Introduction to Pointers in C

Readings: CP:AMA 11, 17.7

The primary goal of this section is to be able use pointers in C.

Address operator

C was designed to give programmers "low-level" access to memory and **expose** the underlying memory model.

The ***address operator*** (&) produces the **location** of an identifier in memory (the **starting address** of where its value is stored).

```
int g = 42;

int main(void) {
  printf("the value of g is:   %d\n",  g);
  printf("the address of g is: %p\n", &g);
}
```

```
the value of g is:   42
the address of g is: 0x71a0a0
```

The `printf` format specifier to display an address (in hex) is `"%p"`.

Pointers

In C, there is also a *type* for **storing an address**: a ***pointer***.

A pointer is defined by placing a *star* (*) *before* the identifier (name). The * is part of the definition syntax, not the identifier itself.

```
int i = 42;
int *p = &i;    // p "points at" i
```

The *type* of `p` is an *"int pointer"* which is written as "`int *`".

For *each type* (*e.g.,* `int`, `char`) there is a corresponding *pointer type* (*e.g.,* `int *`, `char *`).

This definition:

```
int *p = &i;    // p "points at" i
```

is comparable to the following definition and assignment:

```
int *p;         // p is defined (not initialized)
p = &i;         // p now "points at" i
```

The ∗ is part of the definition of p and is not part of the variable name. The name of the variable is simply p, not ∗p.

As with any variable, its value can be changed.

```
p = &j;         // p now "points at" j
p = &i;         // p now "points at" i
```


The **value** of a pointer is an **address**.

```
int i = 42;
int *p = &i;

trace_int(i);
trace_ptr(&i);
trace_ptr(p);
trace_ptr(&p);
```

```
i => 42
&i => 0xf020
p => 0xf020
&p => 0xf024
```

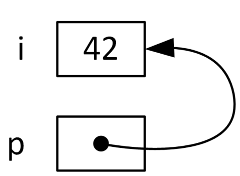
To make working with pointers easier in these notes, we often use shorter, simplified ("fake") addresses.


```
int i = 42;
int *p = &i;
```

identifier	type	address
i	int	0xf020
p	int *	0xf024

value
42
0xf020

When drawing a *memory diagram*, we rarely care about the value of the address, and visualize a pointer with an arrow (that "points").



sizeof a pointer

In most k-bit systems, memory addresses are k bits long, so pointers require k bits to store an address.

In our 64-bit `Seashell` environment, the `sizeof` a pointer is always 64 bits (8 bytes).

The `sizeof` a pointer is always the same size, regardless of the type of data stored at that address.

```
sizeof(int *)  ⇒ 8
sizeof(char *) ⇒ 8
```


Indirection operator

The ***indirection operator*** (∗), also known as the *dereference operator*, is the **inverse** of the *address operator* (&).

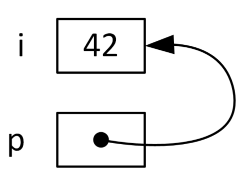
∗p produces the value of what pointer p "points at".

```
int i = 42;
int *p = &i;      // pointer p points at i

trace_ptr(p);
trace_int(*p);

p => 0xf020
*p => 42
```

The value of `*&i` is simply the value of `i`.

The **address operator (&)** can be thought of as:
"get the address of this box".

The **indirection operator (∗)** can be thought of as:
"follow the arrow to the next box and get its contents".



∗p ⇒ 42

The ∗ symbol is used in three different ways in C:

- as the *multiplication operator* between expressions

```
k = i * i;
```

- in pointer *definitions* and pointer *types*

```
int *p = &i;
sizeof(int *)
```

- as the *indirection operator* for pointers

```
j = *p;
*p = 5;
```

`(*p * *p)` is a confusing but valid C expression.

C mostly ignores whitespace, so these are equivalent

```
int *p = &i;     // style A
int * p = &i;    // style B
int* p = &i;     // style C
```

There is some debate over which is the best style. Proponents of style B & C argue it's clearer that the type of `p` is an "`int *`".

However, *in the definition* the ∗ "belongs" to the `p`, not the `int`, and so style A is used in this course and in CP:AMA.

This is clear with multiple definitions: (not encouraged)

```
int i = 42, j = 23;
int *p1 = &i, *p2 = &j; // VALID
int * p1 = &i, p2 = &j;  // INVALID: p2 is not a pointer
```


Pointers to pointers

A common question is: *"Can a pointer point at itself?"*

```
int *p = &p;      // pointer p points at p ???
```

This is actually a **type error**:

- `p` is defined as `(int *)`, a pointer to an `int`, but
- the type of `&p` is `(int **)`, a pointer to a pointer to an `int`.

In C, we can define a **pointer to a pointer**:

```
int i = 42;
int *p1 = &i;      // pointer p1 points at i
int **p2 = &p1;    // pointer p2 points at p1
```

C allows any number of pointers to pointers. More than two levels of "pointing" is uncommon.

`(**p * **p)` is a confusing but valid C expression.

A `void` pointer (`void *`) can point at anything, including a `void` pointer (itself).

Dereferencing pointers to structures

Unfortunately, the structure operator (`.`) has higher precedence than the indirection operator (`*`).

Awkward parenthesis are required to access a field of a pointer to a structure: `(*ptr).field`.

Fortunately, the ***indirection selection operator***, also known as the "arrow" operator (`->`) combines the indirection and the selection operators.

`ptr->field` is equivalent to `(*ptr).field`

example: indirection selection operator

```
struct posn {
  int x;
  int y;
};

int main(void) {
  struct posn my_posn = {0, 0};
  struct posn *ptr = &my_posn;

  (*ptr).x = 3;                 // awkward
  ptr->y = 4;                   // much better

  //...
}
```

The NULL pointer

`NULL` is a special pointer **value** to represent that the pointer points to "nothing".

If the value of a pointer is unknown at the time of definition, or what the pointer points at becomes *invalid*, it's good style to assign the value of `NULL` to the pointer. A pointer with a value of `NULL` is often known as a "NULL pointer".

```
int *p;           // BAD (uninitialized)

int *p = NULL;    // GOOD
```

Some functions return `NULL` to indicate an error.

`NULL` is considered "false" when used in a Boolean context (`false` is defined to be zero *or* `NULL`).

The following two are equivalent:

```
if (p) ...

if (p != NULL) ...
```

If you try to *dereference* a `NULL` pointer, your program will crash.

```
p = NULL;
i = *p;        // crash!
```

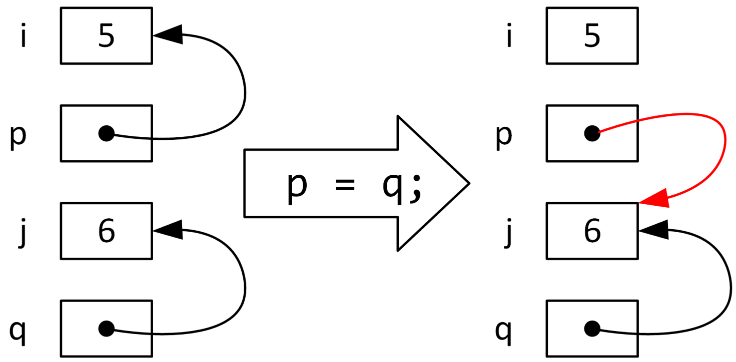

Pointer assignment

Consider the following code

```
int i = 5;
int j = 6;

int *p = &i;
int *q = &j;

p = q;
```

The statement `p = q;` is a ***pointer assignment***. It means "change `p` to point at what `q` points at". It changes the *value* of `p` to be the value of `q`. In this example, it assigns the *address* of `j` to `p`.

It **does not change the value of `i`**.



Using the same initial values,

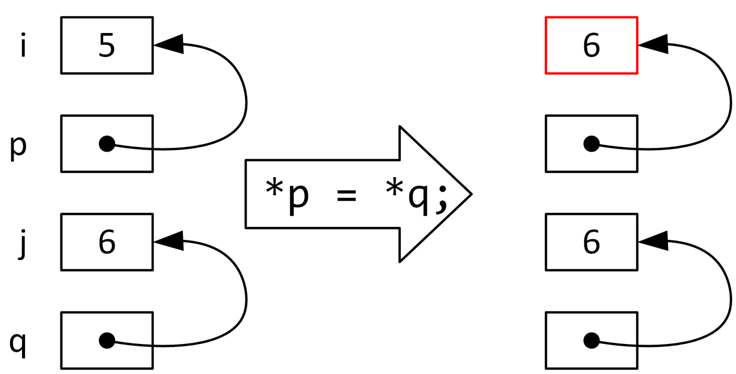
```
int i = 5;
int j = 6;

int *p = &i;
int *q = &j;
```

the statement

```
*p = *q;
```

does **not** change the value of p: it changes the value *of what p points at*. In this example, it **changes the value of i** to 6, *even though i was not used in the statement*.

This is an example of ***aliasing***, which is when the same memory address can be accessed from more than one variable.



example: aliasing

```
int i = 1;
int *p1 = &i;
int *p2 = p1;
int **p3 = &p1;

trace_int(i);
*p1 = 10;               // i changes...
trace_int(i);
*p2 = 100;              // without being used directly
trace_int(i);
**p3 = 1000;
trace_int(i);
```

```
i => 1
i => 10
i => 100
i => 1000
```


Mutation & parameters

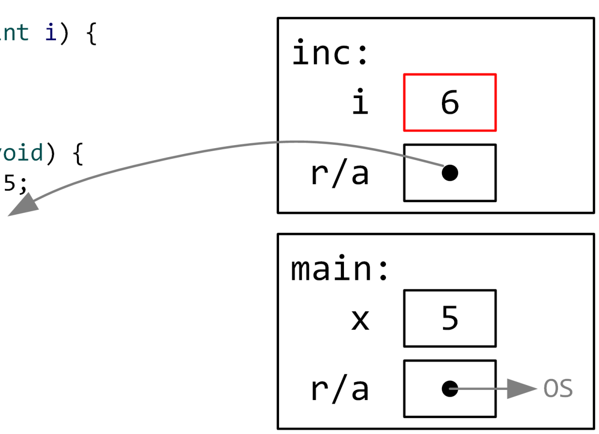
Consider the following C program:

```
void inc(int i) {
  ++i;
}

int main(void) {
  int x = 5;
  inc(x);
  trace_int(x);     // 5 or 6 ?
}
```

It is important to remember that when `inc(x)` is called, a **copy** of `x` is placed in the stack frame, so `inc` cannot change `x`.

The `inc` function is free to change it's own copy of the argument (in the stack frame) without changing the original variable.


```
void inc(int i) {
  ++i;
}

int main(void) {
  int x = 5;
  inc(x);
}
```



In the “pass by value” convention of C, a **copy** of an argument is passed to a function.

The alternative convention is “pass by reference”, where a variable passed to a function can be changed by the function. Some languages support both conventions.

What if we want a C function to change a variable passed to it? (this would be a side effect)

In C we can *emulate* “pass by reference” by passing **the address** of the variable we want the function to change.

This is still actually “pass by value” because we pass the **value** of the address.

By passing the *address* of x, we can change the *value* of x.

It is also common to say “pass a pointer to x”.

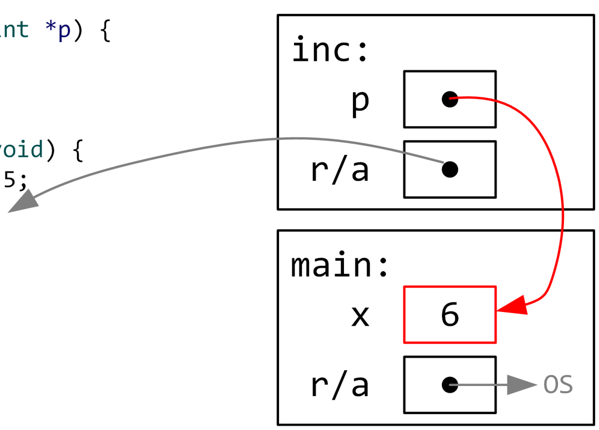
```
void inc(int *p) {
  *p += 1;
}

int main(void) {
  int x = 5;
  trace_int(x);
  inc(&x);                  // note the &
  trace_int(x);
}
```

```
x => 5
x => 6
```

To pass the address of x use the **address operator** (&x).

The corresponding parameter type is an int pointer (int *).


```
void inc(int *p) {
  *p += 1;
}

int main(void) {
  int x = 5;
  inc(&x);
}
```



Most pointer parameters should be **required** to be valid (*e.g.,* non-NULL). In the slides it is often omitted to save space.

```
// inc(p) increments the value of *p
// effects:  modifies *p
// requires: p is a valid pointer

void inc(int *p) {
  assert(p != NULL);      // or assert(p);
  *p += 1;
}
```

Note that instead of `*p += 1;` we could have written `(*p)++;`

The parentheses are necessary because of the order of operations: ++ would have incremented the pointer p, not what it points at (*p).

example: mutation side effects

```
//  effects: modifies *px and *py
void swap(int *px, int *py) {
  int temp = *px;
  *px = *py;
  *py = temp;
}

int main(void) {
  int a = 3;
  int b = 4;
  trace_int(a); trace_int(b);
  swap(&a, &b);                      // Note the &
  trace_int(a); trace_int(b);
}
```

```
a => 3
b => 4
a => 4
b => 3
```


Documenting side effects

We now have a fourth side effect that a function may have:

- produce output
- read input
- mutate a global variable
- **mutate a variable through a pointer parameter**

```
//  effects: modifies *px and *py
void swap(int *px, int *py) {
  int temp = *px;
  *px = *py;
  *py = temp;
}
```

In the *functional paradigm*, there is no observable difference between "pass by value" and "pass by reference".

In Racket, simple values (*e.g.,* numbers) are passed by *value*, but structures are passed by *reference*.

C input: scanf

So far we have been using our tools (*e.g.,* `read_int`) to read input. We are now capable of using the built-in `scanf` function.

```
scanf("%d", &i) // read in an integer, store it in i
```

`scanf` requires a **pointer** to a variable to **store** the value read in from input.

Just as with `printf`, multiple format specifiers can be used to read in more than one value.

However, in this course only read in one value per `scanf`.

This will help you debug your code and facilitate our testing.

scanf return value

The **return value** of `scanf` is an `int`, and either:

- the quantity (count) of values *successfully read*.
  This will be zero if the input is not formatted properly
  (*e.g.,* the input `[hello]` is not a valid `int`).
- the constant `EOF`: the **E**nd **O**f **F**ile (`EOF`) has been reached.

A `Ctrl-D` ("Control D") keyboard sequence sends an `EOF`.

In our seashell environment, `EOF` is defined as `-1`, but it is much better style to use the constant `EOF` instead of `-1`.

Invalid input

Always check the return value of `scanf`: one is "success". (if you are following our advice to read one value per `scanf`).

```
retval = scanf("%d", &i); // read in an integer, store it in i

if (retval != 1) {
  printf("Fail! I could not read in an integer!\n");
}
```

The `read_int()` function returns `READ_INT_FAIL` (`INT_MIN`) if the return value is not `1` (*i.e.,* `0` or `EOF`).

example: reading integers

This function reads in `int`s from input (until `EOF` or an unsuccessful read occurs) and returns their sum.

```
int read_sum(void) {
  int sum = 0;
  int n = 0;
  while (scanf("%d", &n) == 1) {
    sum += n;
  }
  return sum;
}
```

Whitespace

When reading an `int` with `scanf ("%d")` C **ignores any whitespace** (spaces and newlines) that appears before the next `int`.

When reading in a `char`, you *may* or *may not* want to ignore whitespace: it depends on your application.

```
// reads in next character (may be whitespace character)
count = scanf("%c", &c);

// reads in next character, ignoring whitespace
count = scanf(" %c", &c);
```

The extra leading space in the second example indicates that leading whitespace is ignored.

Using pointers to “return” multiple values

C functions can only return a single value.

Pointer parameters can be used to *emulate* “returning” more than one value.

The addresses of several variables can be passed to the function, and the function can change the value of those variables.

example: “returning” more than one value

This function performs division and “returns” both the quotient and the remainder.

```
void divide(int num, int denom, int *quot, int *rem) {
  *quot = num / denom;
  *rem  = num % denom;
}
```

Here is an example of how it can be used:

```
divide(13, 5, &q, &r);
trace_int(q);
trace_int(r);
```

```
q => 2
r => 3
```

This “multiple return” technique is also useful when it is possible that a function could encounter an error.

For example, the previous `divide` example could return `false` if it is successful and `true` if there is an error (*i.e.,* division by zero).

```
bool divide(int num, int denom, int *quot, int *rem) {
  if (denom == 0) return true;
  *quot = num / denom;
  *rem  = num % denom;
  return false;
}
```

Some C library functions use this approach to return an error. Other functions use “invalid” sentinel values such as `-1` or `NULL` to indicate when an error has occurred.

Returning an address

In Section 10, we use functions that return an address (pointer).

A function must never return an address within its stack frame.

```
int *bad_idea(int n) {
  return &n;            // NEVER do this
}

int *bad_idea2(int n) {
  int a = n * n;
  return &a;            // NEVER do this
}
```

As soon as the function `return`s, the stack frame “disappears”, and

all memory within the frame is considered **invalid**.

Passing structures

Recall that when a function is called, a **copy** of each argument value is placed into the stack frame.

For structures, the *entire* structure is copied into the frame. For large structures, this can be inefficient.

```
struct bigstruct {
  int a;
  int b;
  int c;
  int d;
  ...
  int y;
  int z;
};
```


To avoid structure copying, it is very common to pass the *address* of a structure to a function.

```
// sqr_dist(p1, p2) calculates the square of
//   the distance between p1 and p2

int sqr_dist(struct posn *p1, struct posn *p2) {
  int xdist = p1->x - p2->x;
  int ydist = p1->y - p2->y;
  return xdist * xdist + ydist * ydist;
}
```


Passing the address of a structure to a function (instead of a copy) also allows the function to mutate the fields of the structure.

```
// scale(p, f) scales the posn p by f
// requires: p is not null
// effects:  modifies p

void scale(struct posn *p, int f) {
  p->x *= f;
  p->y *= f;
}
```

In the above documentation, we used p, where *p would be more correct. It is easily understood that p represents the structure.

```
// this is more correct, but unnecessary:

// scale(p, f) scales the posn *p by f
// effects:  modifies *p
```

We now have **two** different reasons for passing a structure pointer to a function:

- to avoid copying the structure
- to mutate the contents of the structure

It would be good to communicate whether or not there is a side effect (mutation).

However, documenting the **absence** of a side effect ("no side effect here") is awkward.

const pointers

Adding the `const` keyword to a pointer definition prevents the pointer's destination from being mutated through the pointer.

```
void cannot_change(const struct posn *p) {
  p->x = 5;   // INVALID
}
```

Place `const` **before** the type.

It is good style to add `const` to a pointer parameter to communicate (and enforce) that the pointer's destination does not change.

The syntax for working with pointers and `const` is tricky.

```
int *p;               // p can point at any mutable int,
                      // you can modify the int (via *p)

const int *p;         // p can point at any int,
                      // you can NOT modify the int via *p

int * const p = &i;   // p always points at i, i must be
                      // mutable and can be modified via *p

const int * const p = &i;  // p must always point at i
                           // you can not modify i via *p
```

The rule is "`const` applies to the type to the left of it, unless it's first, and then it applies to the type to the right of it".

```
const int i = 42;      // these are equivalent
int const i = 42;      // but this form is discouraged
```

const parameters

As we just established, it is good style to use `const` with pointer parameters to communicate that the function does not (and can not) mutate the contents of the pointer.

```
void can_change(struct posn *p) {
  p->x = 5;   // VALID
}

void cannot_change(const struct posn *p) {
  p->x = 5;   // INVALID
}
```

What does it mean when `const` is used with simple (non-pointer) parameters?

For a simple value, the `const` keyword indicates that the parameter is immutable *within the function*.

```
int my_function(const int x) {
  // mutation of x here is invalid
  // ...
}
```

It does not require that the argument passed to the function is a constant.

Because a **copy** of the argument is made for the stack, it does not matter if the original argument value is constant or not.

A `const` parameter communicates (and enforces) that **the copy** of the argument will not be mutated.

Minimizing mutative side effects

In Section 03 we used *mutable* global variables to demonstrate mutation and how functions can have mutative side effects.

Global mutable variables are strongly discouraged and considered “poor style”.

They make your code harder to understand, maintain and test.

On the other hand, global **constants** are “good style” and encouraged.

There are rare circumstances where global mutable variables are necessary.

Your preference for function design should be:

1. **"Pure" function**

   No side effects or dependencies on global *mutable* variables.

2. **Only I/O side effects**

   If possible, avoid any mutative side effects.

3. **Mutate data through pointer parameters**

   If mutation is necessary, use a pointer parameter.

4. **Global dependencies**

   Mutable global variables should be avoided.

5. **Mutate global data**

   Only when absolutely necessary (it rarely is).

Function pointers

In Racket, functions are *first-class values*.

For example, Racket functions are values that can be stored in variables and data structures, passed as arguments and returned by functions.

In C, functions are not first-class values, but ***function pointers*** are.

A significant difference is that **new** Racket functions can be created during program execution, while in C they cannot.

A function pointer can only point to a function that already exists.

A *function pointer* stores the (starting) address of a function, which is an address in the code section of memory.

The type of a function pointer includes the *return type* and all of the *parameter types*, which makes the syntax a little messy.

The syntax to define a function pointer with name `fpname` is:

```
return_type (*fpname)(param1_type, param2_type, ...)
```

In an exam, we would not expect you to remember the syntax for defining a function pointer.

example: function pointer

```
int my_add(int x, int y) {
  return x + y;
}

int my_sub(int x, int y) {
  return x - y;
}

int main(void) {
  int (*fp)(int, int) = NULL;
  fp = my_add;
  trace_int(fp(7, 3));
  fp = my_sub;
  trace_int(fp(7, 3));
}
```

```
fp(7, 3) => 10
fp(7, 3) => 4
```


Goals of this Section

At the end of this section, you should be able to:

- define and dereference pointers
- use the new operators (&, ∗, ->)
- describe aliasing
- use the `scanf` function to read input

- use pointers to structures as parameters and explain why parameters are often pointers to structures
- explain when a pointer parameter should be `const`
- use function pointers