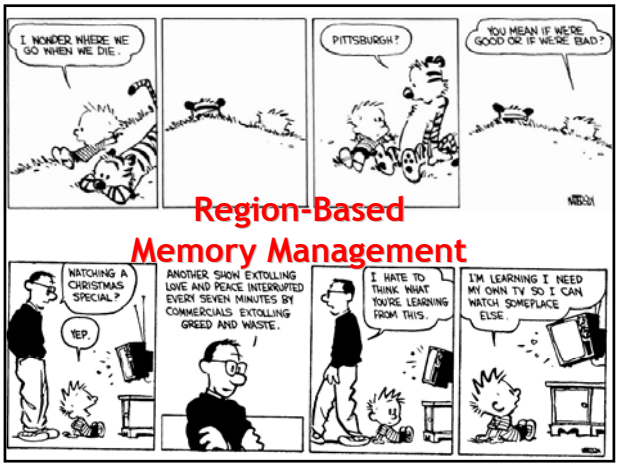


Region-Based Memory Management

Today In A Single Slide

- Memory management has two problems: freeing things too early and freeing things too late.
- Regions are an abstraction in which related objectss are allocated together and freed at once.

proRegion Heilbronn-Franken

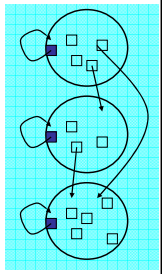
Memory Management

- Manual memory deallocation is dangerous
  - Deallocate too late ⇒ memory leaks ⇒ performance problems
  - Deallocate too early ⇒ dangling pointers ⇒ safety problems
- Most type-safe languages disallow manual memory deallocation
  - Because their type systems cannot check absence of dangling pointers
  - Such languages use garbage collection ⇒ lack of control
- Question: Is there an *effective type system for memory mgmt that allows deallocation*?
  - Current best answer: region-based memory management

#3

Regions

- a.k.a. zones, arenas, …
- Every object is in *exactly one* region
- Allocation via a region *handle*
- Deallocate an *entire region simultaneously*
  (cannot **`free`** an individual object)
- Supports easy serialization



#4

Region-based Memory Management Example

```
Region r = newregion();
for (i = 0; i < 10; i++) {
  int *x = ralloc(r, (i + 1) * sizeof(int));
  work(i, x);
}
deleteregion(r);
```

#5

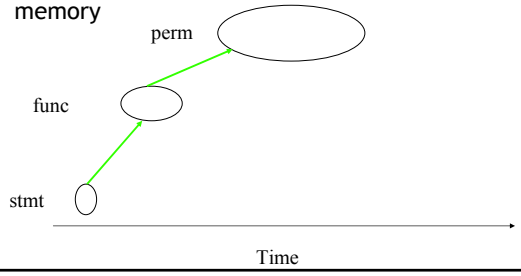
Region Expressiveness

- Adds structure to memory management
- Allocate objects into regions based on *lifetime*
- Works well for objects with related lifetimes
  - e.g., global/per-request/per-phase objects in a server
- Few regions:
  - Easier to keep track of and reason about
  - Delay freeing to convenient "group" time
    - End of an iteration, closing a device, etc
- No writing "free data structure X" functions

#6

Region Expressiveness: lcc

- The lcc C compiler, written using unsafe regions
  - regions bring structure to an application's memory



#7

Region Expressiveness: lcc

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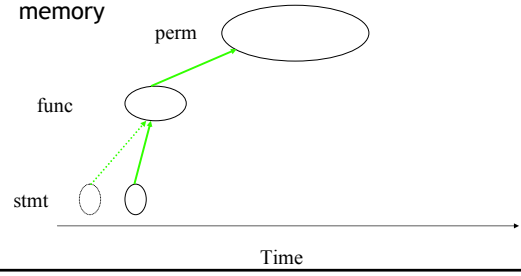

#8

Region Expressiveness: lcc

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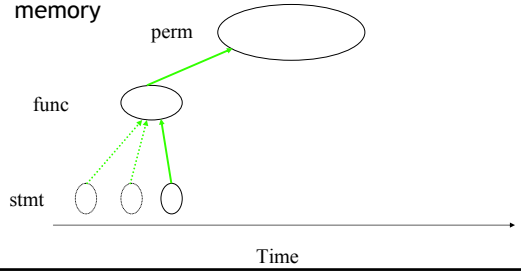

#9

Region Expressiveness: lcc

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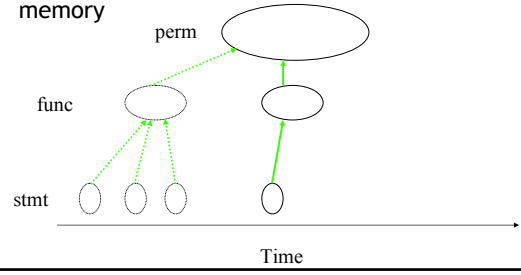
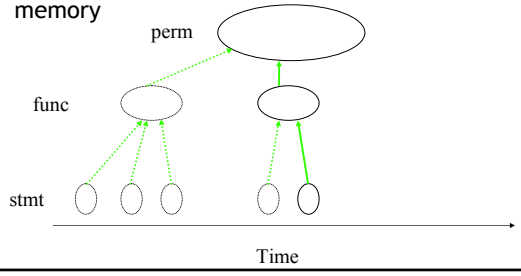


#10

Region Expressiveness: lcc

- The lcc C compiler, written using unsafe regions
  - regions bring structure to an application's memory



#11

Region Expressiveness: lcc

- The lcc C compiler, written using unsafe regions
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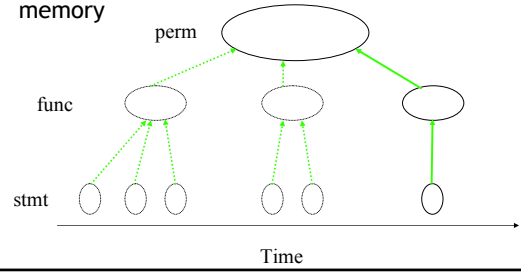


#12

Safe Region-Based Memory Management

- When is it *safe to deallocate* a region?
  - Unsafe if you later user a pointer to an object in it!
  - Safe if objects in the same region point to each other
  - But we must handle pointers between regions
- One Idea: nested regions lifetimes
  - Use a stack of regions
    - last region created is also first region deleted
  - Stack frames are a special case of such regions
  - Cannot point from older regions into newer ones
  - Too restrictive in practice
- Today: use a *type system* to keep track of regions

Region-Flow Type System

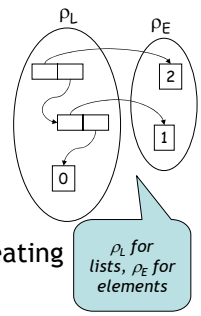
- In F_1 we *did not model* where results of expressions are allocated (e.g., pairs)
  - Now we'll extend F_1 to track regions
- Specify in what region to store expression results

  Expr: $e ::= \lambda x.e \mid e_1\ e_2 \mid \ldots \mid e\ @\ \rho \mid e\ !\ \rho$

  Region names: ρ *("rho", Greek letter "r")*
- New expressions:
  - "$e\ @\ \rho$" evaluates e and *puts the result in region* ρ
    - We assume that each value lives in a region
  - Think of "$e\ !\ \rho$" as an *assertion* that value of e is in region ρ plus "*memcopy* e from ρ"

Example

```
let cons = λxλy. (x, y) @ ρL in
let lst = cons (2 @ ρE)
  (cons (1 @ ρE) (0 @ ρL)) in
 … (fst (lst ! ρL)) ! ρE …
```



- Can deallocate ρ_L without creating dangling pointers
- But if we deallocate ρ_E first we create dangling pointers

Operational Semantics

- Values live in regions

  $v ::= \ldots \mid \langle v \rangle_\rho$

  - "$\langle v \rangle_\rho$" means value v living in region ρ
- Evaluation rules

$$\frac{e \rightarrow v}{e\ @\ \rho \rightarrow \langle v \rangle_\rho} \qquad \frac{e \rightarrow \langle v \rangle_\rho}{e\ !\ \rho \rightarrow v}$$

- Evaluation gets stuck if region check ! fails
  - Check: same ρ above and below line

Typing Rules

- Add a new type to keep track of regions for values

  $\tau ::= b \mid \tau_1 \rightarrow \tau_2 \mid \tau\ @\ \rho$
- Typing rules are straightforward

$$\frac{\Gamma \vdash e : \tau}{\Gamma \vdash e\ @\ \rho : \tau\ @\ \rho} \qquad \frac{\Gamma \vdash e : \tau\ @\ \rho}{\Gamma \vdash e\ !\ \rho : \tau}$$

- Types keep track of regions of values
  - All values that can flow into one variable must be from the same region
- Soundness result:
  - In well-typed programs the annotations in "$e\ !\ \rho$" are always correct
  - i.e., "$e\ !\ \rho$" never gets stuck (and can be removed)

Region-Flow Inference

- We start with *unannotated* programs
- We want to infer the region annotations as follows:
  - Each value constructor v must be annotated
  - Each deconstructor must be annotated

  $v ::= n\ @\ \rho \mid (\lambda x.e)\ @\ \rho$

  $e ::= v \mid (e_1\ !\ \rho)\ e_2 \mid (\text{fst}\ !\ \rho)\ e$

  $\mid \text{if}\ (e\ !\ \rho)\ \text{then}\ e_1\ \text{else}\ e_2$
- We must know, at each use of a value, in what region that value is allocated

Annotation Example

- We abbreviate:

$n \@ \rho$	as	n^{ρ}
$(\lambda\ x.\ e) \@ \rho$	as	$\lambda^{\rho}\ x.e$
$(e_1\ !\ \rho)\ e_2$	as	$e_1{}^{\rho}\ e_2$

- Consider the code:

$$\text{let fst} = \lambda^{\rho_f} u.\ \lambda^{\rho_a} v.\ u \text{ in}$$

$$(\text{let } x = \lambda^{\rho_x} p.(p^{\rho_f}\ 0^{\rho_0})^{\rho_a}\ 1^{\rho_1}$$

$$\text{in } \lambda^{\rho_q} q.\ (q^{\rho_f}\ (x^{\rho_x}\ \text{fst}))^{\rho_a}\ 2^{\rho_1})^{\rho_q}\ \text{fst}$$

#19

Region-Flow Type Inference

- Type inference is always possible in this system
- There are multiple correct solutions
  - e.g., use only one region throughout
- There is a "best" solution (up to renaming of regions; best = uses largest # of regions)
  - All other solutions can be obtained by merging some regions in the best solution
- This program analysis is called value-flow analysis
  - Can tell you what values could *possibly* flow to a use
  - It is a weak form of analysis (equational)
    For "x := y; x := z;" we get flow between x, y, z (in both directions)

#20

Adding Region Allocation and Deallocation

- So far we can track (statically) which values are in which region
- We can think of "e @ ρ" as evaluating e and allocating in region ρ space for the result
- We can think of "e ! ρ" as checking that the result of e is in region ρ, and retrieving the result if so
  - The type system tells us that the check is not necessary at run-time. We do not even need to be able to tell at runtime in which region an object is. No tags.
- Still need to know when it is safe to delete a region

#21

Region Irrelevance

- Assume $\Gamma \vdash e : \tau$ such that
  - Region ρ is used in e
  - Region ρ does not appear in Γ
    - Means that before we start e region ρ is empty
  - Region ρ does not appear in τ
    - Means that the result of e does not refer to any values in ρ
  - The region ρ is *relevant only during the execution* of e
- Example:
  - After evaluation of $(\lambda^{\rho_0} x.\ x)^{\rho_0}\ 1^{\rho_1}$ we can erase ρ_0 if nothing in the context uses it
- Idea: tie region lifetime (relevance) to static scoping

#22

Statically-Scoped Regions

- Add a new construct

  e ::= … | letreg ρ in e
  - Creates a new region and binds it to the name ρ
  - After e terminates the region is deleted

$$\frac{\Gamma, (R, \rho) \vdash e : \tau \qquad \rho \notin \text{RegionVars}(\Gamma, \tau)}{\Gamma, R \vdash \text{letreg } \rho \text{ in } e : \tau}$$

$$\frac{\Gamma, R \vdash e : \tau \@ \rho}{\Gamma, R \vdash e\ !\ \rho : \tau} \qquad \frac{\Gamma, R \vdash e : \tau \qquad \rho \in R}{\Gamma, R \vdash e \@ \rho : \tau \@ \rho}$$

- Example:

  letreg ρ_0 in $(\lambda^{\rho_0} x.\ x)^{\rho_0}\ 1^{\rho_1}$ is well typed

  letreg ρ_0 in $(\text{cons } 1^{\rho_1}\ ((\lambda^{\rho_0} x.\ x)^{\rho_0}\ 2^{\rho_0}))^{\rho_1}$ is ill typed
  - Type system can detect dangling references. What are they here?

#23

Unsoundness

- This system works well in first-order languages, where the type of a value fully describes its dependencies
  - A value of type $(\text{int} \@ \rho_1 \times \text{bool} \@ \rho_2) \@ \rho_1$ has references into regions ρ_1 and ρ_2 only
  - A value of type $(\text{int} \@ \rho_1 + \text{bool} \@ \rho_2) \@ \rho_3$ has references into regions ρ_3 and (ρ_1 or ρ_2). Conservatively in ρ_1, ρ_2 and ρ_3
- In higher-order languages we cannot tell so easily

  t = letreg ρ_0 in let x = true @ ρ_0 in

  λ y.if x ! ρ_0 then y else false @ ρ_1
  - body of letreg has type $\text{bool}^{\rho_1} \to \text{bool}^{\rho_1}$
  - Later, when t is used, it will access a dangling pointer to x
- Problem: The type of a function describes *only the input/output behavior* of the function
  - It does not describe the *execution* of the function!

#24

Types and Effects

- We enrich the type system to contain information about the computation not just the result
  - For each computation we keep a set of effects (interesting events that occur as it executes)
- New Judgment: $\Gamma \vdash e : ^{\phi} \tau$
  - expression e computes a value of type τ *and has effects* among those in the set ϕ
- We extend the function types as well

  $\tau ::= \text{int} \mid \tau \text{ @ } \rho \mid \tau_1 \rightarrow^{\phi} \tau_2$
- Example:

  $\Gamma \vdash e : ^{\phi 1} \text{int} \rightarrow^{\phi 2} \text{int}$
  - Expression e evaluates (with effects ϕ_1) to a function, which when given an int evaluates (with effects ϕ_2) to an int

Effects for Regions

- To detect dangling references we need to compute for each expression what set of regions it references at runtime

$$\frac{\Gamma, x : \tau \vdash e : ^{\phi} \tau}{\Gamma \vdash \lambda x.\ e : ^{\emptyset} \tau_1 \rightarrow^{\phi} \tau_2}$$

$$\frac{\Gamma(x) = \tau}{\Gamma \vdash x : ^{\emptyset} \tau} \qquad \frac{\Gamma \vdash e_1 : ^{\phi 1} \tau \rightarrow^{\phi} \tau' \quad \Gamma \vdash e_2 : ^{\phi 2} \tau}{\Gamma \vdash e_1\ e_2 : ^{\phi 1 \cup \phi 2 \cup \phi} \tau'}$$

$$\frac{\Gamma \vdash e : ^{\phi} \tau}{\Gamma \vdash e \text{ @ } \rho : ^{\phi \cup \{\rho\}} \tau \text{ @ } \rho} \qquad \frac{\Gamma \vdash e : ^{\phi} \tau \text{ @ } \rho}{\Gamma \vdash e\ !\ \rho : ^{\phi \cup \{\rho\}} \tau}$$

$$\frac{\Gamma \vdash e : ^{\phi} \tau \qquad \rho \notin \text{RegionVars}(\Gamma, \tau)}{\Gamma \vdash \text{letreg } \rho \text{ in } e \ : ^{\phi - \{\rho\}} \ \tau}$$

Handling That Old Example

- Consider again the example

  t = letreg ρ_0 in

  let x = true @ ρ_0 in

  λ y. if x ! ρ_0 then y else false @ ρ_1
  - body of letreg has type

    bool @ $\rho_1 \rightarrow^{\{\rho 0,\ \rho 1\}}$ bool @ ρ_1
- Now the type says that ρ_0 is referenced by the result of t. This program is now ill-typed (i.e., we will notice the region leak).

Effect Types Systems

- We have collected a set of regions referenced
- Effects can model other intrinsic properties of functions (depending on how the computation proceeds, not only on the result)
  - Behavioral effects
  - Effects now have structure, with sequencing, choice, recursion
- Effects have also been used to model
  - cryptographic protocols
  - synchronization protocols
  - interference analysis for threads
  - cleanup actions (previous lecture included a type-and-effect system for compensation stacks)

Soundness

- Here is one way to argue soundness
  - Soundness = no dangling pointers
- Change the operational semantics of letreg to get stuck if the region is referenced in the result of the body

$$\frac{\rho' = \text{newregion}() \quad \vdash [\rho'/\rho]e \Downarrow v \quad \rho' \notin \text{RegionVars}(v)}{\vdash \text{letreg } \rho \text{ in } e \Downarrow v}$$

- Prove that well-typed programs never get stuck
- Will this work? Why?

Soundness Problems

- Consider the program

  t = let z = 0 @ ρ_0 in λ x.(λ y. x) z
  - Type is $\emptyset \vdash t : ^{\{\rho 0\}} \text{int} \rightarrow^{\emptyset} \text{int}$
  - Evaluates to t's value = λ x.(λ y.x) $<0>_{\rho_0}$
  - Not true that RegionVars(t's value) = $\emptyset$
- Our system does allow dangling pointers
  - But only when you will *never dereference them*
- In this respect it is more powerful than a garbage collector (able to leap David Bacon in a single bound)
  - Because it can see the rest of the computation
  - The GC only sees a snapshot of the computation state

Soundness Attempt 2

- Introduce a special region called "dangling"
  - Replace all dangling regions with this one
  - And check that we never use it

$$\frac{\rho' = \text{newregion}() \qquad \vdash [\rho'/\rho]e \Downarrow v}{\vdash \text{letreg } \rho \text{ in } e \Downarrow [\text{dangling}/\rho']v}$$

$$\frac{\sigma \vdash e \Downarrow \langle v \rangle_\rho \qquad \rho \neq \text{dangling}}{\vdash e\ !\ \rho \Downarrow v}$$

$$\frac{\sigma \vdash e \Downarrow v \qquad \rho \neq \text{dangling}}{\vdash e\ @\ \rho \Downarrow \langle v \rangle_\rho}$$

- Prove now that well-typed programs do not get stuck
  - No need to introduce the dangling checks at run-time

#31

Region Polymorphism

- Consider this code again
  $\text{let cons} = \lambda\, x \lambda\, y.\ (x, y)\ @\ \rho_L$
- We need a different function to allocate pairs in different regions. Inconvenient!
- Idea: allow functions to take regions as parameters
- This is called region polymorphism
- We write $\text{let cons} = \lambda\rho.\ \lambda\, x.\ \lambda\, y.\ (x, y)\ @\ \rho$
- Type of result of cons depends on the region argument
- Type of cons is $\Pi\rho.\tau_1 \to \tau_2 \to (\tau_1 \times \tau_2)\ @\ \rho$

#32

Region Polymorphism

- We add the following to the language

  $e ::= \ldots \mid \lambda\, \rho.\ e$ (region abstraction)

  $\mid e\ \rho$ (region application)

  $\tau ::= \ldots \mid \Pi\rho.^{\phi}\ \tau$ (region polymorphism)
  - In the type $\Pi\rho.^{\phi}\ \tau$ region variable ρ is bound in ϕ and τ

$$\frac{\Gamma \vdash e :^{\phi} \tau}{\Gamma \vdash \lambda\rho.\ e :^{\emptyset} \Pi\rho.^{\phi}\ \tau} \qquad \frac{\Gamma \vdash e :^{\phi'} \Pi\rho.^{\phi}\ \tau}{\Gamma \vdash e\ \rho' :^{\phi' \cup [\rho'/\rho]\phi}\ [\rho'/\rho]\tau}$$

  - Note that region application does not "reference" the region (it's purely syntactic, as in "`id [int] 5`")
  - More opportunities for harmless dangling references

#33

Effect Polymorphism

- Region polymorphism fails on higher-order languages
- Consider the map function for lists of integers
- Without regions:
  $\text{map} : (\text{int} \to \text{int}) \times \text{intlist} \to \text{intlist}$
- With regions (potentially moving the list also):
  $\text{map} : \Pi\rho.\Pi\rho'.^{\emptyset}\ (\text{int} \to^{\phi} \text{int}) \times (\text{intlist}\ @\ \rho) \to^{\phi \cup \{\rho,\rho'\}} (\text{intlist}\ @\ \rho')$
  - But the effect ϕ is hardcoded
  - Need a different map for each effect
- Déjà vu: Need effect polymorphism

#34

Effect Polymorphism

- We do not add syntax for effect polymorphism
  - It is implicit; our type system tracks it
- We add types and typing rules

  $\varepsilon \in \text{EffectVariables}$

  $\tau ::= \ldots \mid \forall\varepsilon.\ \tau$
  - Very similar to value polymorphism

$$\frac{\Gamma \vdash e :^{\phi} \tau \qquad \varepsilon \notin \text{EffectVars}(\Gamma, \phi)}{\Gamma \vdash e :^{\phi} \forall\varepsilon.\tau} \qquad \frac{\Gamma \vdash e :^{\phi} \forall\varepsilon.\tau}{\Gamma \vdash e :^{\phi} [\phi'/\varepsilon]\tau}$$

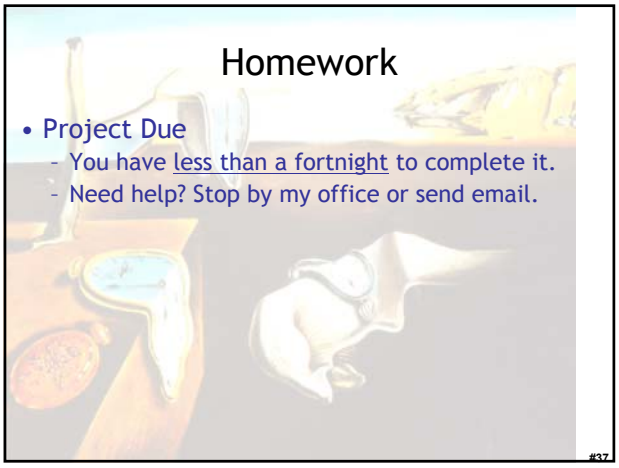
- We can now write the map function:
  $\text{map} : \forall\varepsilon.\Pi\rho.\Pi\rho'.^{\emptyset}\ (\text{int} \to^{\varepsilon} \text{int}) \times (\text{intlist}\ @\ \rho) \to^{\varepsilon \cup \{\rho,\rho'\}} (\text{intlist}\ @\ \rho')$

#35

Regions In Practice

- Despite heavy use of regions in practice (systems code)
  - Apache, Linux kernel, BerkeleyDB, etc.
- The (formal) study of regions is less than 15 years old
- Few languages include regions
  - MLKit (an implementation of ML)
    - Regions are inferred and used as an implementation mechanism
  - RC (Gay and Aiken, Berkeley)
    - Reference counting of inter-region pointers
  - Cyclone (safe variant of C)
    - Somewhat lighter-weight
    - Global region, stack regions, lexically-scoped regions
  - All of which failed to set the world on fire …
- Compromise between complexity of the typing annotations and expressiveness
  - Danger is that the type system may require regions to be long-lived

#36


Homework
• Project Due
– You have less than a fortnight to complete it.
– Need help? Stop by my office or send email.
#37