C Model: Memory & Control Flow

Optional Textbook Readings: CP:AMA 6.1–6.4, 7.1–7.3, 7.6, Appendix E

- the ordering of topics is different in the text
- some portions of the above sections have not been covered yet

The primary goal of this section is to be able to model how C programs execute.

Models of computation

In CS 135, we modelled the computational behaviour of Racket with substitutions (the “stepping rules”).

- all arguments are evaluated to values **before** a function can be called (“applied”)
- to call (“apply”) a function, we substitute the *body* of the function, replacing the parameters with the argument values.

```
(define (my-sqr x) (* x x))

(+ 2 (my-sqr (+ 3 1)))
=> (+ 2 (my-sqr 4))
=> (+ 2 (* 4 4))
=> (+ 2 16)
=> 18
```

In this course, we model the behaviour of C with two complimentary mechanisms:

- **control flow**
- **memory**

Control flow

We use ***control flow*** to model how programs are executed.

During execution, we keep track of the ***program location***, which is *"where"* in the code the execution is currently occurring.

When a program is "run", the *program location* starts at the beginning of the `main` function.

In hardware, the *location* is known as the ***program counter***, which contains the *address* within the machine code of the current instruction (more on this in CS 241).

Types of control flow

In this course, we explore four types of control flow:

- compound statements (blocks)
- function calls
- conditionals (*i.e.*, `if` statements)
- iteration (*i.e.*, loops)

Compound statements (blocks)

We have already seen compound statements (blocks) where a **sequence** of statements (and definitions) are executed **in order**.

```
int main(void) {
  trace_int(1 + 1);    // first
  assert(3 > 2);       // second
  int i = 7;           // third (i is now in scope)
  printf("%d\n", i);   // fourth
  return 0;            // fifth
}
```

Function Calls

When a function is called, the program location “jumps” *from* the current location *to* the start of the function.

The `return` control flow statement changes the program location to go *back* to the **most recent** calling function (where it “jumped from”).

Obviously, C needs to “keep track” of where to go. We revisit this when we introduce memory later in this section.

example: function call flow

```
void blue(void) {
  printf("three\n");
  return;
}

void green(void) {
  blue();
  printf("four\n");
  return;
}
```

```
void red(void) {
  printf("two\n");
  green();
  printf("five\n");
  return;
}

int main(void) {
  printf("one\n");
  red();
  printf("six\n");
}
```

There is a supplemental video for this slide online.

Conditionals (if)

We introduced the `if` control flow statement in Section 02. We now discuss `if` in more detail.

The syntax of `if` is

```
if (expression) statement
```

where the `statement` is only executed `if` the `expression` is true (non-zero).

```
if (n < 0) printf("n is less than zero\n");
```

Remember: the `if` statement does not produce a value. It only controls the flow of execution.

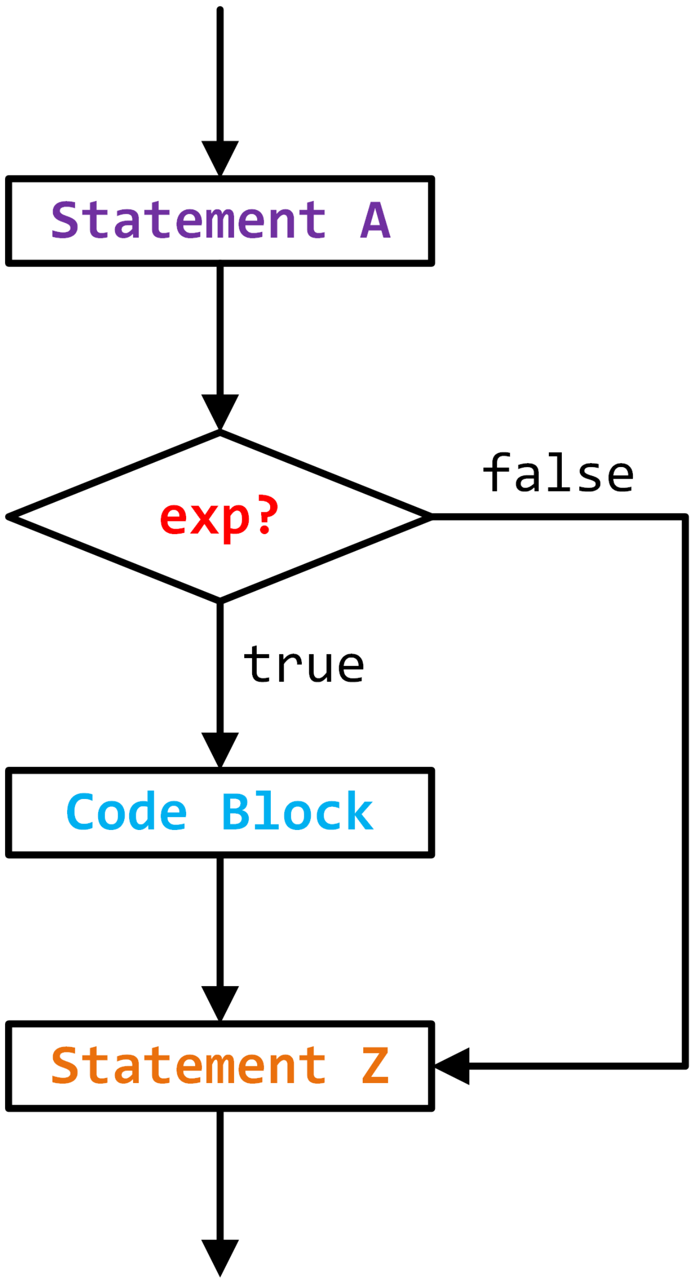
The `if` statement only affects whether the *next* statement is executed. To conditionally execute **more** than one statement, use a *compound statement* (block).

```
if (n <= 0) {
  printf("n is zero\n");              // execute this
  printf("or less than zero\n");      // then this
}
```

Using a block with every `if` is **strongly recommended** *even if there is only one statement*. It is good style: it makes code easier to follow and less error prone.

```
if (n <= 0) {
  printf("n is less than or equal to zero\n");
}
```

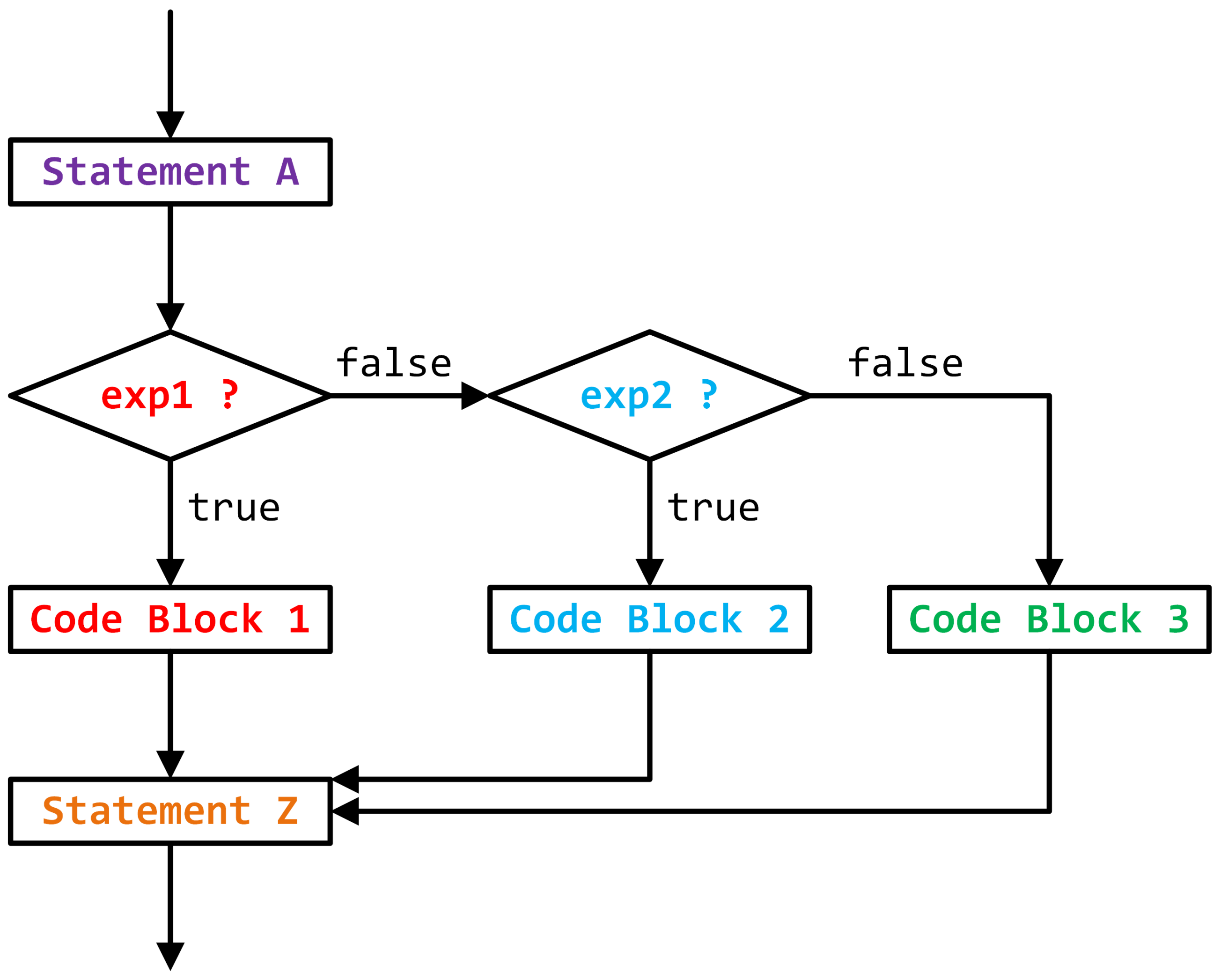
(In the notes, we occasionally omit them to save space.)



```
Statement A;
if (exp) {
  Code Block;
}
Statement Z;
```

As we have seen, the `if` statement can be combined with `else` statement(s) for multiple conditions.

```
if (expression) {
  statement(s)
} else if (expression) {
  statement(s)
} else if (expression) {
  statement(s)
} else {
  statement(s)
}
```



```
Statement A;
if (exp1) {
  Code Block 1;
} else if (exp2) {
  Code Block 2;
} else {
  Code Block 3;
}
Statement Z;
```

If an `if` block contains a `return` statement, there may be no need for an `else` block.

```
int sum(int k) {
  if (k <= 0) {
    return 0;
  } else {
    return k + sum(k - 1);
  }
}

// Alternate equivalent code

int sum(int k) {
  if (k <= 0) {
    return 0;
  }
  return k + sum(k - 1);
}
```

Braces are sometimes necessary to avoid a “dangling” `else`.

```
if (y > 0)
  if (y != 7)
    printf("you lose");
else
  printf("you win!");  // when does this print?
```

The C `switch` control flow statement (see CP:AMA 5.3) has a similar structure to `else if` and `cond`, but very different behaviour.

A `switch` statement has "fall-through" behaviour where more than one branch can be executed.

In our experience, `switch` is very error-prone for beginner programmers.

Do not use `switch` in this course.

The C `goto` control flow statement (CP:AMA 6.4) is one of the most disparaged language features in the history of computer science because it can make *“spaghetti code”* that is hard to understand.

Modern opinions have tempered and most agree it is useful and appropriate in some circumstances.

To use `goto`s, *labels* (code locations) are required.

```
if (k < 0) goto mylabel;
//...
mylabel:
//...
```

Do not use `goto` in this course.

Looping

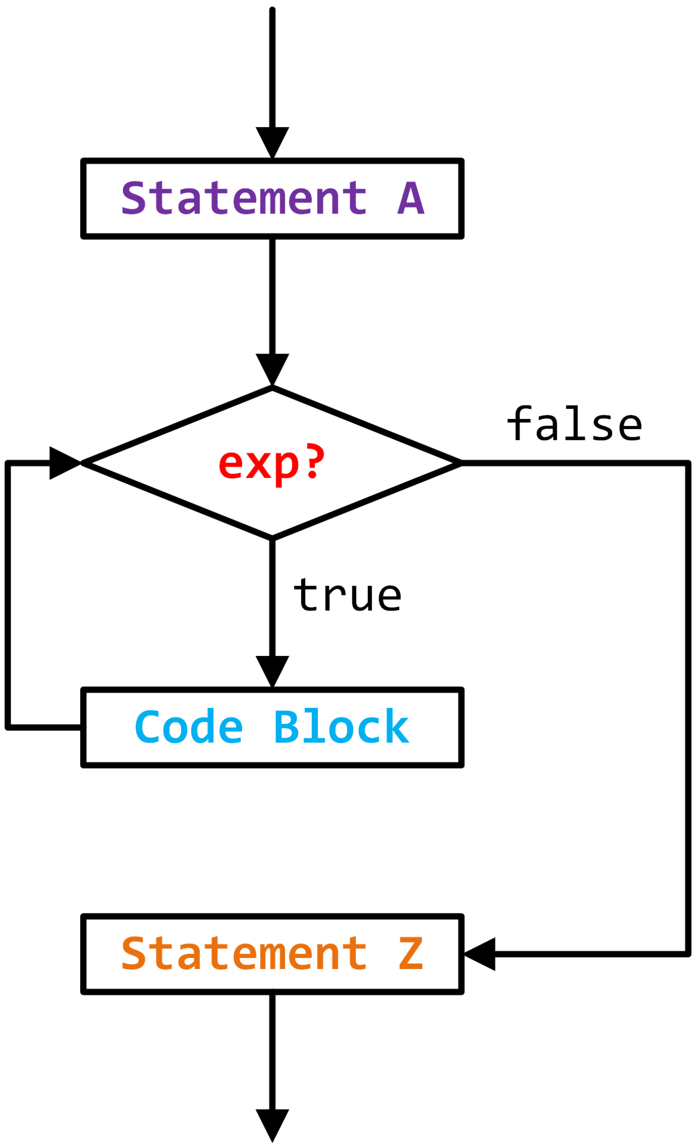
With mutation, we can control flow with a method known as ***looping***.

```
  while (expression) statement
```

`while` is similar to `if`: the `statement` is only executed `if` the `expression` is true.

The difference is, `while` **repeatedly** *"loops back"* and executes the `statement` **until the `expression` is false**.

Like with `if`, always use a block (`{}`) for a *compound statement*, even if there is only a single statement.



```
Statement A;
while (exp) {
  Code Block;
}
Statement Z;
```

example: while loop

```
int i = 2;
while (i >= 0) {
  printf("%d\n", i);
  --i;
}

OUTPUT:
2
1
0
```

There is a supplemental video for this slide online.

Iteration vs. recursion

Using a loop to solve a problem is called ***iteration***.

Iteration is an alternative to *recursion* and is much more common in imperative programming.

```c
// recursion
int sum(int k) {
  if (k <= 0) {
    return 0;
  }
  return k + sum(k - 1);
}
```

```c
// iteration
int sum(int k) {
  int s = 0;
  while (k > 0) {
    s += k;
    --k;
  }
  return s;
}
```

When first learning to write loops, you may find that your code is very similar to using *accumulative recursion*.

```
int accsum(int k, int acc) {
  if (k <= 0) {
    return acc;
  }
  return accsum(k - 1, k + acc);
}

int recursive_sum(int k) {
  return accsum(k, 0);
}
```

```
int iterative_sum(int k) {
  int acc = 0;
  while (k > 0) {
    acc += k;
    --k;
  }
  return acc;
}
```

Looping is very “imperative”. Without mutation (side effects), the while loop condition would not change, causing an “endless loop”.

Loops can be “nested” within each other.

```
int i = 5;
int j = 0;
while (i >= 0) {
  j = i;
  while (j >= 0) {
    printf("*");
    --j;
  }
  printf("\n");
  --i;
}
```

```
******
*****
****
***
**
*
```

Tracing tools

The provided *tracing tools* can be used to help you understand your control flow and “see” what is happening in your program.

This can help you **debug** your code.

The tracing tools do **not** interfere with your I/O testing.

On your assignments, never `printf` any unnecessary output as it may affect your correctness results.

Always use our tracing tools to help debug your code.

example: tracing tools

```
int sum(int k) {
  trace_msg("sum called");
  int s = 0;
  trace_msg("loop starting");
  while (k > 0) {
    trace_int(k);
    s += k;
    trace_int(s);
    --k;
  }
  trace_msg("loop ended");
  return s;
}

int main(void) {
  trace_int(sum(3));
}
```

```
>> "sum called"
>> "loop starting"
>> k => 3
>> s => 3
>> k => 2
>> s => 5
>> k => 1
>> s => 6
>> "loop ended"
>> sum(3) => 6
```

while errors

A simple mistake with `while` can cause an “endless loop” or “infinite loop”. The following examples are endless loops (for `i >= 0`).

```
while (i >= 0)                // missing {}
  printf("%d\n", i);
  --i;

while (i >= 0); {             // extra ;
  printf("%d\n", i);
  --i;
}

while (i = 100) { ... }       // assignment typo

while (1) { ... }             // constant true expression
                              // (this may be on purpose...)
```

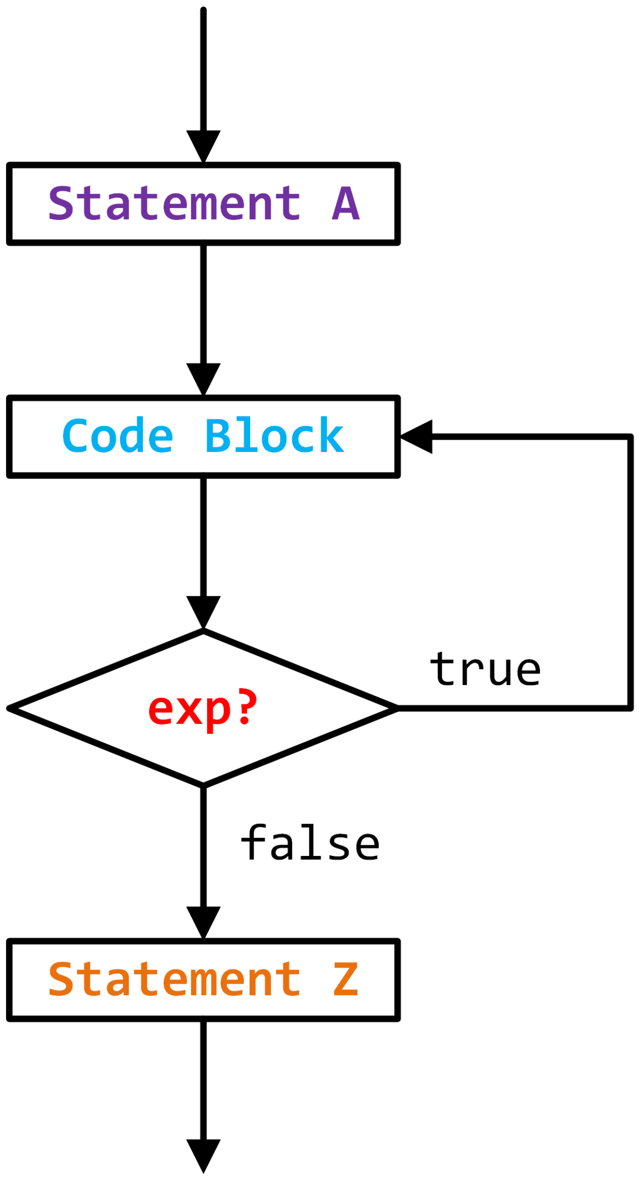
do ... while

The `do` control flow statement is very similar to `while`.

```
do statement while (expression);
```

The difference is that `statement` is always executed *at least* once, and the `expression` is checked at the *end* of the loop.

```
do {
  printf("try to guess my number!\n");
  guess = read_int();
} while (guess != my_number && guess != READ_INT_FAIL);
```



```
Statement A;
do {
   Code Block;
} while (exp);
Statement Z;
```

break

The `break` control flow statement is useful to exit from the *middle* of a loop. `break` immediately terminates the current (innermost) loop.

`break` is often used with a (purposefully) infinite loop.

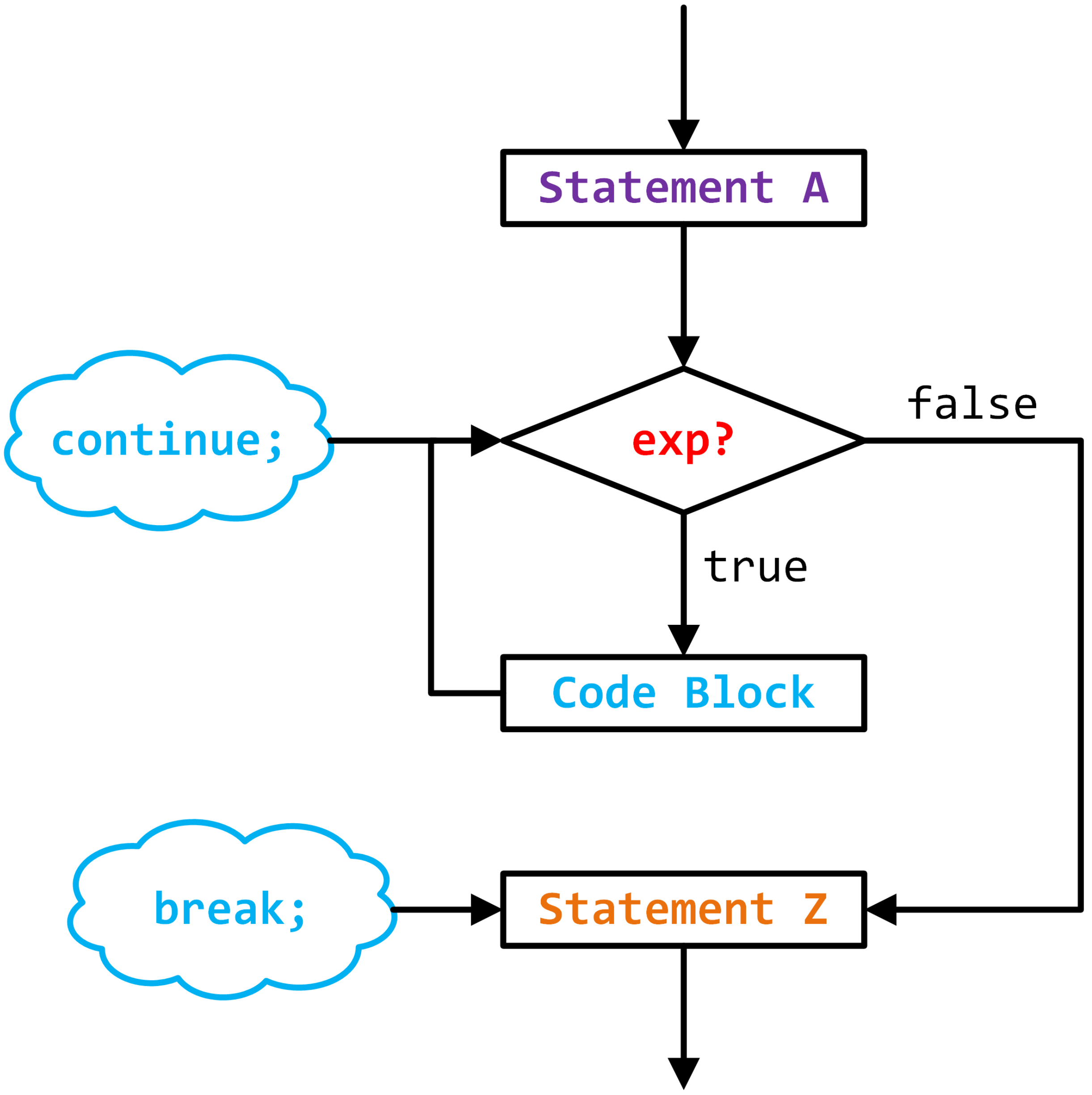
```
while (1) {
  n = read_int();
  if (n == READ_INT_FAIL) {
    break;
  }
  //...
}
```

`break` only terminates loops. You cannot `break` out of an `if`.

continue

The `continue` control flow statement skips over the rest of the statements in the current block (`{}`) and "continues" with the loop.

```
// only concerned with fun numbers
while (1) {
  n = read_int();
  if (n == READ_INT_FAIL) {
    break;
  }
  if (!is_fun(n)) {
    continue;
  }
  //...
}
```



```
Statement A;
while (exp) {
  Code Block;
}
Statement Z;
```

for loops

The final control flow statement we introduce is `for`, which is often referred to as a “`for` loop”.

`for` loops are a “condensed” version of a `while` loop.

The format of a `while` loop is often of the form:

```
setup statement
while (expression) {
  body statement(s)
  update statement
}
```

which can be re-written as a single `for` loop:

```
for (setup; expression; update) { body statement(s) }
```

for vs. while

Recall the `for` syntax.

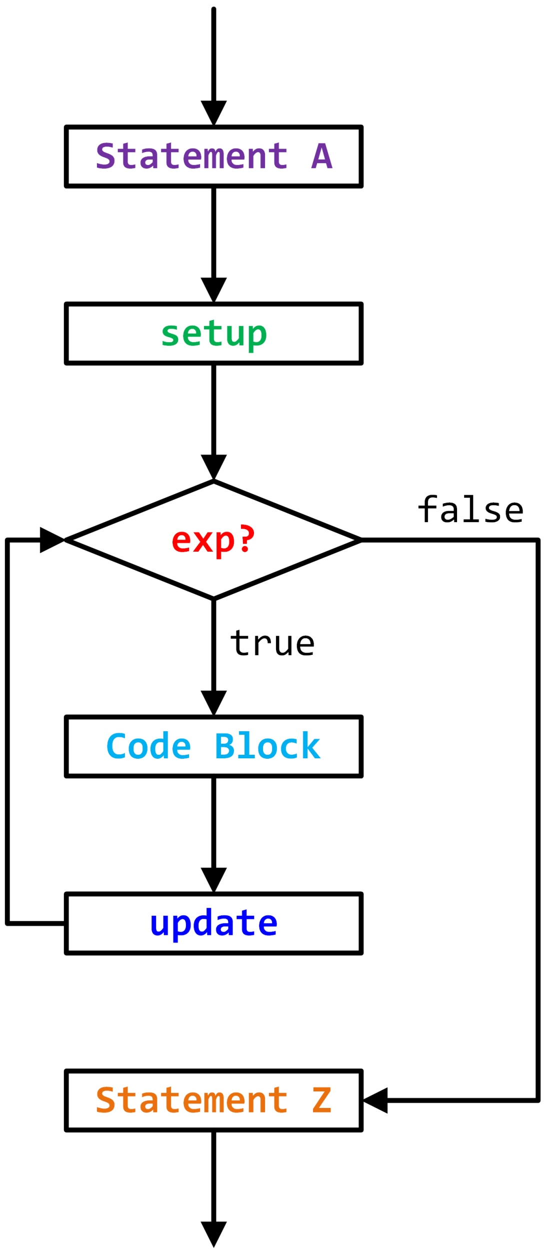
```
for (setup; expression; update) { body statement(s) }
```

This `while` example

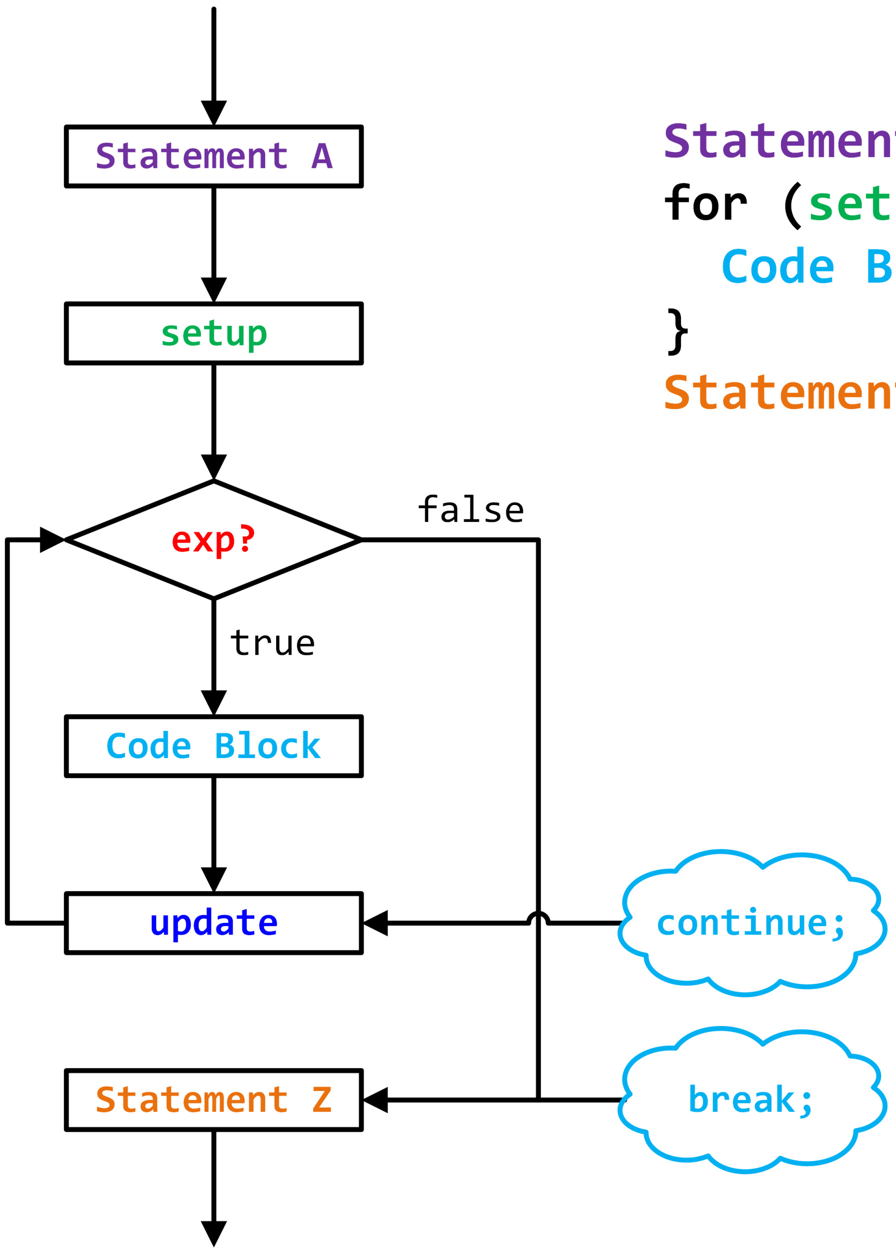
```
i = 100;                        // setup
while (i >= 0) {                // expression
  printf("%d\n", i);
  --i;                          // update
}
```

is equivalent to

```
for (i = 100; i >= 0; --i) {
  printf("%d\n", i);
}
```



```
Statement A;
for (setup; exp; update) {
  Code Block;
}
Statement Z;
```



```
Statement A;
for (setup; exp; update) {
  Code Block;
}
Statement Z;
```

Most `for` loops follow one of these forms (or “idioms”).

```c
// Counting up from 0 to n - 1
for (i = 0; i < n; ++i) {...}

// Counting up from 1 to n
for (i = 1; i <= n; ++i) {...}

// Counting down from n - 1 to 0
for (i = n - 1; i >= 0; --i) {...}

// Counting down from n to 1
for (i = n; i > 0; --i) {...}
```

It is a common mistake to be “off by one” (*e.g.*, using < instead of <=). Sometimes re-writing as a `while` is helpful.

In C99, the *setup* can be a **definition**.

This is very convenient for defining a variable that only has *local (block) scope* within the `for` loop.

```
for (int i = 100; i >= 0; --i) {
  printf("%d\n", i);
}
```

The equivalent `while` loop would have an extra block.

```
{
  int i = 100;
  while (i >= 0) {
    printf("%d\n", i);
    --i;
  }
}
```

Any of the three components of a `for` statement can be omitted.

If the expression is omitted, it is always "true".

```
for (; i < 100; ++i) {...}  // i was setup previously

for (; i < 100;) {...}      // same as a while(i < 100)

for (;;) {...}              // endless loop
```

The *comma operator* (`,`) allows for multiple sub-expressions in the *setup* and *update* statements of a `for` loop. Do not use it in this course. See CP:AMA 6.3 for more details.

```
for (i = 1, j = 100; i < j; ++i, --j) {...}
```

A `for` loop is *not always* equivalent to a `while` loop.

The only difference is when a `continue` statement is used.

In a `while` loop, `continue` jumps back to the expression.

In a `for` loop, the “update” statement is executed before jumping back to the expression.

Memory

One bit of storage (in memory) has two possible **states**: 0 or 1.

A byte is 8 bits of storage. Each byte in memory is in one of 256 possible states.

In this course, we will usually be dealing with *bytes* and not individual *bits*.

Accessing memory

The smallest accessible unit of memory is a byte.

To access a byte of memory, its *position* in memory, which is known as the ***address*** of the byte, must be known.

For example, if you have 1 MB of memory (RAM), the *address* of the first byte is 0 and the *address* of the last byte is 1048575 (or $2^{20} - 1$).

Note: Memory addresses are usually represented in *hex*, so with 1 MB of memory, the address of the first byte is 0x0, and the address of the last byte is 0xFFFFF.

You can visualize computer memory as a collection of “labeled mailboxes” where each mailbox stores a byte.

address (1 MB of storage)	contents (one byte per address)
`0x00000`	`00101001`
`0x00001`	`11001101`
...	...
`0xFFFFE`	`00010111`
`0xFFFFF`	`01110011`

The *contents* in the above table are arbitrary values.

Defining variables

For a **variable definition**, C

- reserves (or “finds”) space in memory to ***store*** the variable
- “keeps track of” the *address* of that storage location
- stores the initial value of the variable at that location (address).

For example, with the definition

```
int n = 0;
```

C reserves space (an address) to store `n`, “keeps track of” the address `n`, and stores the value `0` at that address.

In our CS 135 substitution model, a variable is a “name for a value”.

When a variable appears in an expression, a *substitution* occurs and the name is *replaced* by its value.

In our new model, a variable is a “name for a location” where a value is stored.

When a variable appears in an expression, C “fetches” the contents at its address to obtain the value stored there.

sizeof

When we define a variable, C reserves space in memory to store its value – but **how much space** is required?

It depends on the **type** of the variable.

It may also depend on the *environment* (the machine and compiler).

The ***size operator*** (`sizeof`) produces the number of bytes required to store a type (it can also be used on identifiers). `sizeof` looks like a function, but it is an operator.

```
int n = 0;
trace_int(sizeof(int));
trace_int(sizeof(n));
```

```
sizeof(int) => 4
sizeof(n) => 4
```

In this course, the size of an `int`eger is 4 bytes (32 bits).

In C, the size of an `int` depends on the machine (processor) and/or the operating system that it is running on.

Every processor has a natural ***"word size"*** (*e.g.,* 32-bit, 64-bit). Historically, the size of an `int` was the word size, but most modern systems use a 32-bit `int` to improve compatibility.

In C99, the `inttypes` module (`#include <inttypes.h>`) defines many types (*e.g.,* `int32_t`, `int16_t`) that specify *exactly* how many bits (bytes) to use.

In this course, only use `int`, and there are always 32 bits in an `int`.

example: variable definition

```
int n = 0;
```

For this variable definition C reserves (or “finds”) 4 consecutive bytes of memory to store `n` (*e.g.*, addresses `0x5000...0x5003`) and then “keeps track of” the first (or “*starting*”) address.

identifier	type	# bytes	starting address
n	`int`	4	`0x5000`

C updates the contents of the 4 bytes to store the initial value (0).

address	`0x5000`	`0x5001`	`0x5002`	`0x5003`
contents	`00000000`	`00000000`	`00000000`	`00000000`

Integer limits

Because C uses 4 bytes (32 bits) to store an `int`, there are only 2^{32} (4,294,967,296) possible values that can be represented.

The range of C `int` values is $-2^{31} \ldots (2^{31} - 1)$ or $-$2,147,483,648 . . . 2,147,483,647.

In our CS 136 environment, the constants `INT_MIN` and `INT_MAX` are defined with those limit values.

`unsigned int` variables represent the values $0 \ldots (2^{32} - 1)$ but we do not use them in this course.

In the `read_int` function we provide, the value of the constant `READ_INT_FAIL` is actually `INT_MIN`, so the smallest value of `int` that can be successfully read by our `read_int` function is −2,147,483,647.

Overflow

If we try to represent values outside of the `int` limits, ***overflow*** occurs.

Never assume what the value of an `int` will be after an overflow occurs.

The value of an integer that has overflowed is **undefined**.

By carefully specifying the order of operations, sometimes overflow can be avoided.

In CS 251 / CS 230 you learn more about overflow.

example: overflow

```
int bil = 1000000000;
int four_bil = bil + bil + bil + bil;
int nine_bil = 9 * bil;

trace_int(bil);
trace_int(four_bil);
trace_int(nine_bil);
```

```
bil => 1000000000
four_bil => -294967296
nine_bil => 410065408
```

Remember, do not try to “deduce” what the value of an `int` will be after overflow – its behaviour is **undefined**.

Racket can handle arbitrarily large numbers, such as `(expt 2 1000)`.

Why did we not have to worry about overflow in Racket?

Racket does not use a fixed number of bytes to store numbers.

Racket represents numbers with a *structure* that can use an arbitrary number of bytes (imagine a *list* of bytes).

There are C modules available that provide similar features (a popular one is available at `gmplib.org`).

The char type

Now that we have a better understanding of what an `int` in C is, we introduce some additional types.

The `char` type is also used to store integers, but C only allocates **one byte** of storage for a `char` (an `int` uses 4 bytes).

There are only 2^8 (256) possible values for a `char` and the range of values is ($-128 \ldots 127$) in our `Seashell` environment.

Because of this limited range, `char`s are rarely used for calculations. As the name implies, they are often used to store ***characters***.

ASCII

Early in computing, there was a need to represent text (*characters*) in memory.

The American Standard Code for Information Interchange (ASCII) was developed to assign a numeric code to each character.

Upper case A is 65, while lower case a is 97. A space is 32.

ASCII was developed when *teletype* machines were popular, so the characters 0 . . . 31 are teletype "control characters" (*e.g.*, 7 is a "bell" noise).

The only control character we use in this course is the line feed (10), which is the newline `\n` character.

```
/*
  32 space  48 0      64 @      80 P       96 `      112 p
  33 !      49 1      65 A      81 Q       97 a      113 q
  34 "      50 2      66 B      82 R       98 b      114 r
  35 #      51 3      67 C      83 S       99 c      115 s
  36 $      52 4      68 D      84 T      100 d      116 t
  37 %      53 5      69 E      85 U      101 e      117 u
  38 &      54 6      70 F      86 V      102 f      118 v
  39 '      55 7      71 G      87 W      103 g      119 w
  40 (      56 8      72 H      88 X      104 h      120 x
  41 )      57 9      73 I      89 Y      105 i      121 y
  42 *      58 :      74 J      90 Z      106 j      122 z
  43 +      59 ;      75 K      91 [      107 k      123 {
  44 ,      60 <      76 L      92 \      108 l      124 |
  45 -      61 =      77 M      93 ]      109 m      125 }
  46 .      62 >      78 N      94 ^      110 n      126 ~
  47 /      63 ?      79 O      95 _      111 o
*/
```

ASCII worked well in English-speaking countries in the early days of computing, but in today's international and multicultural environments it is outdated.

The **Unicode** character set supports more than $100{,}000$ characters from all over the world.

A popular method of ***encoding*** Unicode is the `UTF-8` standard, where displayable ASCII codes use only one byte, but non-ASCII Unicode characters use more bytes.

We will not be using Unicode in this course.

C characters

In C, **single** quotes (`'`) are used to indicate an ASCII character.

For example, `'a'` is equivalent to 97 and `'z'` is 122.

C “translates” `'a'` into 97.

In C, there is **no difference** between the following two variables:

```
char letter_a = 'a';
char ninety_seven = 97;
```

Always use **single** quotes with characters:

`"a"` is **not** the same as `'a'`.

example: C characters

The `printf` format specifier to display a *character* is `"%c"`.

```
char letter_a = 'a';
char ninety_seven = 97;

printf("letter_a as a character:   %c\n", letter_a);
printf("ninety_seven as a char:    %c\n", ninety_seven);

printf("letter_a in decimal:       %d\n", letter_a);
printf("ninety_seven in decimal:   %d\n", ninety_seven);
```

```
letter_a as a character:   a
ninety_seven as a char:    a

letter_a in decimal:       97
ninety_seven in decimal:   97
```

Character arithmetic

Because C interprets characters as integers, characters can be used in expressions to avoid having “magic numbers” in your code.

```
bool is_lowercase(char c) {
  return (c >= 'a') && (c <= 'z');
}

// to_lowercase(c) converts upper case letters to
//   lowercase letters, everything else is unchanged
char to_lowercase(char c) {
  if ((c >= 'A') && (c <= 'Z')) {
    return c - 'A' + 'a';
  } else {
    return c;
  }
}
```

Reading characters from input

In Section 03, we used the `read_int` function to read integers from input.

We have also provided `read_char` for reading characters.

When reading `int` values, we ignored whitespace in the input.

When reading in characters, you **may** or **may not** want to ignore whitespace characters, depending on the application.

`read_char` has a parameter for specifying if whitespace is ignored.

Symbol type

There is no C equivalent of the Racket `'symbol` type.

C ***symbols*** are constants (often `int`s) with meaningful identifiers ("names") but arbitrary (meaningless) values.

Use `ALL_CAPS` for symbol names.

```
const int UP = 1;
const int DOWN = 2;

int direction = UP;
```

We have provided some tools for working with C "symbols" on your assignments.

In C, there are ***enumerations*** (`enum`, CP:AMA 16.5) which allow you to create your own `enum` types and help to facilitate defining constants with unique integer values.

Enumerations are an example of a C language feature that we do *not* introduce in this course.

After this course, we would expect you to be able to read about `enum`s in a C reference and understand how to use them.

If you would like to learn more about C or use it professionally, we recommend reading through all of CP:AMA *after* this course is over.

Floating point types

The C `float` (floating point) type can represent real (non-integer) values.

```
float pi = 3.14159;
float avogadro = 6.022e23;   // 6.022*10^23
```

Unfortunately, `float`s are susceptible to precision errors.

C's `float` type is similar to **inexact numbers** in Racket (which appear with an `#i` prefix in the teaching languages):

```
(sqrt 2)           ; => #i1.4142135623730951
(sqr (sqrt 2))     ; => #i2.0000000000000004
```

example 1: inexact floats

```
float penny = 0.01;
float money = 0;

for (int n = 0; n < 100; ++n) {
  money += penny;
}

printf("the value of one dollar is: %f\n", money);
```

```
the value of one dollar is: 0.999999
```

The `printf` format specifier to display a `float` is `"%f"`.

example 2: inexact floats

```
float bil = 1000000000;
float bil_and_one = bil + 1;

printf("a float billion is:     %f\n", bil);
printf("a float billion + 1 is: %f\n", bil_and_one);
```

```
a float billion is:     1000000000.000000
a float billion + 1 is: 1000000000.000000
```

In the previous two examples, we highlighted the precision errors that can occur with the `float` type.

C also has a `double` type that is still inexact but has significantly better precision.

Just as we use `check-within` with inexact numbers in Racket, we can use a similar technique for testing in floating point numbers C.

Assuming that the precision of a `double` is perfect or "good enough" can be a serious mistake and introduce errors.

Unless you are explicitly told to use a `float` or `double`, do not use them in this course.

Floats in memory

A `double` has more precision than a `float` because it uses more memory.

Just as we might represent a number in decimal as 6.022×10^{23}, a `float` uses a similar strategy.

A 32 bit `float` uses 24 bits for the *mantissa* and 8 bits for the *exponent*.

A 64 bit `double` uses (53 + 11).

`float`s and their internal representation are discussed in CS 251 / 230 and in detail in CS 370 / 371.

Structures

Structures (*compound data*) in C are similar to structures in Racket.

```
struct posn {          // name of the structure
  int x;               // type and field names
  int y;
};                     // don't forget this ;
```

Because C is statically typed, structure definitions require the *type* of each field.

Do not forget the last semicolon (`;`) in the structure definition.

The structure *type* includes the keyword "`struct`". For example, the type is "`struct posn`", not just "`posn`". This can be seen in the definition of `p` below.

```
struct posn p = {3, 4};    // note the use of {}

trace_int(p.x);
trace_int(p.y);
```

```
p.x => 3
p.y => 4
```

Instead of *selector functions*, C has a ***structure operator*** (`.`) which "selects" the requested field.

The syntax is `variablename.fieldname`

C99 supports an alternative way to initialize structures:

```
struct posn p = { .y = 4, .x = 3};
```

This prevents you from having to remember the “order” of the fields in the initialization.

Any omitted fields are automatically zero, which can be useful if there are many fields:

```
struct posn p = {.x = 3};   // .y = 0
```

Mutation with structures

The assignment operator can be used with `struct`s to copy all of the fields from another `struct`. Individual fields can also be mutated.

```
struct posn p = {1, 2};
struct posn q = {3, 4};

p = q;
p.x = 23;

trace_int(p.x);
trace_int(p.y);
```

```
p.x => 23
p.y => 4
```

The braces (`{}`) are **part of the initialization syntax** and can not simply be used in assignment. Instead, just mutate each field.

On rare occasions, you may want to define a new `struct` so you can mutate "all at once".

```
struct posn p = {1, 2};

p = {5, 6};                 // INVALID

p.x = 5;                    // VALID
p.y = 6;

// alternatively:
struct posn new_p = {5, 6};
p = new_p;
```

The *equality* operator (==) **does not work with structures**. You have to define your own equality function.

```
bool posn_equal (struct posn a, struct posn b) {
  return (a.x == b.x) && (a.y == b.y);
}
```

Also, `printf` only works with elementary types. Print each field of a structure individually:

```
struct posn p = {3, 4};
printf("The value of p is (%d, %d)\n", p.x, p.y);
```

```
The value of p is (3, 4)
```

Structures in the memory model

For a structure *definition*, no memory is reserved:

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

Memory is only reserved when a `struct` **variable** is defined.

```
struct posn p = {3, 4};
```

sizeof a struct

```
struct mystruct {
  int x;              // 4 bytes
  char c;             // 1 byte
  int y;              // 4 bytes
};
```

The amount of space reserved for a `struct` is **at least** the sum of the `sizeof` each field, but it may be larger.

```
trace_int(sizeof(struct mystruct));

sizeof(struct mystruct) => 12
```

You **must** use the `sizeof` operator to determine the size of a structure.

The size may depend on the *order* of the fields:

```
struct s1 {
  char c;
  int i;
  char d;
};
```

```
struct s2 {
  char c;
  char d;
  int i;
};
```

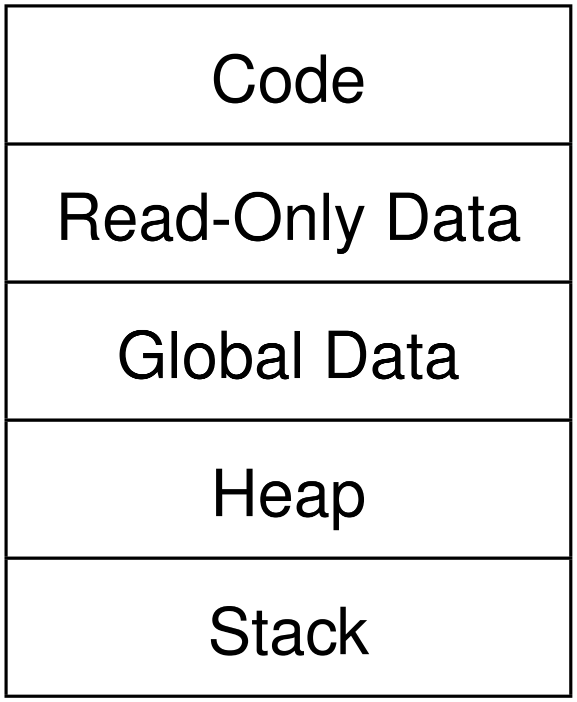
```
trace_int(sizeof(struct s1));
trace_int(sizeof(struct s2));
```

```
sizeof(struct s1) => 12
sizeof(struct s2) => 8
```

C may reserve more space for a structure to improve *efficiency* and enforce *alignment* within the structure.

Sections of memory

In this course we model five ***sections*** (or “regions”) of memory:



Other courses may use alternative names.

The **heap** section is introduced in Section 10.

Sections are combined into memory ***segments***, which are recognized by the hardware (processor).

When you try to access memory outside of a segment, a **segmentation fault** occurs (more on this in CS 350).

Temporary results

When evaluating C expressions, the intermediate results must be *temporarily* stored.

```
a = f(3) + g(4) - 5;
```

In the above expression, C must temporarily store the value returned from `f(3)` “somewhere” before calling `g`.

In this course, we are not concerned with this “temporary” storage.

Temporary storage is discussed in CS 241.

The code section

When you program, you write ***source code*** in a text editor using ASCII characters that are “human readable”.

To “run” a C program, the *source code* must first be converted into ***machine code*** that is “machine readable”.

This machine code is then placed into the **code section** of memory where it can be executed.

Converting source code into machine code is known as ***compiling***. It is briefly discussed in Section 13 and covered extensively in CS 241.

The read-only & global data sections

Earlier we described how C “reserves space” in memory for a variable definition. For example:

```
int n = 0;
```

The location of memory depends on whether the variable is **global** or **local**.

First, we discuss global variables.

All global variables are placed in either the **read-only data** section (**constants**) or the **global data** section (**mutable variables**).

Global variables are available throughout the entire execution of the program, and the space for the global variables is reserved **before** the program begins execution.

- First, the code from the entire program is scanned and all global variables are identified.
- Next, space for each global variable is reserved.
- Finally, the memory is properly initialized.
- This happens **before the `main` function is called**.

The read-only and global memory sections are created and initialized at compile time.

example: read-only & global data

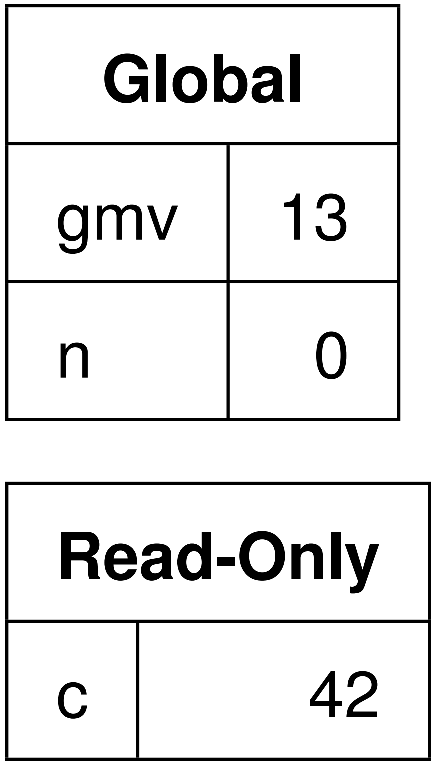
```
// global

int gmv = 13;
int n = 0;

// read-only

const int c = 42;
```

Memory Diagram:



Function Calls (revisited)

Recall the control flow for function calls:

- When a function is called, the program location “jumps” *from* the current location *to* the start of the function
- `return` changes the program location to go *back* to the **most recent** calling function (where it “jumped from”)
- C needs to track where it “jumped from” so it knows where to `return` to

We model function calls with a ***stack***, and store the information in the **stack section** of memory.

Stacks

A **stack** in computer science is similar to a physical stack where items are “stacked” on top of each other.

For example, a stack of papers or a stack of plates.

Only the *top* item on a stack is “visible” or “accessible”.

Items are *pushed* onto the top of the stack and *popped* off of the stack.

The call stack

Whenever a function is called, we can imagine that it is *pushed* onto a stack, and it is now on the *top* of the stack.

If another function is called, it is then *pushed* so it is now on *top*.

The call stack illustrates the “history” or “sequence” of function calls that led us to the current function.

When a function `return`s, it is *popped* off of the stack, and the control flow returns to the function now on *top*.

example: call stack

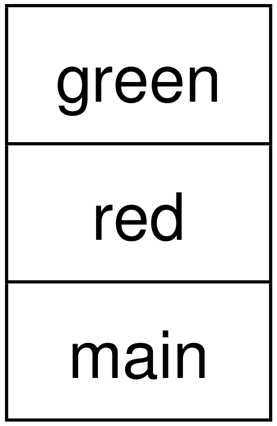
```
void blue(void) {
  return;
}

void green(void) {
  // DRAW DIAGRAM
  return;
}

void red(void) {
  green();
  blue();
  return;
}

int main(void) {
  red();
}
```

```
Call Stack
(when green is called)
```



```
When green returns:
* green is popped
* red is now on top
* control flow returns to red
```

example: call stack 2

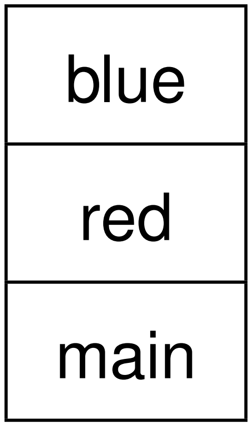
```
void blue(void) {
  // DRAW DIAGRAM
  return;
}

void green(void) {
  return;
}

void red(void) {
  green();
  blue();
  return;
}

int main(void) {
  red();
}
```

```
Call Stack
(when blue is called)
```



```
green does not appear because
it was previously popped
before blue was called
```

The return address

When C encounters a `return`, it needs to know: “where was the program location **before** this function was called?”

In other words, it needs to “remember” the program location to “jump back to” when `return`ing.

This location is known as the ***return address***.

In this course, we use the name of the calling function *and a line number* (or an arrow) to represent the return address.

The *operating system* calls the `main` function, so that is shown as `"OS"`.

example:return address

```
1  void foo(void) {
2    printf("inside foo\n");
3    return;
4  }
5
6  int main(void) {
7    printf("inside main\n");
8    foo();
9    printf("back from foo\n");
10 }
```

When `foo` is called, the program location is on line 8 of the function `main` so we would record the **return address** as:

```
main: 8
```

Stack frames

The “entries” pushed onto the *call stack* are known as ***stack frames***.

Each function call creates a *stack frame* (or a “*frame* of reference”).

Each *stack frame* contains:

- the **argument values**
- all **local variables** (both mutable variables and constants) that appear within the function *block* (including any sub-blocks)
- the **return address** (the program location within the *calling* function to *return to*)

example: stack frames

```
 1  int pow4(int j) {
 2    printf("inside pow4\n");
 3    int k = j * j;
 4    // DRAW DIAGRAM
 5    return k * k;
 6  }
 7
 8  int main(void) {
 9    printf("inside main\n");
10    int i = 1;
11    printf("%d\n", pow4(i + i));
12  }
```

```
=========================
pow4:
  j: 2
  k: 4
  return address: main:11
=========================
main:
  i: 1
  return address: OS
=========================
```

As with Racket, **before** a function can be called, all of the **arguments must be values**.

C **makes a copy** of each argument value and **places the copy in the stack frame**.

This is known as the “pass by value” convention.

Whereas space for a *global* variable is reserved *before* the program begins execution, space for a *local* variable is only reserved **when the function is called**.

The space is reserved within the newly created stack frame.

When the function `return`s, the variable (and the entire frame) is popped and effectively “disappears”.

In C, local variables are known as *automatic* variables because they are “automatically” created when needed. There is an `auto` keyword in C but it is rarely used.

Calling a function

We can now model all of the **control flow** when a function is called:

- a *stack frame* is created (“pushed” onto the Stack)
- the current program location is placed in the stack frame as the *return address*
- a **copy** of each of the arguments is placed in the stack frame
- the program location is changed to the start of the new function
- the initial values of local variables are set when their definition is encountered

return

When a function `return`s:

- the current program location is changed back to the *return address* (which is retrieved from the stack frame)
- the stack frame is removed ("popped" from the Stack memory area)

The return **value** (for non-`void` functions) is stored in a *temporary* memory area we are not discussing in this course. This is discussed further in CS 241.

Return vs. return address

Beginners often confuse the return address and `return` statements.

Remember, the return address is a **location within the calling function**.

It has **nothing** to do with the **location of** any `return` statement(s) in the called function or if one does not exist (*e.g.*, a `void` function).

There is **always** one (and only one) return address in a stack frame.

Recursion in C

Now that we understand how stack frames are used, we can see how *recursion* works in C.

In C, each recursive call is simply a new *stack frame* with a separate frame of reference.

The only unusual aspect of recursion is that the *return address* is a location within the same function.

In this example, we also see control flow with the `if` statement.

example: recursion

```
1  int sum_first(int n) {
2    ⇒if (n == 0) {
3      return 0;
4    } else {
5      return n + sum_first(n - 1);
6    }
7  }
8
9  int main(void) {
10   int a = sum_first(2);
11   //...
12 }
```

```
==============================
sum_first:
  n: 0
  return address: sum_first:5
==============================
sum_first:
  n: 1
  return address: sum_first:5
==============================
sum_first:
  n: 2
  return address: main:10
==============================
main:
  a: ???
  return address: OS
```

Stack section

The *call stack* is stored in the ***stack section***, the fourth section of our memory model. We refer to this section as “the stack”.

In practice, the “bottom” of the stack (*i.e.*, where the `main` stack frame is placed) is placed at the *highest* available memory address. Each additional stack frame is then placed at increasingly *lower* addresses. The stack “grows” toward lower addresses.

If the stack grows too large, it can “collide” with other sections of memory. This is called *“stack overflow”* and can occur with very deep (or infinite) recursion.

Uninitialized memory

In most situations, mutable variables *should* be initialized, but C allows variable definitions without any initialization.

```
int i;
```

For all **global** variables, C automatically initializes the variable to be zero.

Regardless, it is good style to explicitly initialize a global variable to be zero, even if it is automatically initialized.

```
int g = 0;
```

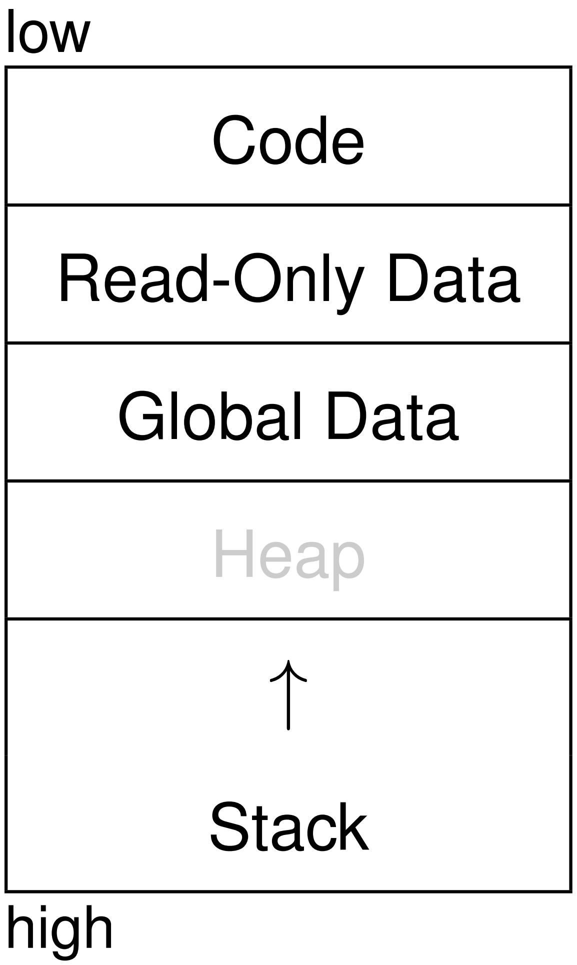
A **local** variable (on the *stack*) that is uninitialized has an **arbitrary** initial value.

```
void mystery(void) {
  int k;
  printf("the value of k is: %d\n", k);
}
```

`Seashell` gives you a warning if you obtain the value of an uninitialized variable.

In the example above, the value of `k` will likely be a leftover value from a previous stack frame.

Memory sections (so far)



Memory snapshot

You may be asked to draw a memory diagram (including the call stack) at a particular moment in the code execution.

For example, “draw the memory when line 19 is reached”.

- make sure you show any variables in the **global** and **read-only** sections, *separate* from the **stack**
- include *all* local variables in stack frames, including definitions that have not yet been reached (or are incomplete)
- local variables not yet fully initialized have a value of ???
- you do not have to show any *temporary* storage (*e.g.,* intermediate results of an expression)

When a variable is defined **inside of a loop**, only one occurrence of the variable is placed in the stack frame. The same variable is *re-used* for each iteration.

Each time the definition is reached in the loop, the variable is **re-initialized** (it does not retain its value from the previous iteration).

```
for (int j = 0; j < 3; ++j) {
  int k = 0;
  k = k + j;
  trace_int(k);
}
```

```
k => 0
k => 1
k => 2
```

Scope vs. memory

Just because a variable exists in memory, it does not mean that it is *in scope*.

Scope is part of the C syntax and determines when a variable is “visible” or “accessible”.

Memory is part of our C model (which closely matches how it is implemented in practice).

example: snapshot and scope

```
 1  int foo(void) {
 2    // SNAPSHOT HERE (at line 2)
 3    // 5 variables are in memory,
 4    // but none are in scope
 5    int a = 1;
 6    {
 7      int b = 2;
 8    }
 9    return a;
10  }
11
12  const int c = 3;
13  int d = 4;
14
15  int main(void) {
16    int e = 5;
17    foo();
18  }
```

```
READ-ONLY DATA:
c: 3
GLOBAL DATA:
d: 4

STACK:
=========================
foo:
  a: ???
  b: ???
  return address: main:17
=========================
main:
  e: 5
  return address: OS
```

Model

We now have the tools to model the behaviour of a C program.

At any moment of execution, a program is in a specific *state*, which is the combination of:

- the current *program location*, and
- the current contents of the *memory*.

To properly interpret a program's behaviour, we must keep track of the program location and all of the memory contents.

Goals of this Section

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

- use the introduced control flow statements, including (`return`, `if`, `while`, `do`, `for`, `break`, `continue`)
- re-write a recursive function with iteration and *vice versa*
- explain why C has limits on integers and why overflow occurs
- use the `char` type and explain how characters are represented in ASCII
- use structures in C

- explain how C execution is modelled with memory and control flow, as opposed to the substitution model of Racket
- describe the 4 areas of memory seen so far: code, read-only data, global data and the stack
- identify which section of memory an identifier belongs to
- explain a stack frame and its components (return address, parameters, local variables)
- explain how C makes copies of arguments for the stack frame
- model the execution of small programs by hand, and draw the memory snapshot (including stack frames) at specific execution points