Cyclone: Safe Programming at the C Level of Abstraction

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A disadvantage of C

- Lack of *memory safety* means code cannot enforce modularity/abstractions:

```
void f(){ *((int*)0xBAD) = 123; }
```

- What might address **`0xBAD`** hold?

- Memory safety is crucial for your favorite policy

No desire to compile programs like this

Safety violations rarely local

```
void g(void**x,void*y);

int  y = 0;
int *z = &y;
g(&z,0xBAD);
*z = 123;
```

- Might be safe, but not if **`g`** does **`*x=y`**
- Type of **`g`** enough for separate code generation
- Type of **`g`** not enough for separate safety checking

Some other problems

- One safety violation can make your favorite policy extremely difficult to enforce

- So prohibit:

  incorrect casts, array-bounds violations, misused unions, uninitialized pointers, dangling pointers, null-pointer dereferences, dangling longjmp, vararg mismatch, not returning pointers, data races, …

What to do?

- Stop using C
  - YFHLL is *usually* a better choice
- Compile C more like Scheme
  - type fields, size fields, live-pointer table, …
  - fail-safe for legacy whole programs
- Static analysis
  - very hard, less modular
- Restrict C
  - not much left

Cyclone in brief

A safe, convenient, and modern language at the C level of abstraction

- Safe: memory safety, abstract types, no core dumps
- C-level: user-controlled data representation and resource management, easy interoperability, “manifest cost”
- Convenient: may need more type annotations, but work hard to avoid it
- Modern: add features to capture common idioms

“New code for legacy or inherently low-level systems”

The plan from here

- Not-null pointers
- Type-variable examples
  - parametric polymorphism
  - region-based memory management
- Dataflow analysis
- Status
- Related work

I will skip many very important features

Not-null pointers

`t*`	pointer to a `t` value or `NULL`
`t@`	pointer to a `t` value

- Subtyping: `t@ < t*` but `t@@` $\not<$ `t*@`
- Downcast via run-time check, often avoided via flow analysis

Example

```
FILE* fopen(const char@, const char@);
int fgetc(FILE @);
int fclose(FILE @);
void g() {
  FILE* f = fopen("foo", "r");
  while(fgetc(f) != EOF) {…}
  fclose(f);
}
```

- Gives warning and inserts one null-check
- Encourages a hoisted check

The same old moral

```
FILE* fopen(const char@, const char@);
int fgetc(FILE @);
int fclose(FILE @);
```

- Richer types make interface stricter
- Stricter interface make implementation easier/faster
- Exposing checks to user lets them optimize
- Can’t check everything statically (e.g., close-once)

“Change `void*` to alpha”

```
struct Lst {
  void* hd;
  struct Lst* tl;
};

struct Lst* map(
  void* f(void*),
  struct Lst*);

struct Lst* append(
  struct Lst*,
  struct Lst*);
```

```
struct Lst<`a> {
  `a hd;
  struct Lst<`a>* tl;
};

struct Lst<`b>* map(
  `b f(`a),
  struct Lst<`a> *);

struct Lst<`a>* append(
  struct Lst<`a>*,
  struct Lst<`a>*);
```

Not much new here

Closer to C than ML:

- less type inference allows first-class polymorphism and polymorphic recursion
- data representation may restrict α to pointers, **`int`** (why not structs? why not **`float`**? why **`int`**?)
- Not C++ templates

Existential types

- Programs need a way for “call-back” types:

```
struct T {
   void (*f)(void*, int);
   void* env;
};
```

- We use an existential type (simplified for now):

```
struct T { <`a>
  void (@f)(`a, int);
  `a env;
};
```

more C-level than baked-in closures/objects

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- Type-variable examples (α, $\forall$, $\exists$, λ)
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Regions

- a.k.a. zones, arenas, …
- Every object is in exactly one region
- Allocation via a region *handle*
- All objects in a region are deallocated simultaneously (no `free` on an object)

An old idea with recent support in languages (e.g., RC) and implementations (e.g., ML Kit)

Cyclone regions

- heap region: one, lives forever, conservatively GC'd
- stack regions: correspond to local-declaration blocks:

  `{int x; int y; `*`s`*`}`

- dynamic regions: scoped lifetime, but growable:

  `region r {`*`s`*`}`

- allocation: **`rnew(r,3)`**, where **`r`** is a *handle*
- handles are first-class
  - caller decides where, callee decides how much
  - no handles for stack regions

That’s the easy part

The implementation is *really simple* because the type system *statically* prevents dangling pointers

```
void f() {
  int* x;
  if(1) {
    int y = 0;
    x = &y; // x not dangling
  }
  *x; // x dangling
}
```

The big restriction

- Annotate all pointer types with a *region name* (a type variable of region kind)

- **`int@`r`** means "pointer into the region created by the construct that introduces **`` `r ``**"

  - heap introduces **`` `H ``**
  - **`L:`** … introduces **`` `L ``**
  - **`region r {s}`** introduces **`` `r ``**

    `r` has type **`region_t<`r>`**

Region polymorphism

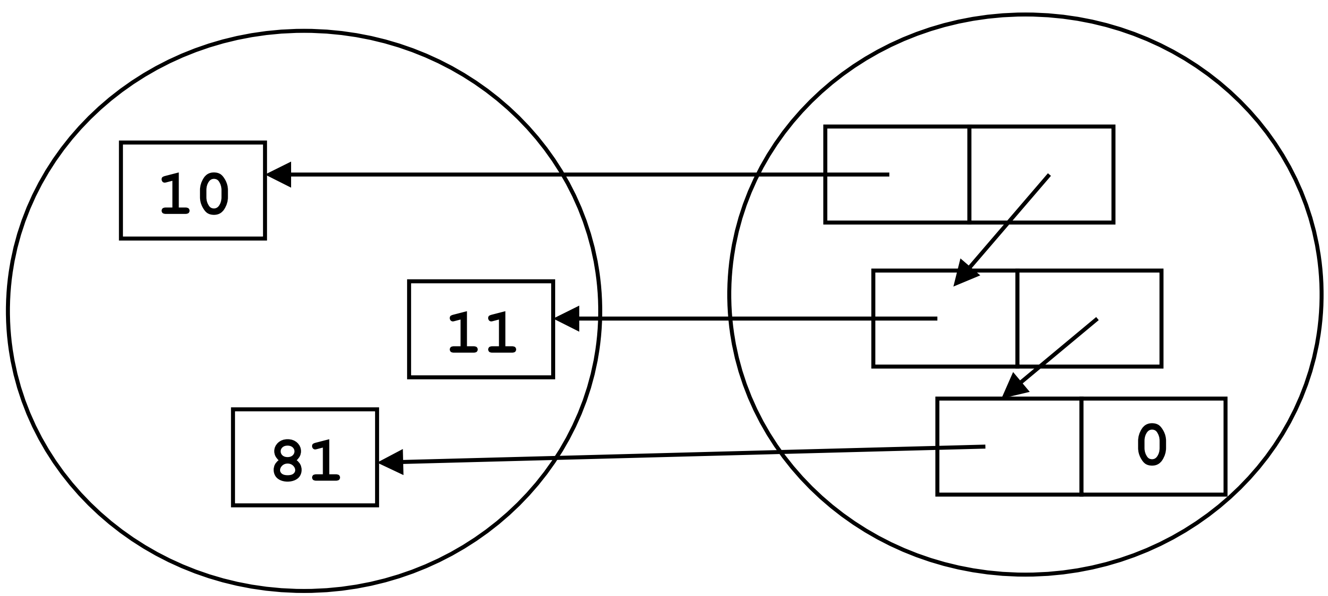
Apply what we did for type variables to region names (only it's more important and could be more onerous)

```
void swap(int @`r1 x, int @`r2 y){
  int tmp = *x;
  *x = *y;
  *y = tmp;
}

int@`r sumptr(region_t<`r> r,int x,int y){
  return rnew(r) (x+y);
}
```

Type definitions

```
struct ILst<`r1,`r2> {
  int@`r1 hd;
  struct ILst<`r1,`r2> *`r2 tl;
};
```



Region subtyping

If **`p`** *points to an* **`int`** *in a region with name* **`` `r1 ``**, *is it ever sound to give* **`p`** *type* **`` int*`r2 ``**?

- If so, let **`` int*`r1 < int*`r2 ``**
- Region subtyping is the outlives relationship

```
region r1 {… region r2 {…}…}
```

- LIFO makes subtyping common

Soundness

- Ignoring ∃, scoping prevents dangling pointers

```
int*`L f() { L: int x; return &x; }
```

- End of story if you don't use ∃

- For ∃, we leak a *region bound*:

```
struct T<`r> { <`a> :regions(`a) > `r
    void (@f)(`a, int);
    `a env;
};
```

- A powerful effect system is there in case you want it

Regions summary

- Annotating pointers with region names (type variables) makes a sound, simple, static system
- Polymorphism, type constructors, and subtyping recover much expressiveness
- Inference and defaults reduce burden

- Other ~~chapters~~ future features:
  - array bounds: `` void f(tag_t<`i>,int*`i); ``
    default 1
  - mutual exclusion: `` void f(lock_t<`L>,int*`L); ``
    default thread-local

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Example

```
int*`r* f(int*`r q) {
  int **p = malloc(sizeof(int*));
  // p not NULL, points to malloc site
  *p = q;
  // malloc site now initialized
  return p;
}
```

- Harder than in Java because of pointers
- Analysis includes must-points-to information
- Interprocedural annotation: “initializes” a parameter

Flow-analysis strategy

- Current uses: definite-assignment, null-checks, array-bounds checks, must return
- When invariants are too strong, program-point information is more useful
- Sound with respect to aliases (programmers can make copies)
- Checked interprocedural annotations keep analysis local

Status

- Cyclone really exists
  - 110KLOC, including bootstrapped compiler, web server, multimedia overlay network, …
  - gcc back-end (Linux, Cygwin, OSX, …)
  - user's manual, mailing lists, …
  - still a research vehicle
  - more features: exceptions, tagged unions, varargs, …
- Publications
  - overview: USENIX 2002
  - regions: PLDI 2002
  - existentials: ESOP 2002

Related work: higher and lower

- Adapted/extended ideas:
  - polymorphism [ML, Haskell, …]
  - regions [Tofte/Talpin, Walker et al., …]
  - safety via dataflow [Java, …]
  - existential types [Mitchell/Plotkin, …]
  - controlling data representation [Ada, Modula-3, …]
- Safe lower-level languages [TAL, PCC, …]
  - engineered for machine-generated code
- Vault: stronger properties via restricted aliasing

Related work: making C safer

- Compile to make dynamic checks possible
  - Safe-C [Austin et al., …]
  - Purify, Stackguard, Electric Fence, …
  - CCured [Necula et al.]
    - performance via whole-program analysis
    - more on array-bounds, less on memory management and polymorphism
- RC [Gay/Aiken]: reference-counted regions separate from stack and heap
- LCLint [Evans]: unsound-by-design, but very useful
- SLAM: checks user-defined property w/o annotations; assumes no bounds errors

Plenty left to do

- Beyond LIFO memory management
- Resource exhaustion (e.g., stack overflow)
- More annotations for aliasing properties
- More “compile-time arithmetic” (e.g., array initialization)
- Better error messages (not a beginner’s language)

Summary

- Memory safety is essential for your favorite policy
- C isn't safe, but the world's software-systems infrastructure relies on it
- Cyclone combines advanced types, flow analysis, and run-time checks, to create a safe, usable language with C-like data, resource management, and control

http://www.research.att.com/projects/cyclone

http://www.cs.cornell.edu/projects/cyclone

best to write some code