Introduction to Pointers in C

Optional Textbook Readings: CP:AMA 11, 17.7

The primary goal of this section is to be able use pointers in C.
We are learning about pointers in this course *early* (before we really “need” them) so you are more comfortable with them when they are required later.

In this section we mostly focus on *syntax* and simple applications. Later we will have more practical applications:

- understanding arrays (Section 07)
- working with dynamic memory (Section 10)
- working with linked data structures (e.g., lists and trees) (Section 11)
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).

```c
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: 0x725520
```

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

A **pointer** is a variable that stores a memory address.

To **define** a pointer, place a **star (⋆)** **before** the identifier (name).

```c
int i;     // i is an integer [uninitialized]
int *p;   // p is a pointer to an integer
           // [uninitialized]
```

The **type** of a pointer is the type of memory address it can store (or “point at”).

The pointer variable `p` above can store the address of an `int`.

```c
p = &i;     // p now stores the address of i
           // or "p points at i"
```
Pointer types

For *each type* there is a corresponding *pointer type*.

```c
int i = 42;
char c = 'z';
struct posn p1 = {3, 4};

int *pi = &i;  // pi points at i
char *pc = &c;  // pc points at c
struct posn *pp = &p1;  // pp points at p1
```

The *type of pi* is a “*int pointer*” which is written as “*int *”.  

The *type of pc* is a “*char pointer*” or “*char *”.  

The *type of pp* is a “*struct posn pointer*” or “*struct posn *”.  

The pointer definition syntax can be a bit overwhelming at first, especially with initialization.

Remember, that the following definition:

```c
int *q = &i;
```

is comparable to the following definition and assignment:

```c
int *q;    // q is defined [uninitialized]
q = &i;    // q now points at i
```

The * is part of the definition and is **not part of the variable name.** The name of the above variable is simply q, not *q.
C mostly ignores whitespace, so these are equivalent

```c
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)

```c
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?"

```c
int *p = &p; // p points at p ?!? // INVALID [type error]
```

This is actually a **type error**: 

The type of `p` is `(int *)`, a pointer to an `int`.

`p` can only point at an `int`, but `p` itself is **not** an `int`.

What if we wanted a variable that points at `p`?
In C, we can define a **pointer to a pointer**:

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

The type of `p2` is “`int **`” or a “pointer to a pointer to an `int`”.

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

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

Remember, pointers are variables, and variables store values.

A pointer is only “special” because the **value** it stores is an **address**.

```c
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
```

Because a pointer is a variable, it **also** has an address itself.
int i = 42;
int *p = &i;

<table>
<thead>
<tr>
<th>identifier</th>
<th>type</th>
<th>address</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>int</td>
<td>0xf020</td>
<td>42</td>
</tr>
<tr>
<td>p</td>
<td>int *</td>
<td>0xf024</td>
<td>0xf020</td>
</tr>
</tbody>
</table>

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

![Memory diagram](image)
The NULL value

**NULL** is a special value that can be assigned to a pointer to represent that the pointer points at “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 called a “NULL pointer”.

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

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

NULL is considered “false” when used in a Boolean context.

In C, false is defined to be zero or NULL.

The following are equivalent:

    if (p) ...

    if (p != NULL) ...

Both are considered “good style”.
Pointer assignment

As with any variable, the value of a pointer can be changed (mutated) with the assignment operator.

```c
int *p = NULL; // p is initialized to NULL
p = &j; // p now points at j
p = NULL; // p now points at nothing
p = &i; // p now points at i
```
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.

\[
\begin{align*}
\text{sizeof(int *)} & \Rightarrow 8 \\
\text{sizeof(char *)} & \Rightarrow 8 
\end{align*}
\]
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”.

```c
i = 42;
p = &i;

trace_int(*p);

*p => 42
```

The value of *&i* or *&*&*&*&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".

\[
\text{i} \quad \begin{array}{|c|}
\hline
42 \\
\hline
\end{array} \\
\quad \rightarrow \\
\text{p} \\
\begin{array}{|c|}
\hline
\bullet \\
\hline
\end{array}
\]

\[
*p \Rightarrow 42
\]
If you try to dereference a **NULL** pointer, your program will crash.

```c
p = NULL;
trace_int(*p);       // crash!
```
Multiple uses of *

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

- as the *multiplication operator* between expressions
  \[ k = i \ast i; \]

- in pointer *definitions* and pointer *types*
  \[
  \text{int } *p = \&i;
  \text{sizeof(int } *)
  \]

- as the *indirection operator* for pointers
  \[
  \text{trace_int}(\*p);
  j = \*p;
  \]
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 \textit{indirection selection operator}, also known as the “arrow” operator ( - > ) combines the indirection and the selection operators.

\texttt{ptr->field} is equivalent to ( *ptr ).field
example: indirection selection operator

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

int main(void) {
    struct posn my_posn = {3, 4};
    struct posn *ptr = &my_posn;

    trace_int((*ptr).x); // awkward
    trace_int(ptr->x);   // much better
}
```
**Pointer assignment**

Consider the following code

```c
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`. 
p = q;
Using the same initial values,

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

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

the statement

```c
*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.
*p = *q;
example: aliasing

```c
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;  // same as *(p3)
trace_int(i);
```

```
i => 1
i => 10
i => 100
i => 1000
```
Mutation & parameters

Consider the following C program:

```c
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 its 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 \( x \)”.

```c
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** (\texttt{int *}).
```c
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.

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

void inc(int *p) {
    assert(p); // or assert(p != NULL);
    *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

```c
// 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**

```c
// 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*. 
Returning an address

A function may return an address.

```c
int *ptr_to_max(int *a, int *b) {
    if (*a >= *b) {
        return a;
    }
    return b;
}

int main(void) {
    int x = 3;
    int y = 4;

    int *p = ptr_to_max(&x, &y); // note the &
    assert(p == &y);
}
```

Returning addresses become more useful in Section 10.
A function must **never** return an address to a variable within its stack frame.

As soon as the function **returns**, the stack frame “disappears”, and all memory within the frame is considered **invalid**.

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

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

```c
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, or
- the constant EOF: the End Of File (EOF) has been reached.

If input is not formatted properly a zero is returned (e.g., the input is \texttt{[hello]} and we try to scanf an int with \texttt{"%d"}).

In Seashell, a Ctrl-D (“Control D”) keyboard sequence (or the [EOF] button) sends an EOF.

In our environment, EOF is defined as -1, but it is much better style to use the constant \texttt{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`).

```c
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");
}
```
Multiple side effects

Consider the following statement:

```c
retval = scanf("%d", &i);
```

There are three separate side effects:

- a value is read from input
- `i` is mutated
- `retval` is mutated

Earlier we encouraged you to only have one side effect per statement. Unfortunately, when using `scanf` it is impossible.
This function reads in integers from input (until EOF or an unsuccessful read occurs) and returns their sum.

```c
int read_sum(void) {
    int sum = 0;
    int n = 0;
    while (scanf("%d", &n) == 1) {
        sum += n;
    }
    return sum;
}
```
We can now see how the `read_int` function is implemented.

```c
const int READ_INT_FAIL = INT_MIN;

int read_int(void) {
    int i = 0;
    int result = scanf("%d", &i);
    if (result == 1) {
        return i;
    }
    return READ_INT_FAIL;
}
```

On assignments and exams, you will now be using `scanf` instead of `read_int`. 
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.

```c
// 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.

However, recall how `scanf` is used:

```c
retval = scanf("%d", &i);
```

We “receive” two values: the return value, *and* the value read in (stored in `i`).

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

The addresses of several variables can be passed to a 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.

```c
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:

```c
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).

```c
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.
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.

```c
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.

```c
// 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.

```c
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.

```c
void scale(struct posn *p, int f) {
    p->x *= f;
    p->y *= f;
}
```
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 the start of a pointer definition prevents the pointer’s destination (the variable it points at) from being mutated through the pointer.

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

It is good style to add const to a pointer parameter to communicate (and enforce) that the pointer’s destination does not change.
Remember, a pointer definition that begins with \texttt{const} prevents the pointer's \textbf{destination} from being mutated \textit{via the pointer}.

\begin{verbatim}
int i = 5;
const int *p = &i;

*p = 10;           // INVALID
i = 10;            // still valid
\end{verbatim}

However, the pointer variable itself is still mutable, and can point to another \texttt{int}.

\begin{verbatim}
p = &j;            // valid
*p = 10;          // INVALID
\end{verbatim}

A handy tip is to read the definition \textbf{backwards}:

\begin{verbatim}
const int *p \Rightarrow "p is a pointer to an \texttt{int} that is \texttt{constant}".
\end{verbatim}

See the following advanced slide for more details.
The syntax for working with pointers and `const` is tricky.

```c
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”.

```c
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 cannot) mutate the contents of the pointer.

```c
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*.

Remember that parameters behave the same as local variables and are stored in the stack frame.

```c
int my_function(const int x) {
    const int y = 13;
    x = 0;       // INVALID
    y = 0;       // 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.
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. **Dependency on global mutable variables**
   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

```c
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
In the previous example:

```c
fp = my_add;
```

We could have also used:

```c
fp = &my_add;
```

Because functions are not “first class values” C cannot get the “value” of a function. Instead it uses the `address` of the function.

Since both are equivalent, in practice `my_add` is used more often than `&my_add` because it is “cleaner”, even though `&my_add` is more correct.
example: passing a function to a function

```c
// io_apply(f) reads in each int [n] from input
// and prints out f(n)
// effects: produces output
// reads input
void io_apply(int (*f)(int)) {
    int n = 0;
    while (scanf("%d", &n) == 1) {
        printf("%d\n", f(n));
    }
}

int sqr(int i) {
    return i * i;
}

int main(void) {
    io_apply(sqr);
}
```
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