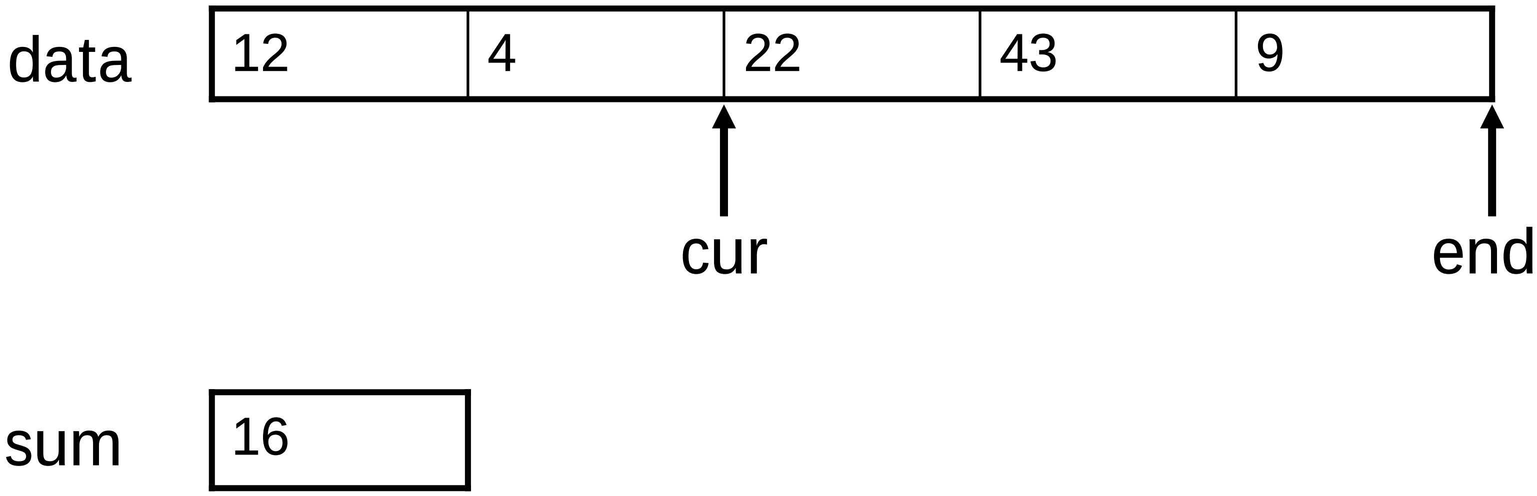

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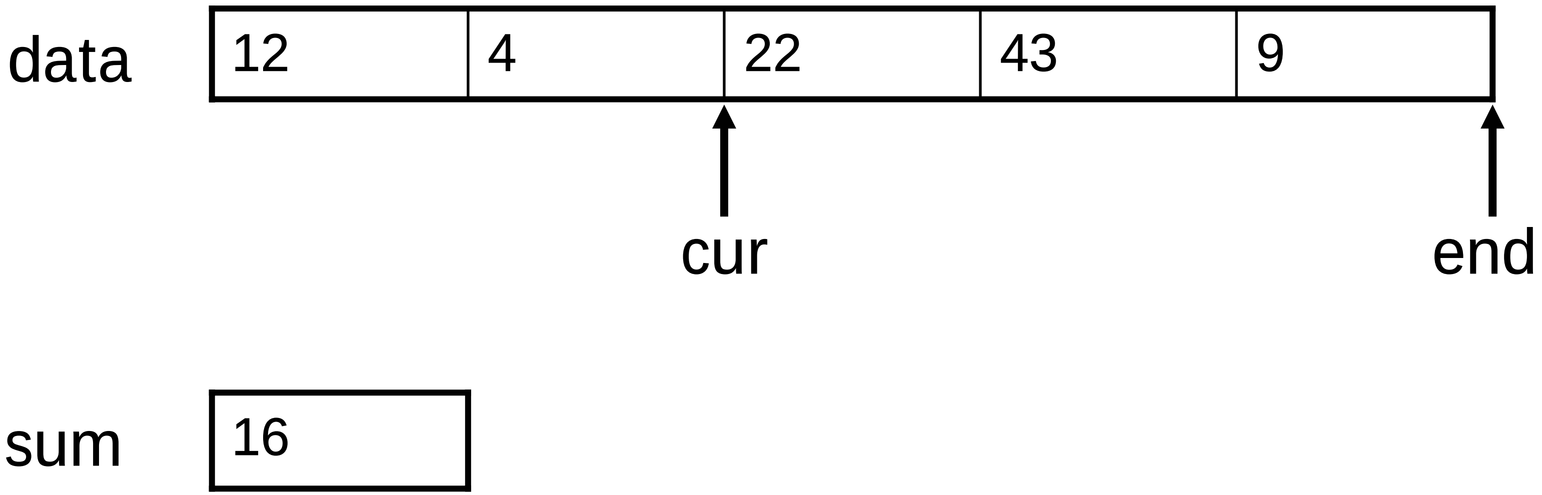

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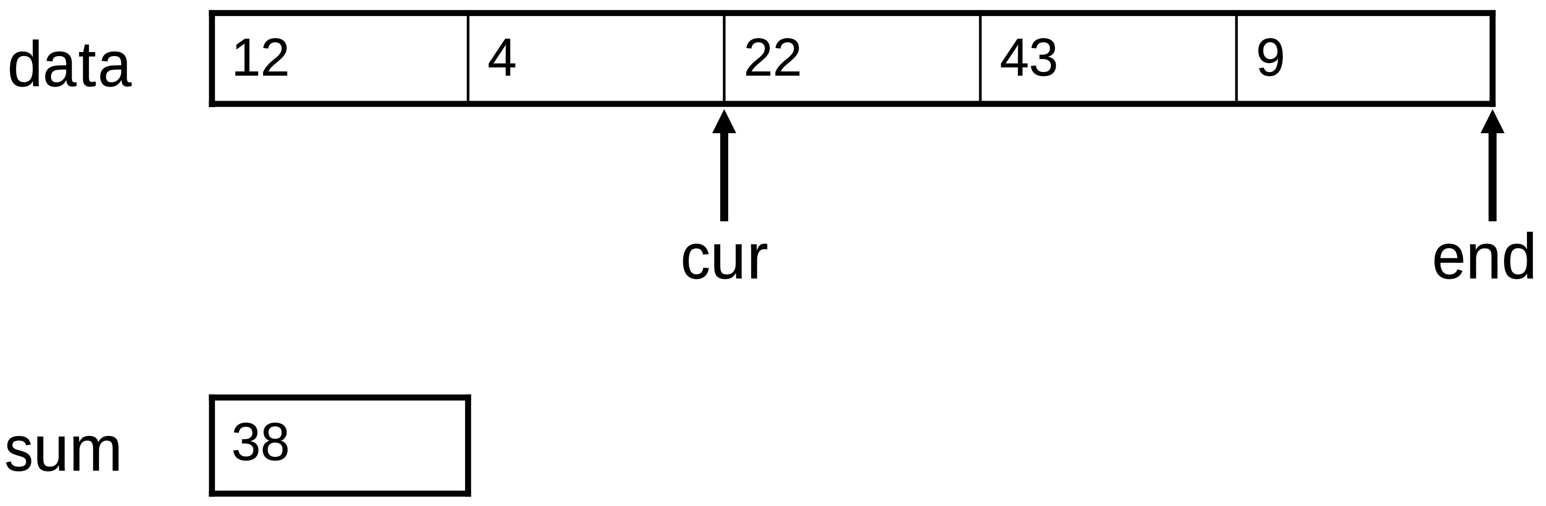

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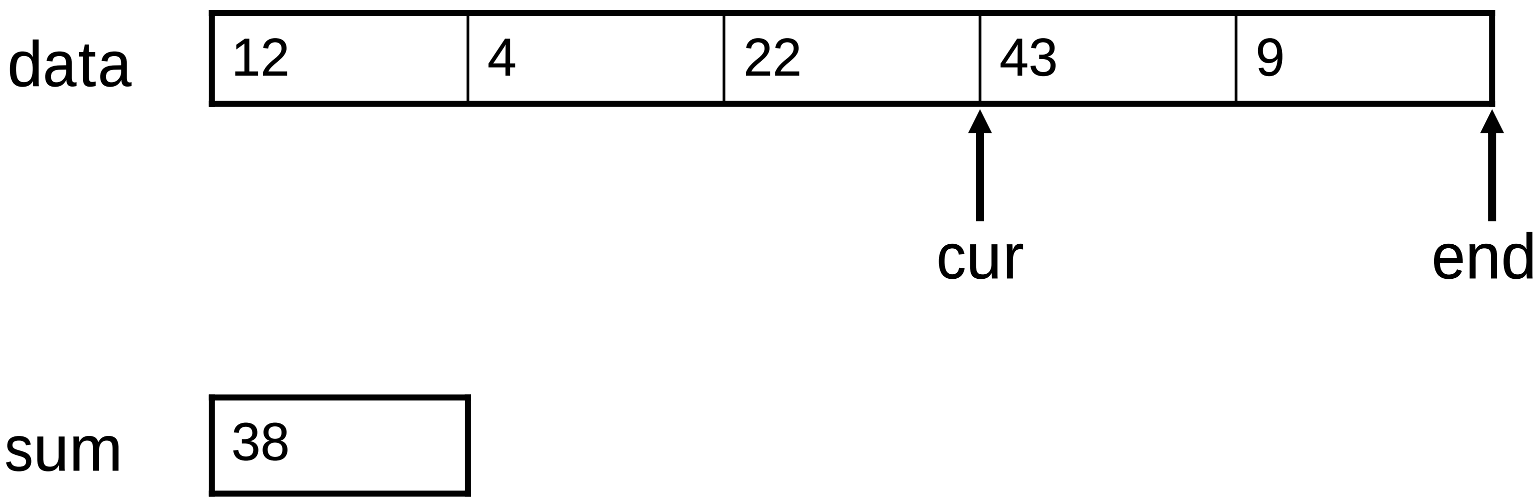

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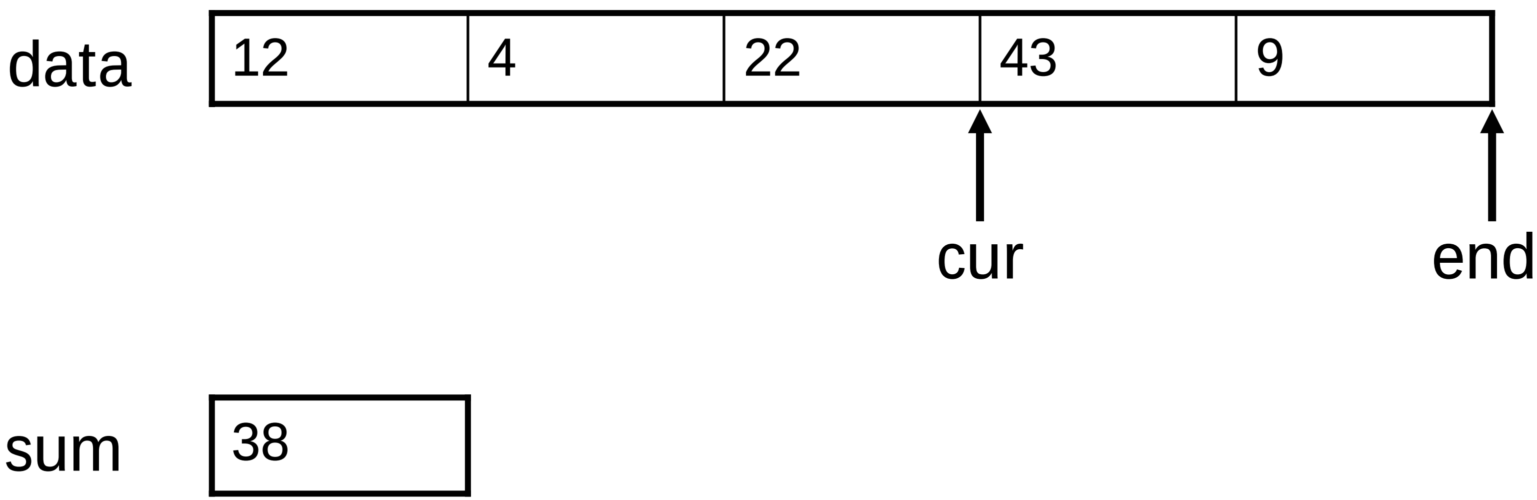

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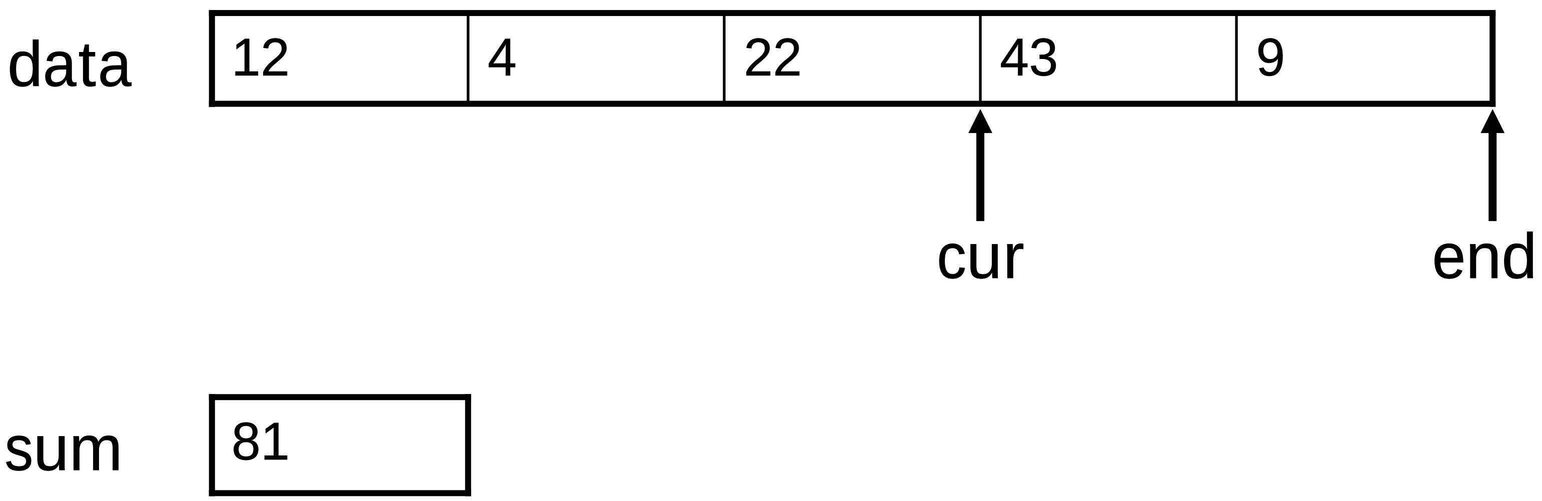

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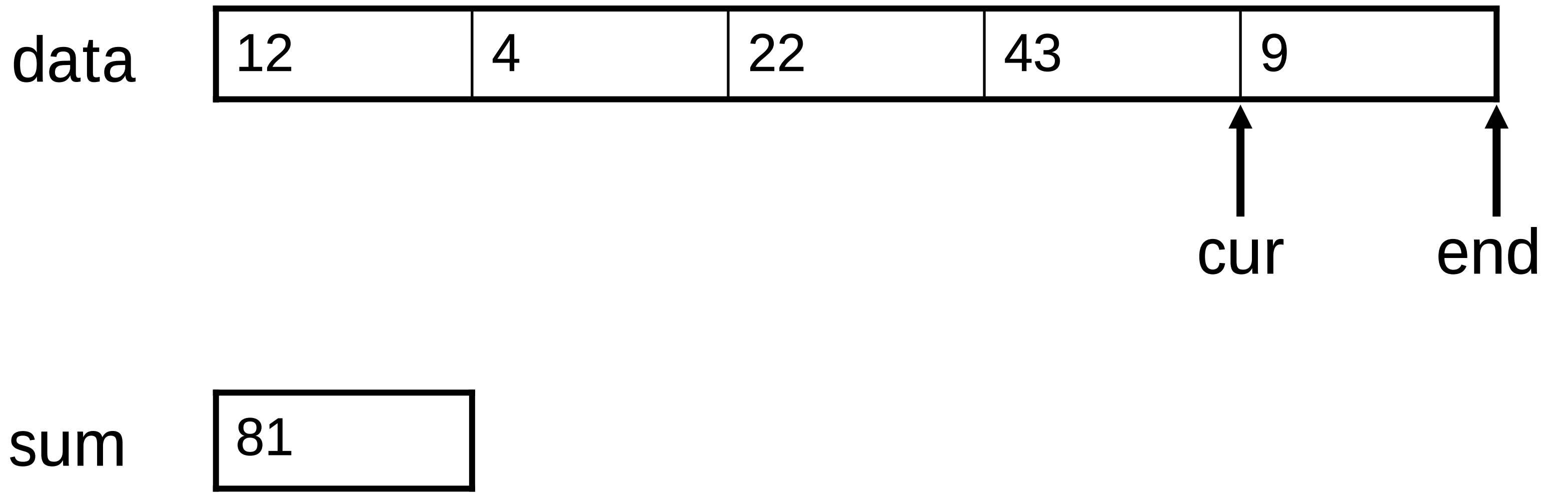

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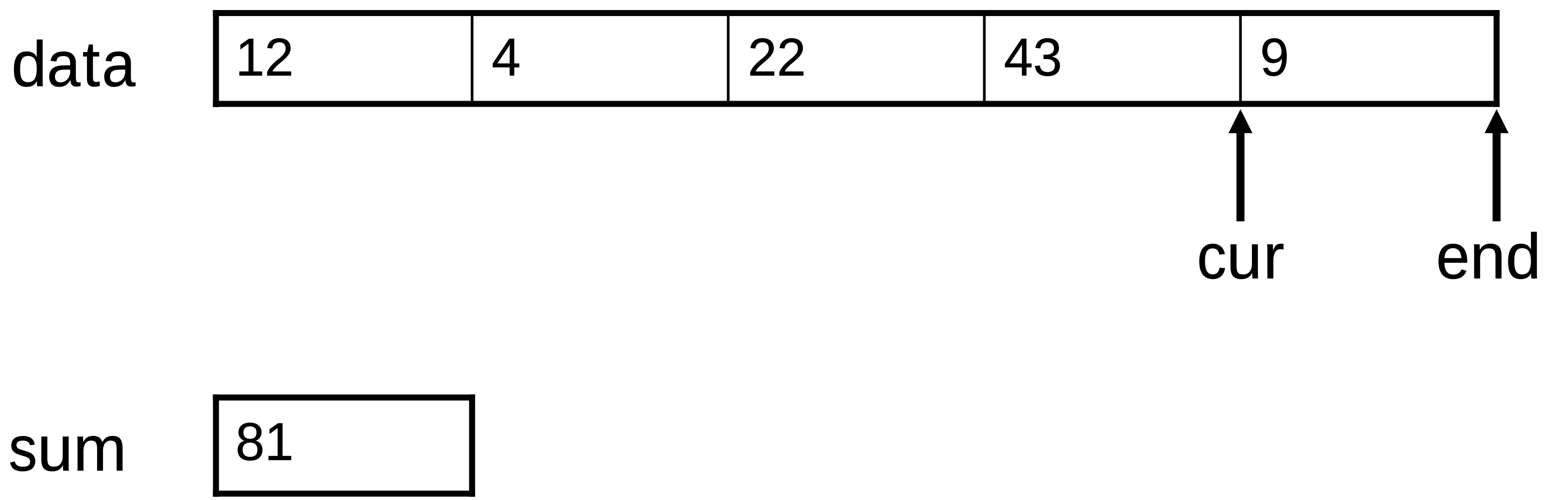

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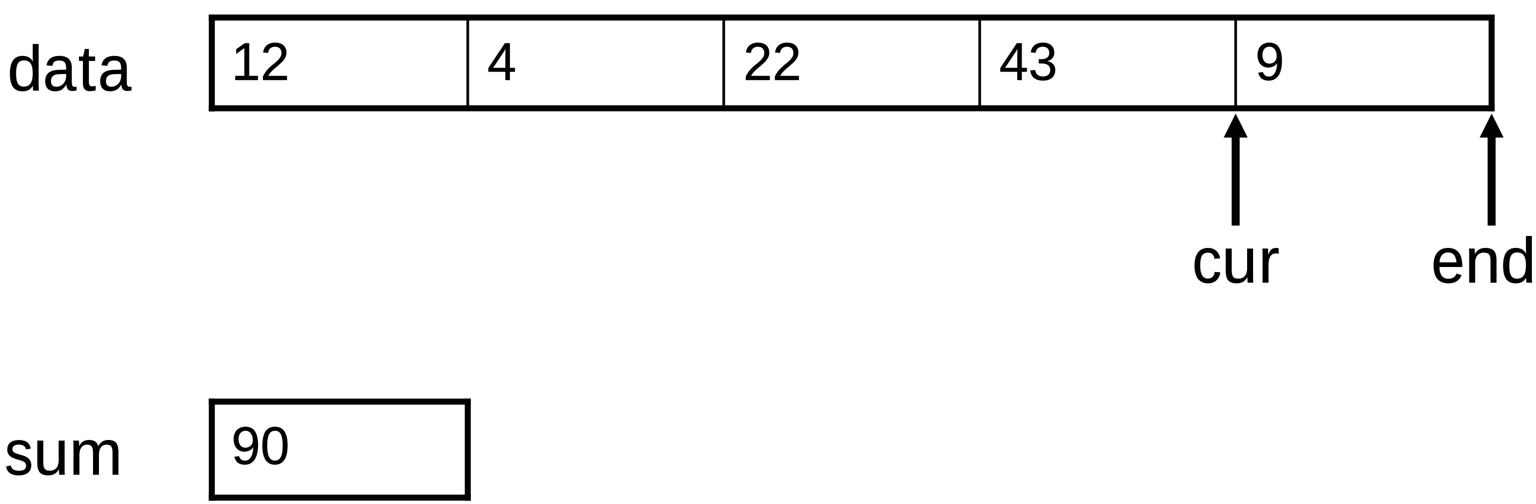

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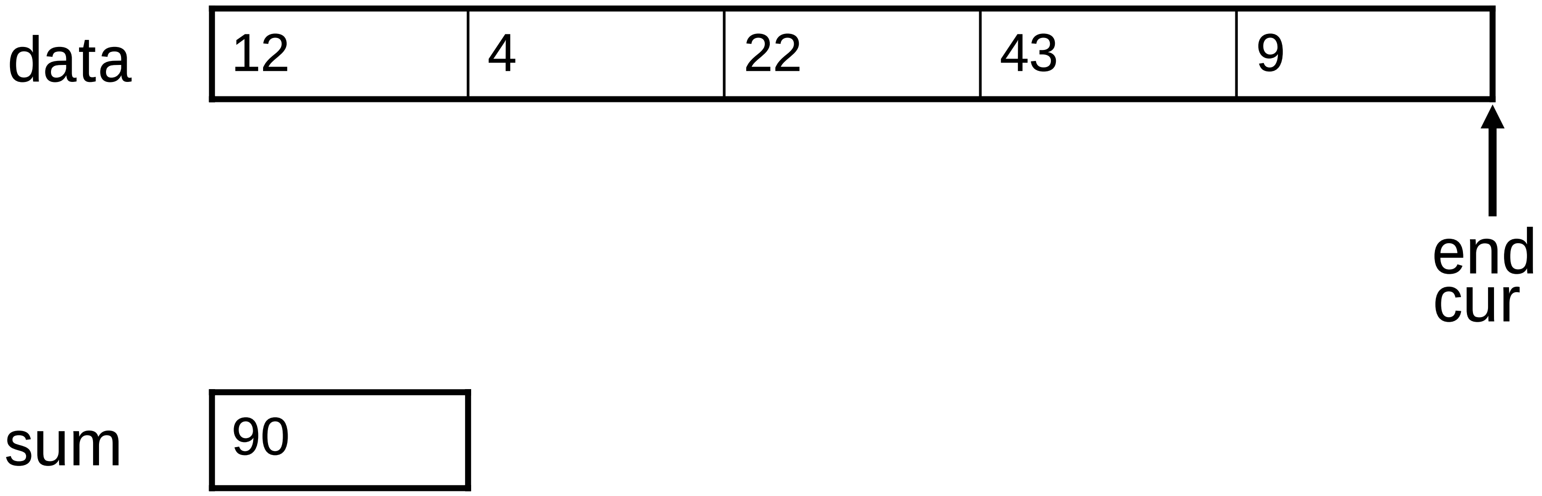

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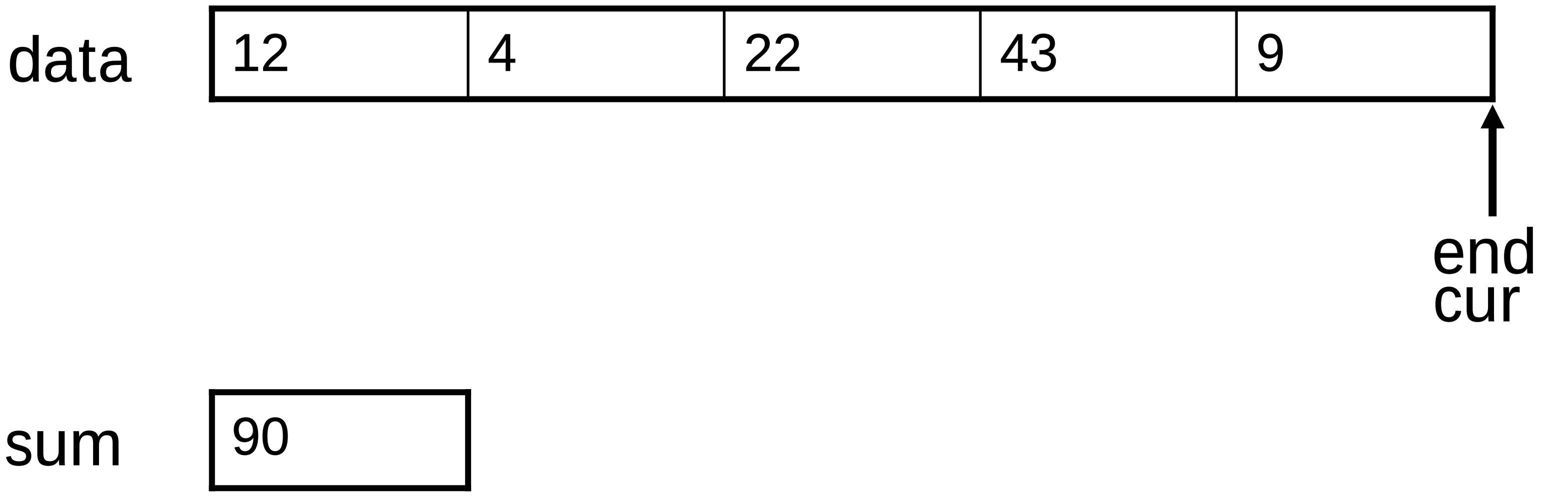


Null Pointers

- A pointer with value 0 (zero) is called a "null pointer"
- A null pointer doesn't point to anything

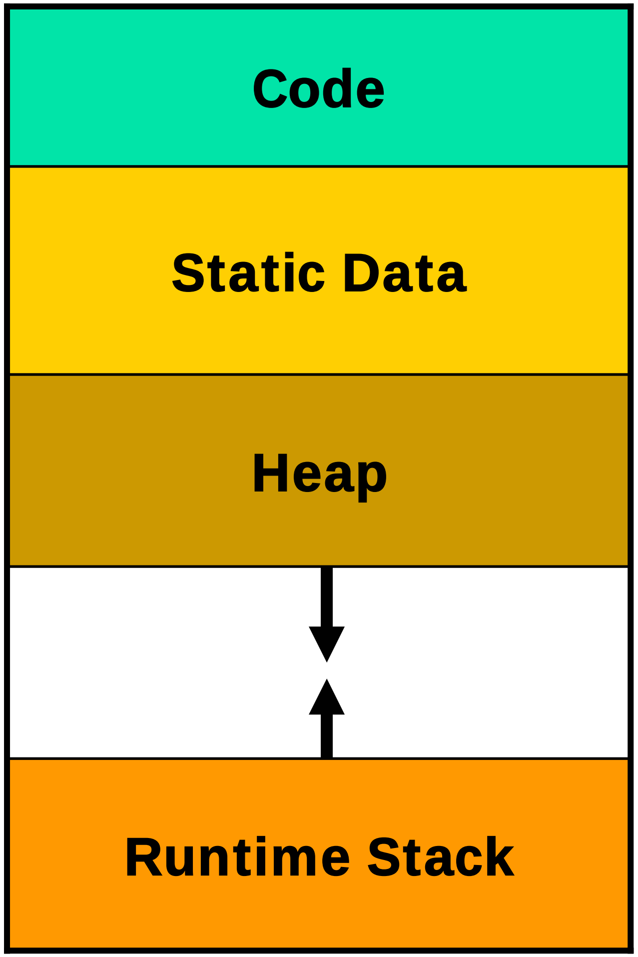
```
char * ptr = 0;
```

- Dereferencing a null pointer is a fatal error

```
// assume that p1 and p2 are null
*p1 = 'X';          // disaster!
p2->name = "fred"; // disaster!
```

The C++ Memory Model

- A C++ program's address space is divided into several different areas
  - Code
  - Static data
  - Heap
  - Runtime stack
- Maximum sizes of heap and stack can be set using ulimit before running program
  - ulimit –d #kb
  - ulimit –s #kb



Static Variables

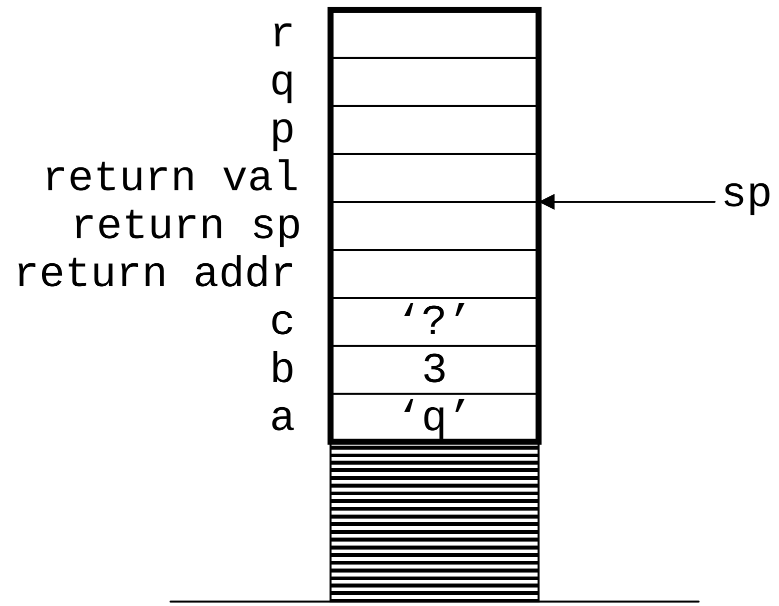
- Stored in static data area
- Allocated when program is loaded, never deallocated
- Initialized by compiler to all zeros (guaranteed by C++)
- Kinds of static variables
  - Global variables
    - variables declared outside of any function or class
  - Static variables inside a class
    - all instances of the class share one instance of the variable
  - Static local variables
    - local variables that retain their values between function invocations because they're not on the runtime stack

Parameters and Local Variables

- Parameters and local variables are pushed onto the runtime stack when a function is called, and popped off the stack when the function returns

```
int f(char a, int b, char c) {
    char * p;
    float q, r;
    …
}

r = f('q', 3, '?');
```



Runtime Stack

Parameters and Local Variables

- Never use the address of a parameter or local variable after the function returns

```
Student * CreateStudent(long id, string name) {
   Student s;
   s.id = id;        // ok
   s.name = name;    // ok
   return &s;        // disaster!
}

int main() {
   Student * a = CreateStudent(4978L, “Fred”);
   Student * b = CreateStudent(3925L, “Barney”);
   cout << “Fred’s ID: ” << a->id << endl;
   return 0;
}
```

Dynamic Memory Allocation

- Programs can dynamically allocate memory from the heap
- The new operator is used to allocate heap memory
- The delete operator is used to free heap memory
- Heap memory should be freed whenever possible so that the program won't run out of memory

```
Student * CreateStudent(long id, string name) {
   Student * s = new Student;
   s->id = id;      // ok
   s->name = name; // ok
   return s;       // ok
}
int main() {
   Student * a = CreateStudent(4978L, “Fred”);
   Student * b = CreateStudent(3925L, “Barney”);
   cout << “Fred’s ID: ” << a->id << endl;
   delete a;
   delete b;
   return 0;
}
```

Dynamic Memory Allocation

- Use [] when allocating and deallocating arrays

```
Student * CreateStudentArray(int n) {
   Student * s = new Student[n];
   for (int x=0; x < n; ++x) {
      s[x].id = 0L;
      s[x].name = "";
   }
   return s;
}

int main() {
   int number;
   cout << "How many students? ";
   cin >> number;
   Student * s = CreateStudentArray(number);

   // use student array for something . . .

   delete [] s;
   return 0;
}
```

Runtime stack vs. Heap

- Runtime Stack:
  - Memory is automatically allocated/deallocated by the compiler (easy for programmer)
  - Allocation/deallocation is very fast (just move the stack pointer)
  - Stack has a limited size, much smaller than heap (although this can be changed)
  - Stack can't be used to store dynamic data structures (e.g., linked list, BST, array whose size isn't known until runtime, etc.)
  - Programmer has no control over variable's lifetime (when subroutine exits, variable is popped no matter what)
- Heap:
  - Programmer must call new and remember to call delete (more work)
  - New and delete are expensive operations, much slower than adjusting stack pointer
  - Heap is normally much larger than the stack
  - Dynamic data structures must be heap allocated
  - Programmer completely controls the time of birth and death of an object