Memory Safety in Rust

CS110L
Jan 10, 2022

Logistics

- Please make sure you're on Slack & that you've filled out the intro form (linked in last week's slides)
- Week 1 exercises due tonight
- Slides posted on website before class
- Undergrad class: remote through next week
- Today: What is Rust's "ownership model," and how does it prevent common memory errors?
  - Specifically focusing on memory leaks, double frees, and use-after frees
  - Thursday will show how Rust prevents other sorts of memory errors

Identifying Memory Errors

A Memory Exercise

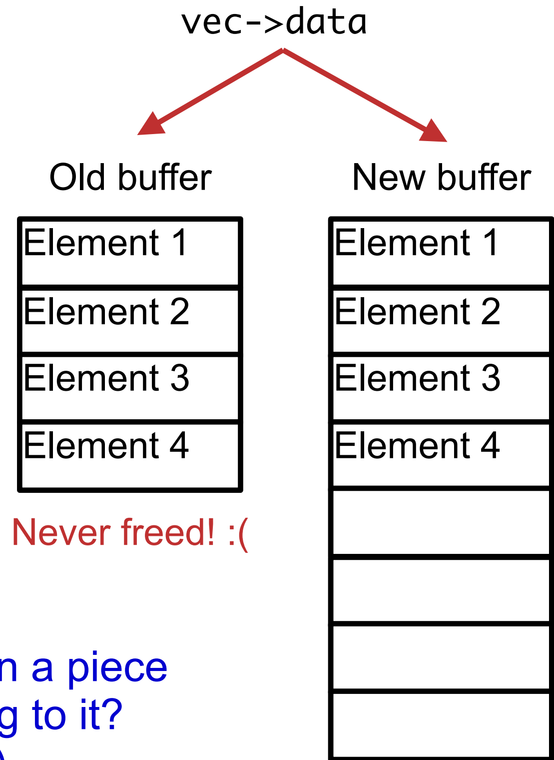
- Thanks to Will Crichton for this exercise and for giving permission to use it in this class!
- Discuss your answers to the exercise in groups (we'll assign you to different breakout rooms in Zoom)

Aside: the language and the compiler

- In C and C++, we notice these memory errors by *reasoning* and testing.
- The language and the compiler can't help us much.
- In order to make it easier to reason about programs, Rust places some restrictions on the programs you can write
  - This can be annoying…
  - But it also gives us some nice guarantees!

Memory Leaks

```c
void vec_push(Vec* vec, int n) {
  if (vec->length == vec->capacity) {
    int new_capacity = vec->capacity * 2;
    int* new_data = (int*) malloc(new_capacity);
    assert(new_data != NULL);

    for (int i = 0; i < vec->length; ++i) {
      new_data[i] = vec->data[i];
    }

    vec->data = new_data; // OOP: we forget to free the old data
    vec->capacity = new_capacity;
  }

  vec->data[vec->length] = n;
  ++vec->length;
}
```



Wouldn't it be nice if the compiler noticed when a piece of heap data no longer had anything pointing to it? (and so then it could safely be freed?)

Double Frees

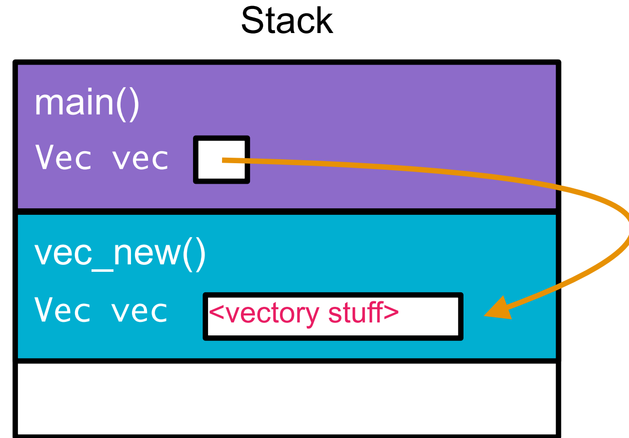
```c
void main() {
  Vec* vec = vec_new();
  vec_push(vec, 107);

  int* n = &vec->data[0];
  vec_push(vec, 110);
  printf("%d\n", *n);

  free(vec->data);
  vec_free(vec); // YIKES
}
```

Wouldn’t it be nice if the compiler enforced that once free is called on a variable, that variable can no longer be used?

Double free: a buffer is `free`d twice. (Sounds innocuous, but can actually lead to Remote Code Execution: take CS 155)
(Here, we `free(vec->data)`, and then call `vec_free`, which does the same thing)

Dangling Pointers

```
Vec* vec_new() {
  Vec vec;
  vec.data = NULL;
  vec.length = 0;
  vec.capacity = 0;
  return &vec; // OOF
}
```



Dangling pointer: A pointer that is referencing memory that isn’t there anymore

(Here, `vec` points into the stack frame of `vec_new`, but as soon as `vec_new` returns, that memory is gone)

Dangling Pointers

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Vec* vec_new() {
  Vec vec;
  vec.data = NULL;
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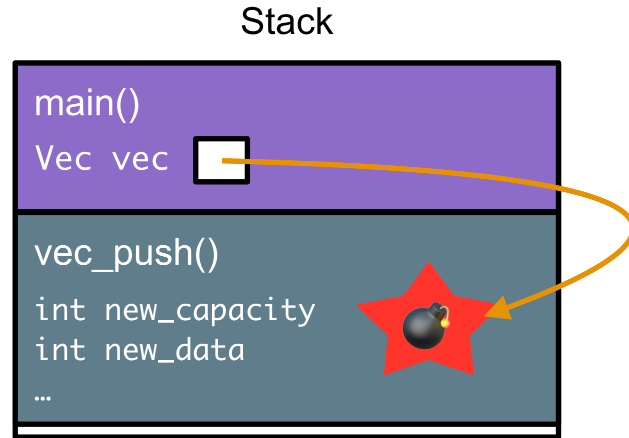


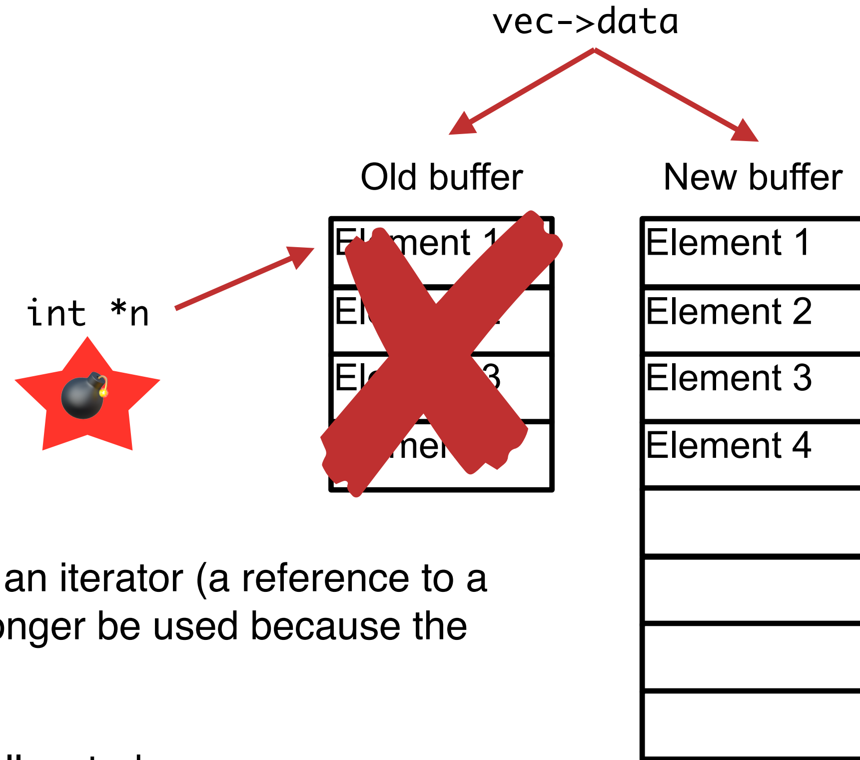
Dangling pointer: A pointer that is referencing memory that isn't there anymore

(Here, `vec` points into the stack frame of `vec_new`, but as soon as `vec_new` returns, that memory is gone)

Wouldn't it be nice if the compiler realized that vec "lives" within those two curly braces and therefore its address shouldn't be returned from the function?

Iterator Invalidation

```
void main() {
  Vec* vec = vec_new();
  vec_push(vec, 107);

  int* n = &vec->data[0];
  vec_push(vec, 110);
  printf("%d\n", *n); // :(

  free(vec->data);
  vec_free(vec);
}
```

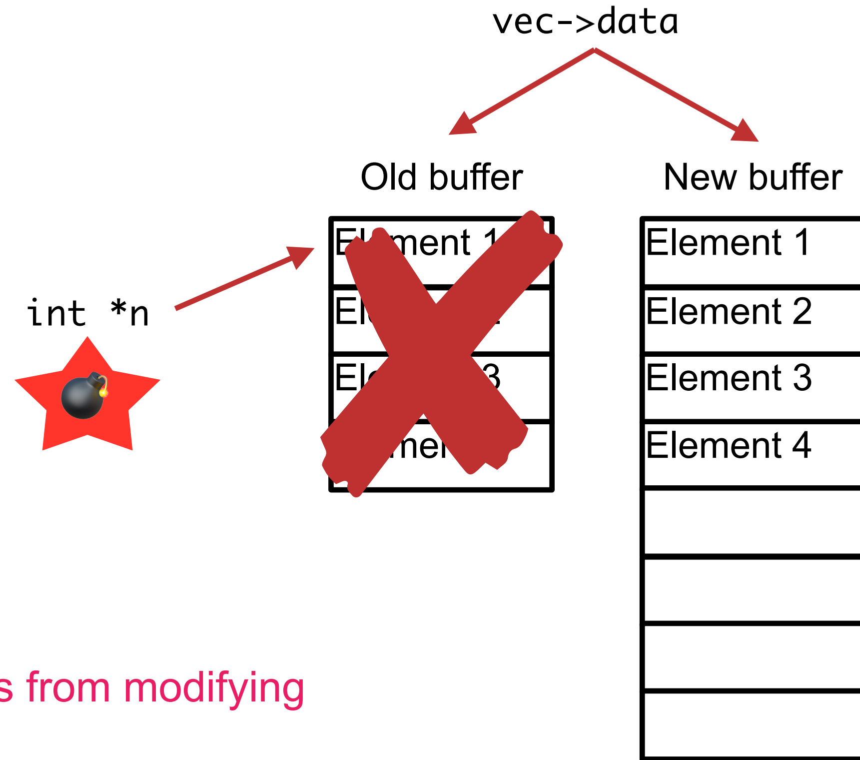


Iterator invalidation: a type of dangling pointer where an iterator (a reference to a certain position within an iterable container) can no longer be used because the container was modified

Here, vec_push can cause the vector buffer to be reallocated

Iterator Invalidation

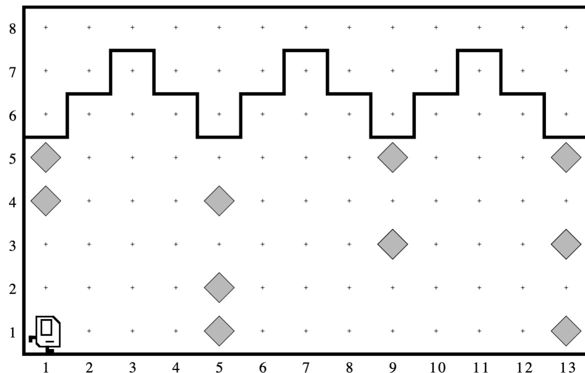
```
void main() {
  Vec* vec = vec_new();
  vec_push(vec, 107);

  int* n = &vec->data[0];
  vec_push(vec, 110);
  printf("%d\n", *n); // :(

  free(vec->data);
  vec_free(vec);
}
```



Wouldn't it be nice if the compiler stopped us from modifying the data n was pointing to?

Taking a step back

What makes good code?



- A natural decomposition for StoneMasonKarel is to implement a repairColumn function, then write:

```
while (frontIsClear()) {
    repairColumn();
    moveToNextColumn();
}
repairColumn();
```

- Many 106A students write repairColumn functions that sometimes end with Karel facing south, and other times end with Karel facing east; sometimes with Karel at the top of the column and sometimes with Karel at the bottom of the column; etc.
- Why is this bad?

What makes good code?

- Pre/postconditions are essential to breaking code into small pieces with well-defined interfaces in between
  - We want to be able to reason about each small piece in isolation
  - Then, if we can verify that preconditions/postconditions are upheld in isolation, we can string together a bunch of components and simply verify that the preconditions/postconditions all fit together without needing to keep the *entire program* in our heads
- It's the programmer's responsibility to make sure the pre/postconditions are upheld

Good memory management

- In any complex program, you'll allocate memory and pass it around the codebase. Where should that memory be freed?
  - If you free too early, other parts of your code might still be using pointers to that memory
  - If you don't free anywhere (or you free in a function that only gets called sometimes), you'll have a memory leak
- Good C/C++ code will clearly define how memory is passed around and "who" is responsible for cleaning it up
- If you read C/C++ code, you'll see notions of "ownership" in the comments, where the "owner" is responsible for the memory

```c
/* Get status of the virtual port (ex. tunnel, patch).
 *
 * Returns '0' if 'port' is not a virtual port or has no errors.
 * Otherwise, stores the error string in '*errp' and returns positive errno
 * value. The caller is responsible for freeing '*errp' (with free()).
 *
 * This function may be a null pointer if the ofproto implementation does
 * not support any virtual ports or their states.
 */
int (*vport_get_status)(const struct ofport *port, char **errp);
```

Open vSwitch

```c
/**
 * @note Any old dictionary present is discarded and replaced with a copy of the new one. The
 * caller still owns val is and responsible for freeing it.
 */
int av_opt_set_dict_val(void *obj, const char *name, const AVDictionary *val, int search_flags);
```

ffmpeg

```c
/**
 * iscsi_boot_create_target() - create boot target sysfs dir
 * @boot_kset: boot kset
 * @index: the target id
 * @data: driver specific data for target
 * @show: attr show function
 * @is_visible: attr visibility function
 * @release: release function
 *
 * Note: The boot sysfs lib will free the data passed in for the caller
 * when all refs to the target kobject have been released.
 */
struct iscsi_boot_kobj *
iscsi_boot_create_target(struct iscsi_boot_kset *boot_kset, int index,
                void *data,
                ssize_t (*show) (void *data, int type, char *buf),
                umode_t (*is_visible) (void *data, int type),
                void (*release) (void *data))
{
     return iscsi_boot_create_kobj(boot_kset, &iscsi_boot_target_attr_group,
                          "target%d", index, data, show, is_visible,
                          release);
}
EXPORT_SYMBOL_GPL(iscsi_boot_create_target);
```

Linux kernel

Sometimes, custom cleanup functions must be used to free memory. Calling free() on this memory would be a bug!

```c
/* Looks up a port named 'devname' in 'ofproto'.  On success, returns 0 and
 * initializes '*port' appropriately. Otherwise, returns a positive errno
 * value.
 *
 * The caller owns the data in 'port' and must free it with
 * ofproto_port_destroy() when it is no longer needed. */
int (*port_query_by_name)(const struct ofproto *ofproto,
                          const char *devname, struct ofproto_port *port);
```

Open vSwitch

Sometimes, custom cleanup functions must be used to free memory. Calling free() on this memory would be a bug!

```
/**
 * dvb_unregister_frontend() - Unregisters a DVB frontend
 *
 * @fe: pointer to &struct dvb_frontend
 *
 * Stops the frontend kthread, calls dvb_unregister_device() and frees the
 * private frontend data allocated by dvb_register_frontend().
 *
 * NOTE: This function doesn't frees the memory allocated by the demod,
 * by the SEC driver and by the tuner. In order to free it, an explicit call to
 * dvb_frontend_detach() is needed, after calling this function.
 */
int dvb_unregister_frontend(struct dvb_frontend *fe);
```

Linux kernel

Ownership can sometimes get extremely complicated, where one part of the codebase is responsible for freeing part of a data structure and a different part of the codebase is responsible for freeing a different part

```
static void mapper_count_similar_free(mapper_t* pmapper, context_t* _) {
     mapper_count_similar_state_t* pstate = pmapper->pvstate;
     slls_free(pstate->pgroup_by_field_names);

     // lhmslv_free will free the keys: we only need to free the void-star values.
     for (lhmslve_t* pa = pstate->pcounts_by_group->phead; pa != NULL; pa = pa->pnext) {
          unsigned long long* pcount = pa->pvvalue;
          free(pcount);
     }
     lhmslv_free(pstate->pcounts_by_group);

    ...
}
```

Miller

Pre/postconditions must be consistently upheld

- It’s up to the programmer to make sure to get this right. If you don’t uphold the interface, your program is broken
  - Consequences: anything from denial of service (e.g. memory leak) to remote code execution (e.g. double free, use-after free, buffer overflow)
- The compiler cannot help you out
  - Static analyzers can help *sometimes*, but not always (see week 1 exercises)
- Key point: *compiler does not know what your postconditions are, **because it’s not possible to express in the C language***

Type systems

- The *types* of a programming language are the *nouns* of a spoken language
  - When you talk, what do you talk *about*?
- C type system: numbers, pointers, structs… not much else
  - Extremely simple: can learn most of the C language in half a quarter of CS 107
  - Simple != easy

strdup definition:

```
char *strdup(const char *s);
```

Bad strdup usage:

```
const char *hello = "hello world";
char *duplicate = strdup(hello);
return;
```

strdup manpage:

> The strdup() function returns a pointer to a new string which is a duplicate of the string s. Memory for the new string is obtained with malloc(3), and can be freed with free(3).

Compiler's analysis:

Passes a char to strdup* ✅

*Stores the return value in a char** ✅

Everything looks good! ✅

Experienced programmer's analysis

Give `strdup` a C-string ✅

Get back: a heap-allocated C-string from strdup ✅

Returns before freeing the string! 🚫

Type systems

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- The pre/postconditions may be written in comments, but they are not present in the actual code, because the C language does not have a way for them to be expressed
- Consequently: the compiler is unaware of what you're trying to do

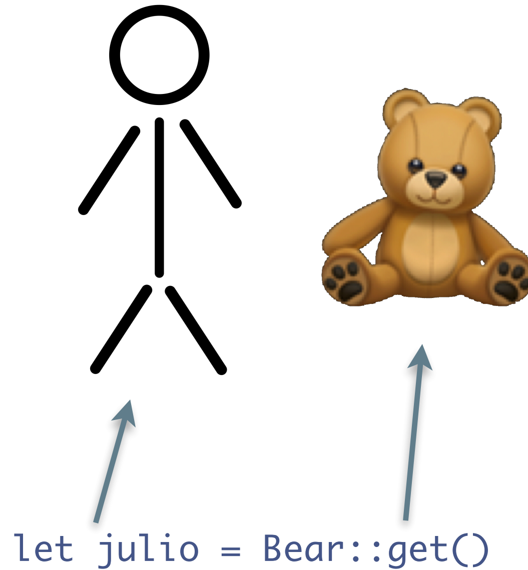
Are there better type systems that we can use to specify our preconditions/postconditions *in the code*?

(implication: if the compiler can understand your pre/postconditions, it can verify that they are met)

(Meet Rust 🦀)

What if Ownership lived in the programming language?

Ownership Visualized

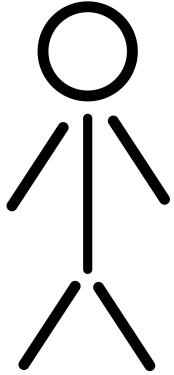


If CS terms are more useful:

- *Think of `julio` (owner) as a* ***variable*** *in a function or a member of a struct*
- *Think of the teddy bear (thing that is owned) as “data” or a “value”*

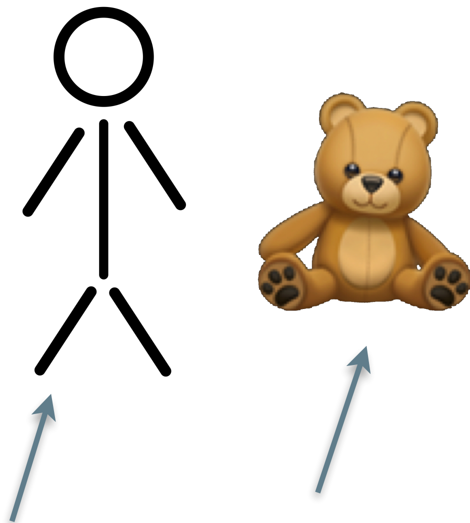
Ownership Visualized

Toys need to be put back when we're done!



```
fn main() {
    let julio = Bear::get();
    // play with bear
}
```

Ownership Visualized

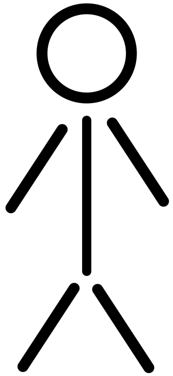


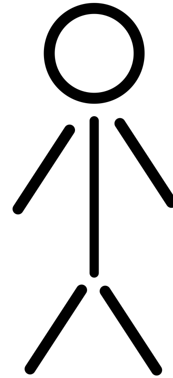
```
let julio = Bear::get();
```

- This 'julio' is the owner of the bear.
    - (They own it)
- They (julio) can do anything they want with the toy, like call functions wrapped within it
- Julio is responsible for putting the gift back where they found it before leaving (free the memory!)
    - *And there's a teacher around to enforce that rule!*

Ownership Visualized - What happens now?

```
let julio = Bear::get();
let ryan = julio;
```

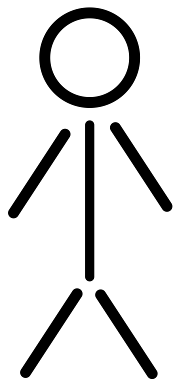




`let julio = ...`

`let ryan = julio;`

Ownership Visualized - What happens now?

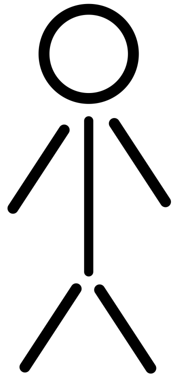


```
let ryan = julio;
```

- Now, Ryan is the owner of the toy!
- Ryan can do anything he wants with the toy, such as call functions on it.
- Ryan is now responsible for putting the toy back where Julio found it before leaving (free the memory!
    - And there's a teacher around to enforce that rule!

What about Julio?

Ownership Visualized - What happens now?

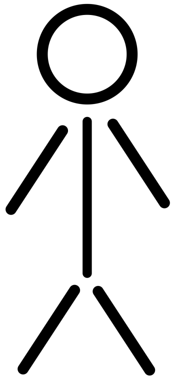


```
let julio = ...
```

- Julio has given the toy to Ryan!!
- No ownership of the toy anymore :(
- Can't do ANYTHING with this bear anymore :(
- sad.
- But no longer responsible for putting the toy back :D

Let's see it run!

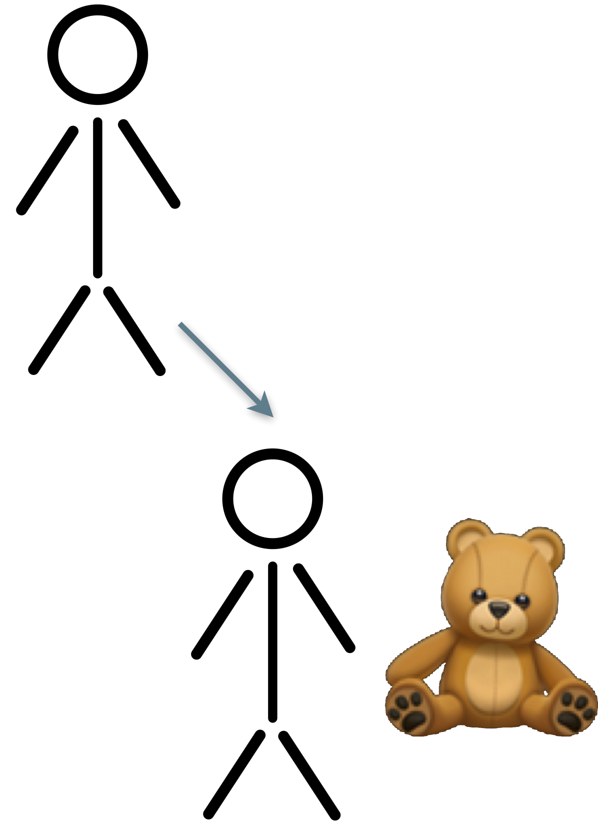
When else is ownership transferred?



- Function calls can take ownership of variables as well!
- This means that at the end of the function execution, they will be responsible for freeing the toy in memory
- It also means you can no longer use your toy back when the function returns!

```
let julio = Bear::get()
my_cool_bear_function(julio); <-- This is letting the function own the toy!
/* julio no longer owns the toy D: Compiler wont let you use it! */
```

When else is ownership transferred?



- This is also like transferring ownership between variables

```
my_cool_bear_function(/* parameter */ ) {
   // Do stuff
}
```

- (Can think of) `parameter` as
  - a new local variable in this function,
  - …which now *owns* the data
  - …and is responsible for cleaning it up when it goes out of scope (when function returns)
  - Once data is cleaned up, it can no longer be used (e.g., by variable `julio` in original function.
- *In teddy bear terms: `julio` gives bear to someone else, that person "goes home" at the end of the function, and that person is responsible for putting the bear away. After bear is put away, `julio` can no longer play with the bear.*

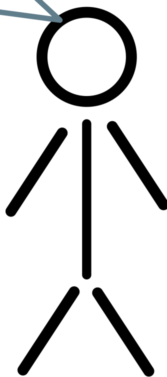
How will I ever decompose code????

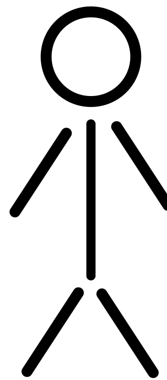
Borrowing

Hey,
my_cool_bear_function,
you could BORROW this toy.
Just give it back when you're
done!

```
let julio = Bear::get();
my_cool_bear_function(&julio)
/* The julio variable can still be used here
   to access the teddy bear! */
```

Thank
you, this means
you'll have to put the
toy back when you're
done though!





```
let julio = ...
```

```
my_cool_bear_function(Bear: &Bear)
```

Ownership (From The Rust Book!)

Ownership Rules

First, let's take a look at the ownership rules. Keep these rules in mind as we work through the examples that illustrate them:

- Each value in Rust has a variable that's called its *owner*.
- There can only be one owner at a time.
- When the owner goes out of scope, the value will be dropped.

Reminder: The ownership and borrowing rules are enforced at compile time!

Takeaways

- In Rust, every piece of memory is “owned” by a variable/function
  - This ownership is explicit in the code (as opposed to C/C++, where ownership is usually described in function comments)
  - When the owner goes out of scope, the compiler inserts code to free the memory
- Because of the ownership model, you can’t have:
  - Memory leaks
  - Double frees
  - Use-after-frees
  - Other memory errors — next class!

Next Time + Resources [End]

- What other kinds of references / variables can we create in Rust?
- What does ownership transferring look like in memory?
- More code examples :D
- Ownership and borrowing for visual learners!
- A great resource on iterating over vectors in Rust
- A Medium article about ownership, borrowing, and lifetimes
- CS242 lecture notes — shout out to Will Crichton to providing advice on explaining some of these concepts!
- The Rust book
- Check out sections 4.1 and 4.2 (deeper explanation of lifetimes)