Type-Safe Multithreading in Cyclone

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TLDI 2003

18 Jan 2003

Cyclone + threads = ?

- Cyclone is a safe language at the C level
- Target domains often use threads
- Races are a notorious source of errors
  - Automated help would be welcome
- Data races can violate safety
  - Safety guarantee requires prevention

Data races break safety

Data race: one thread mutating some memory while another thread accesses it (w/o synchronization)

1. Pointer update must be atomic
   - shared-memory MP semantics must be sane
   - source pointers must translate to addresses

2. Writing addresses atomically insufficient

```
struct SafeArr { int len; int* arr; };

if(p->len > i)          ||  *p=*p2 // p2 longer
  (p->arr)[i]=42;       ||
```

Preventing data races

- Dynamic
  - Detect races as they occur
  - Control scheduling and preemption
  - ...
- 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
  - ...

Lock types

The type system ensures that:

For each (shared) data object, there exists a lock that a thread must hold to access the object

- Flanagan, Abadi, Freund, Qadeer
  - invented basic approach
  - found real Java bugs
- Boyapati, Rinard, Lee
  - reuse code for shared and local data
  - advanced features I have not adapted

Contributions

1. Adapt the approach to a C-level language
2. Integrate with parametric polymorphism
3. Integrate/compare with region-based memory management
4. Kinds to explain thread-local data and code reuse
5. Type-safety result for 1, 2, and 4 for an abstract machine where data races violate safety

The plan from here

- Multithreading language
  - terms
  - types
  - kinds
- Limitations
- Formalism: insight into why it's safe
- Related work

Multithreading terms

- **`spawn(f,p,sz)`** run **`f(p2)`** in a thread where **`*p2`** is a shallow copy of **`*p`** and **`sz`** is **`sizeof(*p)`**
  - new thread starts with no locks held
  - new thread terminates when **`f`** returns
  - allows **`*p`** to be thread-local
- **`sync e s`** acquire lock **`e`**, run **`s`**, release lock
- **`newlock()`** create a new lock
- **`nonlock`** a pseudolock for thread-local data

Only sync requires language support
(others are C terms with Cyclone types)

Simple examples (w/o types)

- Suppose `*p1` is shared (lock `lk`) and `*p2` is local
- Caller-locks:

```
    void f(int *p) { /* use *p */ }
  sync lk { f(p1) };
  f(p2);
```

- Callee-locks:

```
    void g(int *p, lock_t l) {
      sync l {/* use *p */}
    }
  g(p1,lk);
  g(p2,nonlock);
```

Types

- Obligation: Each shared memory *location* has a lock that is acquired before access
- Key: *Lock names* (types of kind L) in pointer types and lock types
  - ``int*`L`` is a type for pointers to locations guarded by a lock with type ``lock_t<`L>``
  - mutual exclusion b/c ``lock_t<`L>`` is a *singleton*
- Thread-local locations use lock name `loc`
- `newlock()` has type ``∃`L. lock_t<`L>``
- `nonlock` has type `lock_t<loc>`

Access rights

- Obligation: Each shared memory location has a lock that is *acquired before access*
- Key: Each program point has a set of lock names
  - using location guarded by `` `L `` requires `` `L `` in set (`loc` is always in set)
  - `sync e s` adds `` `L `` if `e` has type `lock_t<`L>`
  - functions have explicit preconditions
    (default is caller locks)
- Lexical scope on `sync` convenient but nonessential

Examples, with types

- Suppose **`*p1`** is shared (lock **`lk`**) and **`*p2`** is local
- Caller-locks:

```
      void f(int*`L p ;{`L}){/* use *p */}
    sync lk { f(p1) };
    f(p2);
```

- Callee-locks:

```
      void g(int*`L p, lock_t<`L> l ;{}) {
        sync l {/*use *p */}
      }
    g(p1,lk);
    g(p2,nonlock);
```

Second-order lock types

- Functions universally quantify over lock names
- Existential types for data structures

  ```
  struct LkInt {<`L> int*`L; lock_t<`L>;};
  ```

  (same race problem as SafeArr example)
- Type constructors for reusing locks

  ```
  struct Lst<`L> {
    int*`L hd;
    struct Lst<`L>*`L tl;
  };
  ```
- Easy to add because Cyclone had second-order types

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No data races only if local data is really local

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:
  L for locks
  A for all (non-lock) types

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

Enforcing loc cont'd

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

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

Keeps local data local

Threads shortcomings

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

The plan from here

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Abstract Machine

Program state: (H, L0, (L1,s1), ..., (Ln,sn))

- One heap (local vs. shared not a run-time notion)
- Li are disjoint lock sets: a lock is available (L0) or held by some thread
- A thread has held locks (Li) and control state (si)

Thread scheduling non-deterministic

- any thread can take the next primitive step

Dynamic semantics

- Single-thread steps can:
  - change/create a heap location
  - acquire/release/create a lock
  - spawn a thread
  - rewrite the thread's statement (control-stack)
- Mutation takes two steps. Informally:

$$H[x \rightarrow v],\quad x{=}v'\,;\, s \quad\Rightarrow$$

$$H[x \rightarrow junk(v')],\quad x{=}junk(v');\, s \quad\Rightarrow$$

$$H[x \rightarrow v'],\quad s$$

- Data races exist and can lead to stuck threads

Static semantics – source

- Distinguishes statements and left/right expressions (as does dynamic semantics and C)
- Type-checking right-expressions: $\Delta;\Gamma;\gamma;\varepsilon \vdash e : \tau$

  Δ : type variables and their kinds

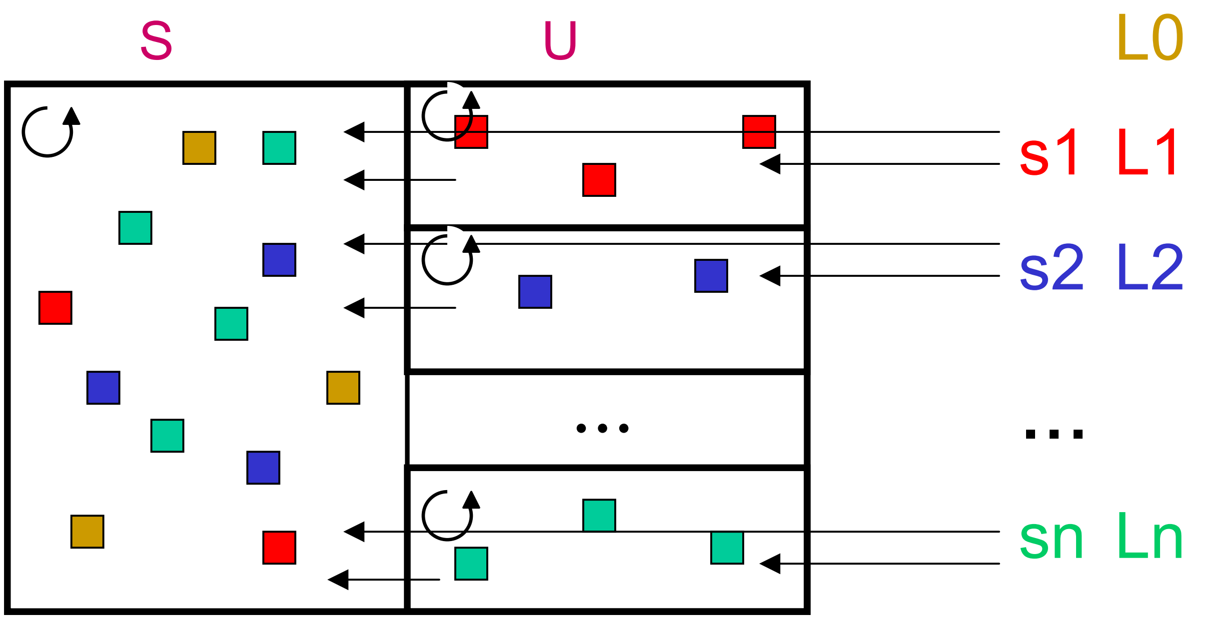
  Γ : term variables and their types & lock-names

  γ : effect constraints (for polymorphism)

  ε : effect (lock names currently allowed)
- junk expressions never well-typed in source
- Largely conventional – no surprises

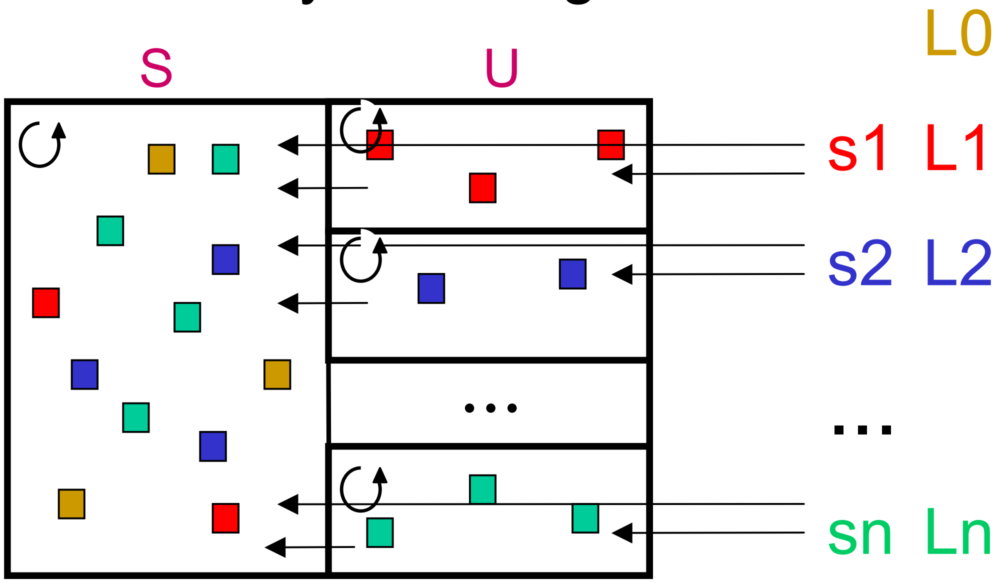
Static semantics – program state

- Evaluation preserves implicit structure on the heap
- spawn preserves the invariant because of the kind restriction on its argument
- Acquiring/releasing a lock “recolors” the shared heap



No data races

- Invariant on where junk(v) can appear:
  - Color has one junk if si is mutating an element
  - Else color is junk-free
- So no thread gets stuck due to junk
- Theorem: thread stuck only if waiting on lock (can deadlock)



Formalism summary

- One run-time heap (colors and boxes for the proof)
- A trick for making data races a problem
- Straightforward type system for source programs
- Syntactic safety proof requires understanding how the type system imposes structure on the heap...
- ... which was invaluable in understanding, “what’s really going on” especially with spawn

- First proof for a system with thread-local data

Related work

- This work in line of Flanagan, Boyapati, et al.
- Guava (race-free Java, rigid local/shared distinction)
- Bug-finding tools (ESC/Java, Warlock, ...)
- Dynamic race detection (novel code and run-time)

- Other safe low-level languages (CCured, Vault, PCC, TAL, ...) single-threaded

Cannot implement an array-bounds check in the presence of data races

Conclusions

- Data races and safe C do not mix well
- Static support for lock-based mutual exclusion becoming well understood
- Designed and formalized multithreading for Cyclone
- May need more bells and whistles for realistic multithreaded programs
- Implementation high on the to-do list

[End of Presentation – an auxiliary slide follows]

Important extensions (see the paper)

- Parametric polymorphism
  - What locks are needed to access an `` `a ``
  - How do we ensure these locks are acquired while allowing polymorphic code
- Region-based memory management
  - How do we prevent one thread from accessing objects another thread has deallocated
  - Type systems for regions and locks very similar, so what do the differences teach us