Type-Safety, Concurrency, and Beyond: Programming-Language Technology for Reliable Software

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15 February 2005

PL for Better Software

- Software is part of society's critical infrastructure

  Where we learn of security lapses:
  bboards → tech news → business-page → front-page

- PL is uniquely positioned to help. "We own":
  - The build process and run-time
  - Intellectual tools to prove program properties

- But solid science/engineering is key
  - The UMPLFAP* solution is a non-starter
  - Crisp problems and solutions

*Use My Perfect Language For All Programming

Better low-level code

My focus for the last *n* years:

bring type-safety to low-level languages

- For some applications, C remains the best choice (!)
  - Explicit data representation
  - Explicit memory management
  - Tons of legacy code
- But C without the dangerous stuff is too impoverished
  - No arrays, threads, null-pointers, varargs, …
- Cyclone: a safe, modern language at the C-level
  - A necessary but insufficient puzzle piece

Beyond low-level type safety

0. Brief Cyclone overview
   - Synergy of types, static analysis, dynamic checks (example: not-NULL pointers)
   - The need for more (example: data races)
1. Better concurrency primitives (AtomCAML)

Brief plug for:

2. A C-level module system (CLAMP)
3. Better error messages (SEMINAL)

Research that needs doing and needs eager, dedicated, clever people

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
- 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"

Status

Cyclone really exists (except memory-safe threads)

- >150K lines of Cyclone code, including the compiler
  - Compiles itself in 30 seconds
- Targets gcc

  (Linux, Cygwin, OSX, OpenBSD, Mindstorm, Gameboy, …)
- User's manual, mailing lists, …
- Still a research vehicle

Example projects

- Open Kernel Environment [Bos/Samwel, OPENARCH 02]
- MediaNet [Hicks et al, OPENARCH 03]
- RBClick [Patel/Lepreau, OPENARCH 03]
- STP [Patel et al., SOSP 03]
- FPGA synthesis [Teifel/Manohar, ISACS 04]
- Maryland undergrad O/S course (geekOS) [2004]
- Windows device driver (6K lines)

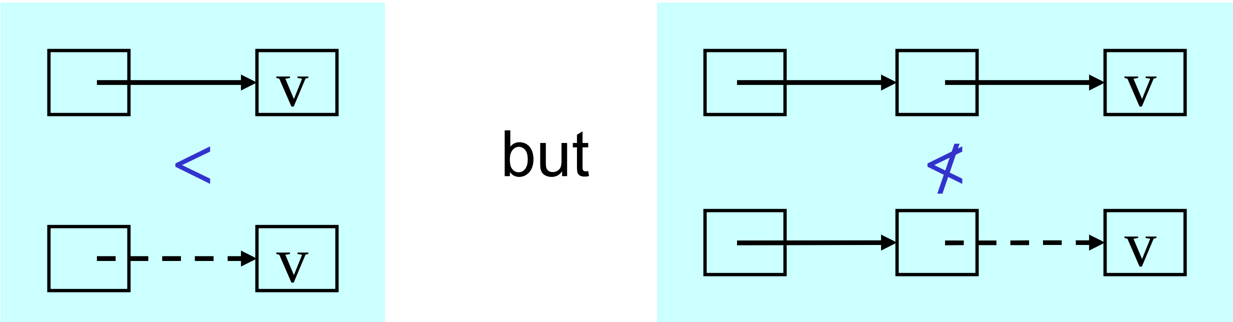
- Always looking for systems projects that would benefit from Cyclone

www.research.att.com/projects/cyclone

Not-null pointers

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

- Subtyping: **t@ < t*** but **t@@ ≮ 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”);
  int c;
  while((c = fgetc(f)) != EOF) {…}
  fclose(f);
}
```

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

A classic moral

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

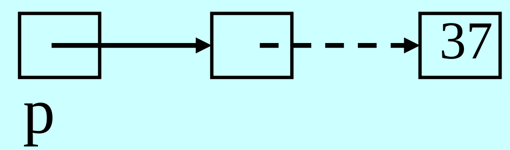
- Richer types make interface stricter
- Stricter interface make implementation easier/faster
- Exposing checks to user lets them optimize
- Can’t check everything statically (e.g., close-once)

Key Design Principles in Action

- Types to express invariants
  - Preconditions for arguments
  - Properties of values in memory
- Flow analysis where helpful
  - Lets users control explicit checks
  - *Soundness* + *aliasing limits usefulness*
- Users control data representation
  - Pointers are addresses unless user allows otherwise
- Often can interoperate with C safely just via types

It’s always aliasing

```
void f(int*@p) {
 if(*p != NULL) {
  g();
  **p = 42;//inserts check
 }
}
```



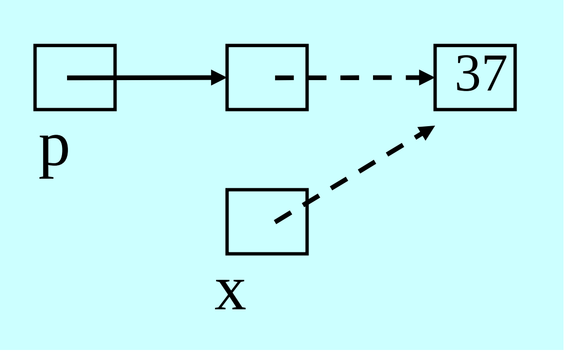
But can avoid checks when compiler knows all aliases.

Can know by:

- Types: precondition checked at call site
- Flow: new objects start unaliased
- Else user should use a temporary (the safe thing)

It’s always aliasing

```
void f(int*@p) {
 int* x = *p;
 if(x != NULL) {
   g();
   *x = 42;//no check
 }
}
```



But can avoid checks when compiler knows all aliases.

Can know by:

- Types: precondition checked at call site
- Flow: new objects start unaliased
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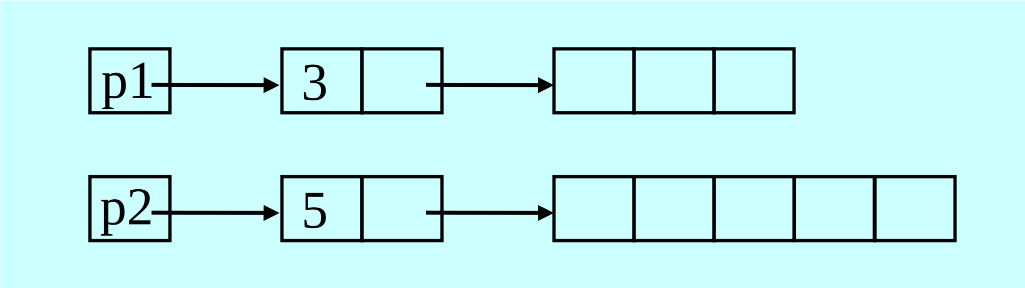
Data-race example

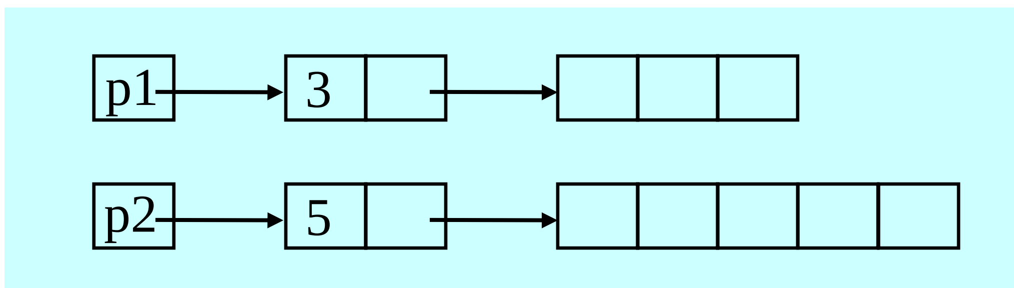
```
struct SafeArr {
  int  len;
  int* arr;
};
```




```
if(p1->len > 4)                 ||  *p1 = *p2;
 (p1->arr)[4] = 42;             ||
```

Data-race example

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




```
if(p1->len > 4)
 (p1->arr)[4] = 42;
```

||

```
*p1 = *p2;
```

change ***p1->len*** *to 5*

change ***p1->arr***

Data-race example

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struct SafeArr {
  int  len;
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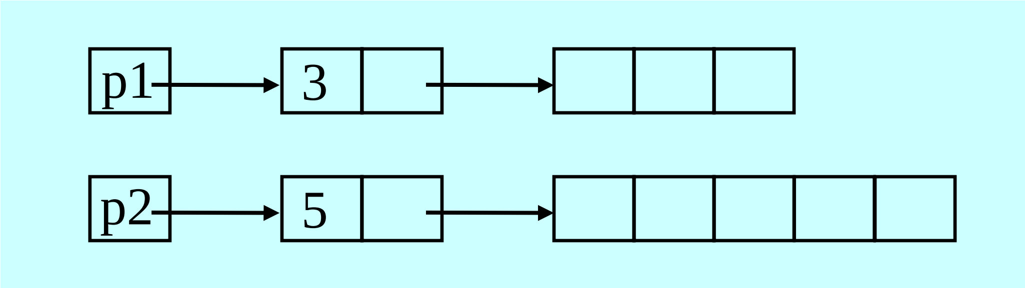
};
```




```
if(p1->len > 4)
  (p1->arr)[4] = 42;
```

||

```
*p1 = *p2;
```

check ***p1->len > 4***

write ***p1->arr[4]*** *XXX*

change ***p1->len*** *to 5*

change ***p1->arr***

Lock types

Type system ensures:

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

- Basic approach for Java found many bugs
  [Flanagan et al, Boyapati et al]

- Adaptation to Cyclone works out
  - See my last colloquium talk (March 2003)
  - But locks are the wrong thing for reliable concurrency

Cyclone summary

Achieving memory safety a key first step, but

1. Locks for memory safety is really weak (applications always need to keep multiple objects synchronized)
   – Solve the problem for high-level PLs first

2. A million-line system needs more modularity than “no buffer overflows”

3. Fancy types mean weird error messages and/or buggy compiler

Good news: 3 new research projects

Atomicity overview

- Why “atomic” is better than mutual-exclusion locks
  - And why it belongs in a language
- How to implement atomic on a uniprocessor
- How to implement atomic on a multiprocessor
  - Preliminary ideas that use locks cleverly

Foreshadowing:

- hard part is efficient implementation
- key is cheap logging and rollback

Threads in PL

- Positive shift: Threads are a C library and a Java language feature
- But: Locks are an error-prone, low-level mechanism that is a poor match for much programming
  - Java programs/libraries full of races and deadlocks
  - Java 1.5 just provides more low-level mechanisms
- Target domain: Apps that use threads to mask I/O latency and provide responsiveness (e.g., GUIs)
  - Not high-performance scientific computing

Atomic

An easier-to-use and harder-to-implement primitive:

```
void deposit(int x){
synchronized(this){
  int tmp = balance;
  tmp += x;
  balance = tmp;
}}
```

semantics:
  lock acquire/release

```
void deposit(int x){
atomic {
  int tmp = balance;
  tmp += x;
  balance = tmp;
}}
```

semantics:
  (behave as if)
  no interleaved execution

No fancy hardware, code restrictions, deadlock, or unfair scheduling (e.g., disabling interrupts)

6.5 ways atomic is better

1. Atomic makes deadlock less common

```
transfer(Acct that,
             int x){
synchronized(this){
synchronized(that){
  this.withdraw(x);
  that.deposit(x);
}}}
```

- Deadlock with parallel "untransfer"
  - Sun JDK had this for buffer append!
- Trivial deadlock if locks not re-entrant
- 1 lock at a time $\Rightarrow$ race with "total funds available"

6.5 ways atomic is better

2. Atomic allows modular code evolution
   – Race avoidance: global object→lock mapping
   – Deadlock avoidance: global lock-partial-order

```
// x, y, and z are
// globals
void foo() {
synchronized(???){
 x.f1 = y.f2+z.f3;
}}
```

- Want to write **foo** to be race and deadlock free
  – What locks should I acquire? (Are y and z immutable?)
  – In what order?

6.5 ways atomic is better

3. Atomic localizes errors

   (Bad code messes up only the thread executing it)

```
void bad1() {
 x.balance = -1000;
}

void bad2(){
 synchronized(lk) {
   while(true) ;
 }
}
```

- Unsynchronized actions by other threads are invisible to atomic
- Atomic blocks that are too long may get starved, but won't starve others
  - Can give longer time slices

6.5 ways atomic is better

4. Atomic makes abstractions thread-safe without committing to serialization

```
class Set { // synchronization unknown
 void insert(int x) {…}
 bool member(int x) {…}
 int size() {…}
}
```

To wrap this with synchronization:

Grab the same lock before any call. But:

- Unnecessary: no operations run in parallel (even if member and size could)
- Insufficient: implementation may have races

6.5 ways atomic is better

5. Atomic is usually what programmers want [Flanagan, Qadeer, Freund]

- Vast majority of Java methods marked **`synchronized`** are actually atomic
- Of those that aren't, vast majority of races are application-level bugs
- **`synchronized`** is an implementation detail
  – does not belong in interfaces (atomic does)!

```
interface I { synchronized int m(); }
class A { synchronized int m() {// an I
             <<call code with races>>
          }}
class B { int m() { return 3; }}// not an I
```

6.5 ways atomic is better

6. Atomic can efficiently implement locks

```
class Lock {
  bool b = false;
  void acquire() {
    while(true) {
      while(b) /*spin*/;
      atomic {
       if(b) continue;
       b = true;
       return; }
    }
  }
  void release() {
   b = false;
  }
}
```

- Cute O/S homework problem
- In practice, implement locks like you always have
- Atomic and locks peacefully co-exist
  - Use both if you want

6.5 ways atomic is better

6.5 Concurrent programs have the granularity problem:

- Too little synchronization:

  non-determinism, races, bugs
- Too much synchronization:

  poor performance, sequentialization

Example: Should a chaining hashtable have one lock, one lock per bucket, or one lock per entry?

`atomic` doesn't solve the problem, but makes it easier to mix coarse-grained and fine-grained operations

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Interleaved execution

The "uniprocessor" assumption:

Threads communicating via shared memory don't execute in "true parallel"

Actually more general than uniprocessor: threads on different processors can pass messages

An important special case:

- Many language implementations make this assumption
- Many concurrent apps don't need a multiprocessor (e.g., a document editor)
- If uniprocessors are dead, where's the funeral?

Implementing atomic

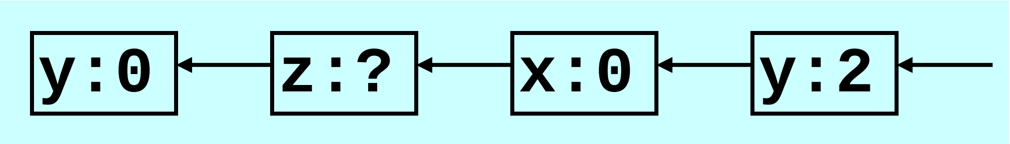
Key pieces:

- Execution of an atomic block logs writes
- If scheduler pre-empts a thread in an atomic block, rollback the thread
- Duplicate code so non-atomic code is not slowed down by logging/rollback
- In an atomic block, buffer output and log input
  - Necessary for rollback but may be inconvenient

Logging example

```
int x=0, y=0;
void f() {
  int z = y+1;
  x = z;
}
void g() {
  y = x + 1;
}
void h() {
  atomic {
    y = 2;
    f();
    g();
  }
}
```

- Executing atomic block in **h** builds a LIFO log of old values:

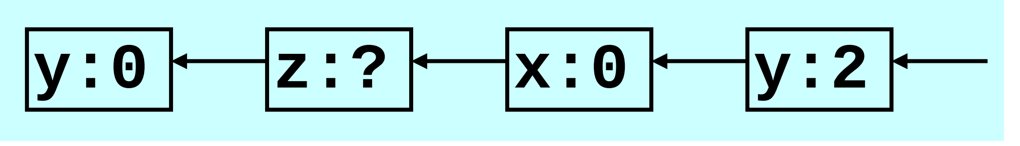


Rollback on pre-emption:

- Pop log, doing assignments
- Set program counter and stack to beginning of atomic

On exit from atomic: drop log

Logging efficiency



Keeping the log small:

- Don't log reads (key uniprocessor optimization)
- Don't log memory allocated after atomic was entered (in particular, local variables like **`z`**)
- No need to log an address after the first time
  - To keep logging fast, only occasionally "trim"
- Tell programmers non-local writes cost more

Keeping logging fast: Simple resizing or chunked array

Duplicating code

```
int x=0, y=0;
void f() {
  int z = y+1;
  x = z;
}
void g() {
  y = x + 1;
}
void h() {
  atomic {
    y = 2;
    f();
    g();
  }
}
```

Duplicate code so callees know to log or not:

- For each function **`f`**, compile **`f_atomic`** and **`f_normal`**
- Atomic blocks and atomic functions call atomic functions
- Function pointers (e.g., vtables) compile to pair of code pointers

Cute detail: compiler erases any atomic block in **`f_atomic`**

Qualitative evaluation

- Non-atomic code executes unchanged
- Writes in atomic block are logged (2 extra writes)
- Worst case code bloat of 2x

- Thread scheduler and code generator must conspire

- Still have to deal with I/O
  - Atomic blocks probably shouldn't do much

Handling I/O

- Buffering sends (output) is easy and necessary
- Logging receives (input) is easy and necessary
  - And may as well rollback if the thread blocks
- But may miss subtle non-determinism:

```
void f() {
 write_file_foo(); // flushed?
 read_file_foo();
}
void g() {
  atomic {f();} // read won't see write
  f();          // read may   see write
}
```

- Alternative: receive-after-send-in-atomic throws exception

Prototype

- AtomCAML: modified OCaml bytecode compiler
- Advantages of mostly functional language
  - Fewer writes (don’t log object initialization)
  - To the front-end, **`atomic`** is just a function

```
atomic : (unit -> ’a) -> ’a
```

- Key next step: port applications that use locks
  - Planet active network from UPenn
  - MetaPRL logical framework from CalTech

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A multiprocessor approach

- Give up on zero-cost reads
- Give up on safe, unsynchronized accesses
  - All shared-memory access must be within atomic (conceptually; compiler can insert them)
- But: Try to minimize inter-thread communication

Strategy: Use locks to implement **`atomic`**

- Each *shared* object guarded by a readers/writer lock
  - Key: many objects can share a lock
- Logging and rollback to prevent deadlock

Example redux

```
int x=0, y=0;
void f() {
  int z = y+1;
  x = z;
}
void g() {
  y = x + 1;
}
void h() {
  atomic {
    y = 2;
    f();
    g();
  }
}
```

- Atomic code acquires lock(s) for **x** and **y** (1 or 2 locks)
- Release locks on rollback or completion
- Avoid deadlock automatically. Possibilities:
  - Rollback on lock-unavailable
  - Scheduler detects deadlock, initiates rollback
- Only 1 problem…

What locks what?

There is little chance any compiler in my lifetime will infer a decent object-to-lock mapping

- More locks = more communication
- Fewer locks = less parallelism

What locks what?

There is little chance any compiler in my lifetime will infer a decent object-to-lock mapping

- More locks = more communication
- Fewer locks = less parallelism
- Programmers can't do it well either, though we make them try

What locks what?

There is little chance any compiler in my lifetime will infer a decent object-to-lock mapping

When stuck in computer science, use 1 of the following:

a. Divide-and-conquer
b. Locality
c. Level of indirection
d. Encode computation as data
e. An abstract data-type

Locality

Hunch: Objects accessed in the same atomic block will likely be accessed in the same atomic block again

- So while holding their locks, change the object-to-lock mapping to share locks
  - Conversely, detect false contention and break sharing
- If hunch is right, future atomic block acquires fewer locks
  - Less inter-thread communication
  - And many papers on heuristics and policies ☺

Related Work on Atomic

Old ideas:

- Transactions in databases and distributed systems
  - Different trade-offs and flexibilities
- Rollback for various recoverability needs
- Atomic sequences to implement locks [Bershad et al]
- Atomicity via restricted sharing [ARGUS]

Rapid new progress:

- Atomicity via shadow-memory & versioning [Harris et al]
- Checking for atomicity [Qadeer et al]
- Transactional memory in SW [Herlihy et al] or HW [tcc]

PLDI03, OOPSLA03, PODC03, ASPLOS04, …

Beyond low-level type safety

0. Brief Cyclone overview
   – Synergy of types, static analysis, dynamic checks
   – The need for more
1. Better concurrency primitives

Brief plug for:

2. A C-level module system (CLAMP)
3. Better error messages (SEMINAL)

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Clamp

Clamp is a C-like Language for Abstraction, Modularity, and Portability (it holds things together)

Go beyond Cyclone by *using a module system to encapsulate low-level assumptions*, e.g.,:

- Module X assumes big-endian 32-bit words
- Module Y uses module X
- Do I need to change Y when I port?

(Similar ideas in Modula-3 and Knit, but no direct support for the data-rep levels of C code.)

Clamp doesn’t exist yet; there are many interesting questions

Error Messages

What happens:

1. A researcher implements an elegant new analysis in a compiler that is great for correct programs.
2. But the error messages are inscrutable, so the compiler gets hacked up:
   - Pass around more state
   - Sprinkle special cases and strings everywhere
   - Slow down the compiler
   - Introduce compiler bugs

Recently I fixed a dangerous bug in Cyclone resulting from not type-checking **`e->f`** as **`(*e).f`**

A new approach

- One solution: 2 checkers, trust the fast one, use the other for messages
  - Hard to keep in sync; slow one no easier to write
- SEMINAL*: use fast one as a subroutine for *search:*
  - Human speed (1-2 seconds)
  - Find a similar term (with holes) that type-checks
    - Easier to read than types
    - Offer multiple ranked choices
- Example: "**`f(e1,e2,e3)`** doesn't type-check, but **`f(e1,_,e3)`** does and **`f(e1,e2->foo,e3)`** does"
- Help! (PL, compilers, AI, HCI, …)

*Searching for Error Messages in Advanced Languages

Summary

- We must make it easier to build large, reliable software
  - Current concurrency technology doesn’t
  - Current modules for low-level code doesn’t
  - Type systems are hitting the error-message wall

- Programming-languages research is fun
  - Ultimate blend of theory and practice
  - Unique place in “tool-chain control”
  - Core computer science with much work remaining

Acknowledgments

- Cyclone is joint work with Greg Morrisett (Harvard), Trevor Jim (AT&T Research), Michael Hicks (Maryland)
  - Thanks: Ben Hindman for compiler hacking
- Atomicity is joint work with Michael Ringenburg
  - Thanks: Cynthia Webber for some benchmarks
  - Thanks: Manuel Fähndrich and Shaz Qadeer (MSR) for motivating us

- For updates and other projects:

  www.cs.washington.edu/research/progsys/wasp/