Cyclone: Safe C-Level Programming (With Multithreading Extensions)

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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
  - multithreading
- 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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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 = 123; // 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

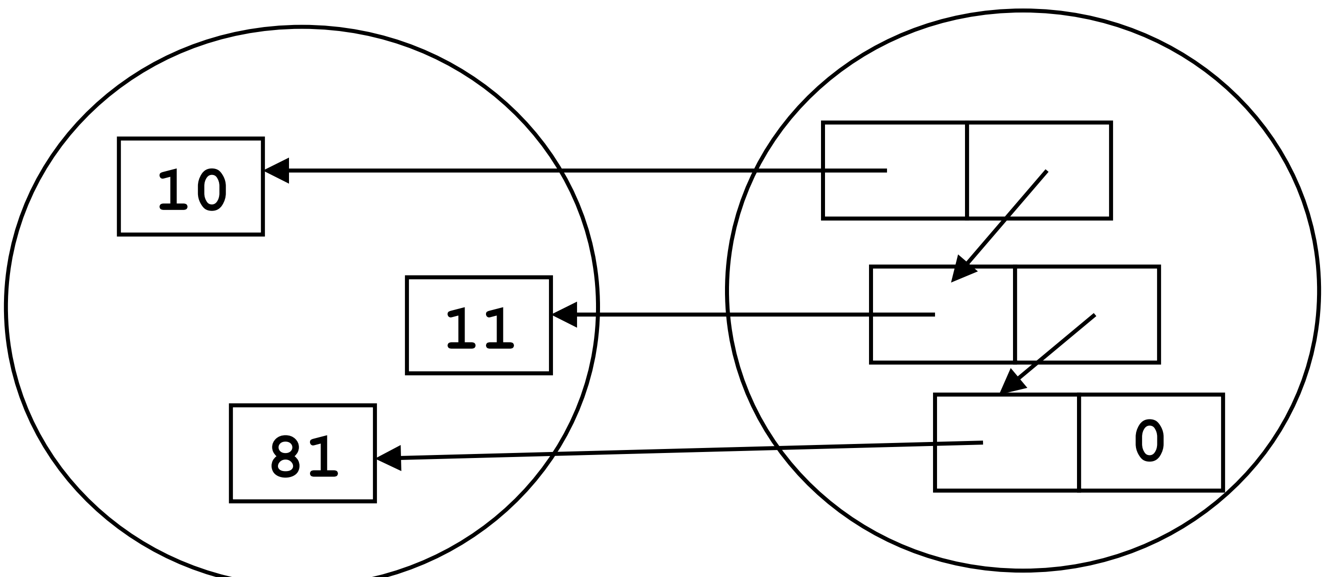
Apply what we did for type variables to region names (only it's more important and could be more onerous)

```
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

- With additional run-time checks, can move beyond LIFO, but checks can fail
- Key point: do not check on every access

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Data races break safety

- Data race: One thread accessing memory while another thread writes it
- On shared-memory MPs, a data race can corrupt a pointer
- Atomic word writes insufficient
  - struct with array bound and pointer to array
  - more generally, existential types

Cyclone must prevent data races

Preventing data races

- Static
  - Don’t have threads
  - Don’t have thread-shared memory
  - Require mutexes for all memory
  - Require mutexes for shared memory
  - Require sound synchronization for shared memory
  - ...
- Dynamic
  - Detect races as they occur
  - Control scheduling and preemption
  - ...

Mutual exclusion support

Require mutual exclusion for shared memory:

- For each shared object, there exists a lock that must be acquired before access
- Thread-local data must not escape its thread

New terms:

- **`spawn(f,p,sz)`** run **`f(p2)`** in a thread where **`*p2`** is a shallow copy of **`*p1`** and **`sz`** is **`sizeof(*p1)`**
- **`newlock()`** create a new lock
- **`nonlock`** a pseudolock for thread-local data
- **`sync e s`** acquire lock e, run s, release lock

Only sync requires language support

Example (w/o types)

```
void inc(int@ p){*p = *p + 1;}
void inc2(lock_t m,int@ p){sync m inc(p);}
struct LkInt {lock_t m; int@ p;};
void g(struct LkInt@ s){inc2(s->m, s->p);}

void f(){
  lock_t lk = newlock();
  int@   p1 = new 0;
  int@   p2 = new 0;
  struct LkInt@ s = new LkInt{.m=lk, .p=p1};
  spawn(g, s, sizeof(*s));
  inc2(lk, p1);
  inc2(nonlock, p2);
}
```

Once again, this is the easy part

Haven’t we been here before

- Annotate all pointers and locks with a lock name (e.g., `lock_t<`L>`, `` int@`L ``)
- Special lock name `loc` for thread-local (`nonlock` has type `lock_t<loc>`)
- `newlock` has type `∃`L. lock_t<`L>`
- `sync e s` where e has type `lock_t<`L>` allows `*p` in `s` where `p` has type `` int@`L ``
- default is caller locks (perfect for thread-local):

```
void inc(int@`L p;{`L}){*p=*p+1;}
```

More about access rights

- For each program point, there is a set of lock names describing “held locks”
  - loc is always in the set
  - functions have set annotations, but default is caller-locks
  - sync adds appropriate name to the set
- Lexical scope for sync keeps rules simple, but is not essential

Analogy with regions

• region_t<`r>	• lock_t<`L>
• int*`r	• int*`L
• `H	• loc
• region r s	• {let m<`L>=newlock(); sync m s}

- Access rights: region live or lock held
- Static rights amplified in lexical scope: region, sync
- Can ignore for prototyping or common case: **`H**, **loc**

Differences as well

- `...`
- `region r s`

- `...`
- `{let m<`L>=newlock();`
  `sync m s}`

- A region's objects are accessible from region creation to region deletion (which happens once)
- A lock's objects are accessible within a **`sync`** (which happens many times)
- So region combines newlock and sync
- So locks don't induce subtyping

Language/type-system design reflects reality

Safe multithreading, so far

- Terms **newlock**, **nonlock**, **sync**, **spawn**
- Types **lock_t<`L>**, **t*`L**, **lock_t<loc>**, **t*loc**
- Type system assigns access rights to each program point
- Strikingly similar to memory management
- But have we prevented data races?

__If__ we never pass thread-local data to spawn!

Enforcing loc

- A possible type for spawn:

```
void spawn(void f(`a@loc ;{}), `a@`L,
                  sizeof_t<`a> ;{`L});
```

- But not any `` `a `` will do

- We already have different kinds of type variables: R for regions, L for locks, B for pointer types, A for all types

- Examples: **loc::L**, **`H::R**, **int*`H::B**,
  struct T :: A

Enforcing loc cont'd

- Enrich kinds with *sharabilities*, `S` or `U`
- `loc::LU`
- `newlock()` has type `∃`L::LS. lock_t<`L>`
- A type is sharable only if every part is sharable
- Every type is unsharable
- Unsharable is the default

```
void spawn<`a::AS>(void(@f)(`a@;{}),
                   `a@`L,
                   sizeof_t<`a>
                   ;{`L});
```

Threads summary

- A type system where:
  - thread-shared data must have locks
  - thread-local data must not escape
  - locks are first-class and code is reusable
- Like regions except locks are reacquirable and thread-local is harder than lives-forever
- Did not discuss: thread-shared regions (must not deallocate until all threads are done with it)

Threads shortcomings

- Global variables need top-level locks
  - *otherwise, single-threaded code works unchanged*
- Shared data enjoys an initialization phase
- Object migration
- Read-only data and reader/writer locks
- Semaphores, signals, ...
- Deadlock (not a safety problem)

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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
- Checked interprocedural annotations keep analysis local
- Two hard technical issues:
  - sound and explainable with respect to aliases
  - under-specified evaluation order

Status

- Cyclone really exists (except for threads)
  - 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 (threads work submitted)
  - 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., …]
  – lock types [Flanagan et al., Boyapati 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 array-bounds, less memory management
    - inherently single-threaded
- RC [Gay/Aiken]: reference-counted regions, unsafe 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