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Region-based Memory Management

Advanced Operating Systems
Lecture 10

Lecture Outline

- Rationale
- Stack-based memory management
- Region-based memory management
  - Ownership
  - Borrowing
  - Benefits and limitations

Rationale

- Garbage collection tends to have unpredictable timing and high memory overhead
  - Real-time collectors exist, but are uncommon and have significant design implications for applications using them
- Manual memory management is too error prone
- Region-based memory management aims for a middle ground between the two approaches
  - Safe, predictable timing
  - Limited impact on application design

Stack-based Memory Management

- Automatic allocation/deallocation of variables on the stack is common and efficient:

```
#include <math.h>
#include <stdio.h>
#include <stdlib.h>

static double pi = 3.14159;

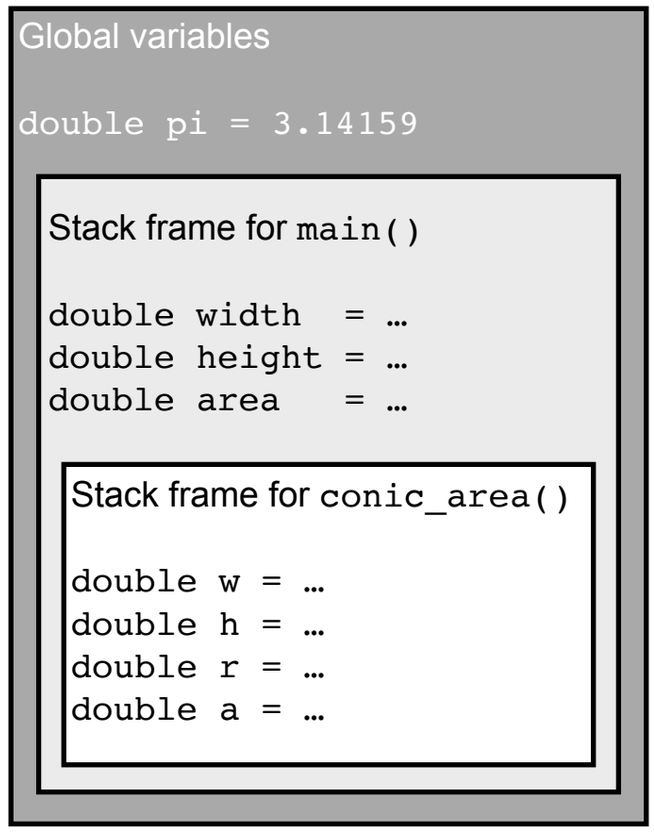
static double conic_area(double w, double h) {
  double r = w / 2.0;
  double a = pi * r * (r + sqrt(h*h + r*r));

  return a;
}

int main() {
  double width  = 3;
  double height = 2;
  double area = conic_area(width, height);

  printf("area of cone = %f\n", area);

  return 0;
}
```



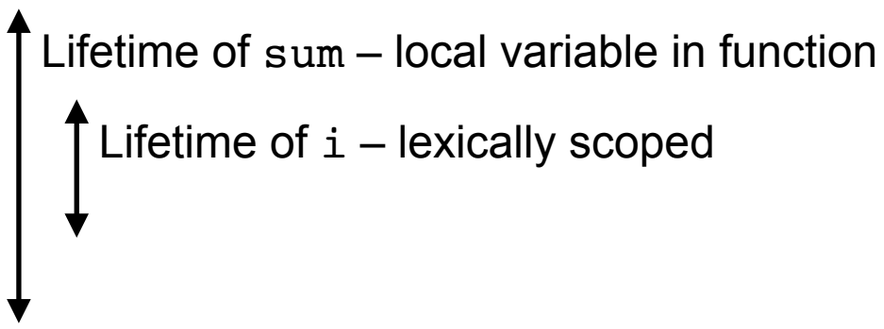
Stack-based Memory Management

- Hierarchy of regions corresponding to call stack:
  - Global variables
  - Local variables in each function
  - Lexically scoped variables within functions

```
double vector_avg(double *vec, int len) {
  double sum = 0;

  for (int i = 0; i < len; i++) {
    sum += vec[i];
  }

  return sum / len;
}
```



- Variables live within regions, and are deallocated at end of region scope

Stack-based Memory Management

- Limitation: requires data to be allocated on stack
  - Example:

```
int hostname_matches(char *requested, char *host, char *domain) {
  char *tmp = malloc(strlen(host) + strlen(domain) + 2);

  sprintf(tmp, “%s.%s”, host, domain);

  if (strcmp(requested, host) == 0) {
    return 1;
  }
  if (strcmp(requested, tmp) == 0) {
    return 1;
  }
  return 0;
}
```

The local variable `tmp` (pointer of type `char *`) is freed when the function returns; the allocated memory is not freed

- Heap storage has to be managed manually

Region-based Memory Allocation

- Stack allocation effective within a narrow domain – can we extend the ideas to manage the heap?
  - Create pointers to heap allocated memory
  - Pointers are stored on the stack and have lifetime matching the stack frame – pointers have type `Box<T>` for a pointer to heap allocated `T`
  - The heap allocation has lifetime matching that of the `Box` – when the `Box` goes out of scope, the heap memory it references is freed
    - i.e., the destructor of the `Box<T>` frees the heap allocated `T`

- Efficient, but loses generality of heap allocation since ties heap allocation to stack frames

Region-based Memory Management

- For effective region-based memory management:
  - Allocate objects with lifetimes corresponding to regions
  - Track object ownership, and *changes of ownership:*
    - What region owns each object at any time
    - Ownership of objects can move between regions
    - Deallocate objects at the end of the lifetime of their owning region
      - Use scoping rules to ensure objects are not referenced after deallocation

- Example: the Rust programming language
  - Builds on previous research with Cyclone language (AT&T/Cornell)
  - Somewhat similar ideas in Microsoft's Singularity operating system

Returning Ownership of Data

- Returning data from a function causes it to outlive the region in which it was created:

```
const PI: f64 = 3.14159;

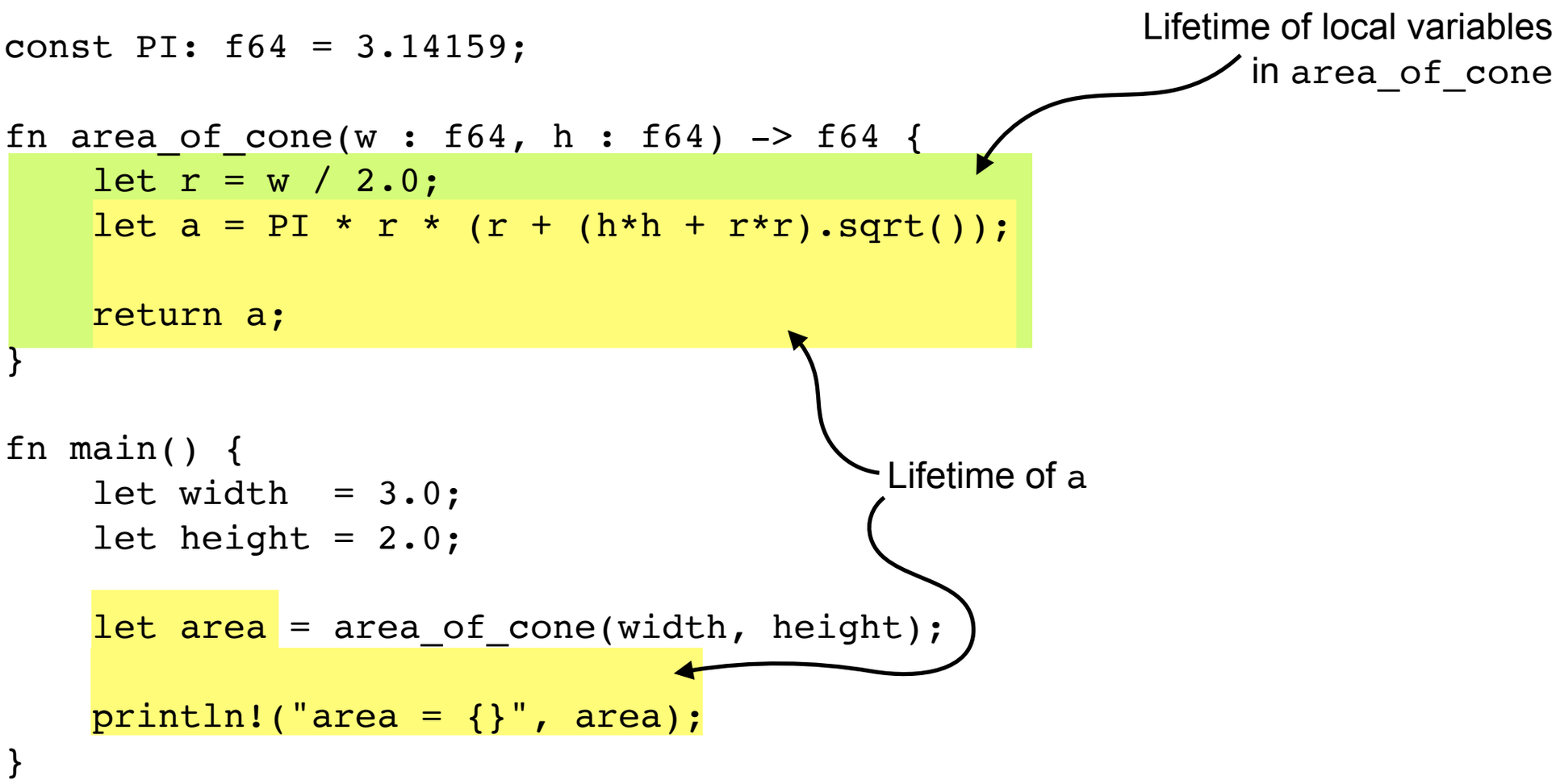
fn area_of_cone(w : f64, h : f64) -> f64 {
    let r = w / 2.0;
    let a = PI * r * (r + (h*h + r*r).sqrt());

    return a;
}

fn main() {
    let width  = 3.0;
    let height = 2.0;

    let area = area_of_cone(width, height);

    println!("area = {}", area);
}
```



Returning Ownership of Data

- Runtime must track changes in ownership as data is returned
  - Copies made of stack-allocated local variables; original deallocated, copy has lifetime of stack-allocated local variable in calling function
  - Allows us to return a copy of a `Box<T>` that references a heap allocated value of type `T`
    - Effective with a reference counting implementation
    - Creating the new `Box<T>` temporarily increases the reference count on the heap-allocated `T`
    - The original box is then immediately deallocated, reducing the reference count again
    - (An optimised runtime can eliminate the changes to the reference count)
    - The heap-allocated `T` is deallocated when the box goes out of scope of the outer region
- Allows data to be passed around, if it always has a single owner

Giving Ownership of Data

```
% cat consume.rs
fn consume(mut x : Vec<u32>) {
  x.push(1);
}

fn main() {
  let mut a = Vec::new();

  a.push(1);
  a.push(2);

  consume(a);

  println!("a.len() = {}", a.len());
}
```

Lifetime of `a`

Ownership of `a` transferred to `consume()`

```
% rustc consume.rs
consume.rs:15:28: 15:29 error: use of moved value: `a` [E0382]
consume.rs:15   println!("a.len() = {}", a.len());
                                         ^
```

- Ownership of parameters passed to a function is transferred to that function
  - Deallocated when function ends, unless it returns the data
  - Data cannot be later used by the calling function – enforced at compile time

Borrowing Data

```
% cat borrow.rs
fn borrow(mut x : &mut Vec<u32>) {
  x.push(1);
}

fn main() {
  let mut a = &mut Vec::new();

  a.push(1);
  a.push(2);

  borrow(a);

  println!("a.len() = {}", a.len());
}

% rustc borrow.rs
% ./borrow
a.len() = 3
%
```



- Functions can *borrow* references to data owned by an enclosing scope
  - Does not transfer ownership of the data
  - Naïvely safe to use, since live longer than the function

- Can also return references to input parameters passed as references
  - Safe, since these references must live longer than the function

Problems with Naïve Borrowing

```
% cat borrow.rs
fn borrow(mut x : &mut Vec<u32>) {
  x.push(1);
}

fn main() {
  let mut a = &mut Vec::new();

  a.push(1);
  a.push(2);

  borrow(a);

  println!("a.len() = {}", a.len());
}

% rustc borrow.rs
% ./borrow
a.len() = 3
%
```

- The `borrow()` function changes the contents of the vector
- But – it cannot know whether it is safe to do so
  - In this example, it is safe
  - If `main()` was iterating over the contents of the vector, changing the contents might lead to elements being skipped or duplicated, or to a result to be calculated with inconsistent data
  - Known as *iterator invalidation*

Safe Borrowing

- Rust has two kinds of pointer:
  - &T – a shared reference to an immutable object of type T
  - &mut T – a unique reference to a mutable object of type T
- Runtime system controls pointer ownership and use
  - An object of type `T` can be referenced by one or more references of type `&T`, or by exactly 1 reference of type `&mut T`, but not both
  - Cannot get an `&mut T` reference to data of type `T` that is marked as immutable
- Allows functions to safely borrow objects – without needing to give away ownership

- To change an object:
  - You either own the object, and it is not marked as immutable; or
  - You have the only `&mut` reference to it
- Prevents iterator invalidation
  - The iterator requires an `&T` reference, so other code can't get a mutable reference to the contents to change them:

```
fn main() {
  let mut data = vec![1, 2, 3, 4, 5, 6];
  for x in &data {
    data.push(2 * x);
  }
}
```

fails, since push takes an `&mut` reference

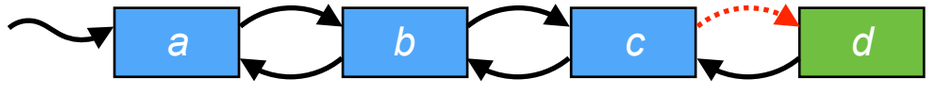
enforced at compile time

Benefits

- Type system tracks ownership, turning run-time bugs into compile-time errors:
  - Prevents memory leaks and use-after-free bugs
  - Prevents iterator invalidation
  - Prevents race conditions with multiple threads – borrowing rules prevent two threads from getting references to a mutable object
  - Efficient run-time behaviour – timing and memory usage are predictable

Limitations of Region-based Systems

- Can’t express cyclic data structures
  - E.g., can’t build a doubly linked list:



Can’t get mutable reference to *c* to add the link to *d*, since already referenced by *b*

  - Many languages offer an escape hatch from the ownership rules to allow these data structures (e.g., raw pointers and `unsafe` in Rust)
- Can’t express shared ownership of mutable data
  - Usually a good thing, since avoids race conditions
  - Rust has `RefCell<T>` that dynamically enforces the borrowing rules (i.e., allows upgrading a shared reference to an immutable object into a unique reference to a mutable object, if it was the only such shared reference)
  - Raises a run-time exception if there could be a race condition, rather than preventing it at compile time

Limitations of Region-based Systems

- Forces programmer to consider object ownership early and explicitly
  - Generally good practice, but increases conceptual load early in design process – may hinder exploratory programming

Summary

- Region-based memory management with strong ownership and borrowing rules
  - Efficient and predictable behaviour
  - Strong correctness guarantees prevent many common bugs
  - Constrains the type of programs that can be written

- Further reading:
  - D. Grossman, G. Morrisett, T. Jim, M. Hicks, Y. Wang, and J. Cheney, “Region-based memory management in Cyclone”, Proc. ACM Conference on Programming Language Design and Implementation, Berlin, Germany, June 2002. DOI: 10.1145/512529.512563
  - You’re not expected to read/understand section 4
  - Will be discussed in tutorial 5



Region-Based Memory Management in Cyclone *

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ABSTRACT

Cyclone is a type-safe programming language derived from C. The primary design goal of Cyclone is to let programmers control data representation and memory management without sacrificing type-safety. In this paper, we focus on the region-based memory management of Cyclone and its static typing discipline. The design incorporates several advancements, including support for region subtyping and a coherent integration with stack allocation and a garbage collector. To support separate compilation, Cyclone requires programmers to write some explicit region annotations, but a combination of default annotations, local type inference, and a novel treatment of region effects reduces this burden. As a result, we integrate C idioms in a region-based framework. In our experience, porting legacy C to Cyclone has required altering about 8% of the code; of the changes, only 6% (of the 8%) were region annotations.

Categories and Subject Descriptors

D.3.3 [**Programming Languages**]: Language Constructs and Features—*dynamic storage management*

General Terms

Languages

1. INTRODUCTION

Many software systems, including operating systems, device drivers, file servers, and databases require fine-grained control over data representation (e.g., field layout) and resource management (e.g., memory management). The *de facto* language for coding such systems is C. However, in providing low-level control, C admits a wide class of dangerous — and extremely common — safety violations, such as incorrect type casts, buffer overruns, dangling-pointer dereferences, and space leaks. As a result, building large systems in C, especially ones including third-party extensions, is perilous. Higher-level, type-safe languages avoid these drawbacks, but in so doing, they often fail to give programmers the control needed in low-level systems. Moreover, porting or extending legacy code is often prohibitively expensive. Therefore, a safe language at the C level of abstraction, with an easy porting path, would be an attractive option.

Toward this end, we have developed *Cyclone* [6, 19], a language designed to be very close to C, but also safe. We have written or ported over 110,000 lines of Cyclone code, including the Cyclone compiler, an extensive library, lexer and parser generators, compression utilities, device drivers, a multimedia distribution overlay network, a web server, and many smaller benchmarks. In the process, we identified many common C idioms that are usually safe, but which the C type system is too weak to verify. We then augmented the language with modern features and types so that programmers can still use the idioms, but have safety guarantees.

For example, to reduce the need for type casts, Cyclone has features like parametric polymorphism, subtyping, and tagged unions. To prevent bounds violations without making hidden data-representation changes, Cyclone has a variety of pointer types with different compile-time invariants and associated run-time checks. Other projects aimed at making legacy C code safe have addressed these issues with somewhat different approaches, as discussed in Section 7.

In this paper, we focus on the most novel aspect of Cyclone: its system for preventing dangling-pointer dereferences and space leaks. The design addresses several seemingly conflicting goals. Specifically, the system is:

- *Sound:* Programs never dereference dangling pointers.
- *Static:* Dereferencing a dangling pointer is a compile-time error. No run-time checks are needed to determine if memory has been deallocated.
- *Convenient:* We minimize the need for explicit programmer annotations while supporting many C idioms. In particular, many uses of the addresses of local variables require no modification.

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