Memory Safety in Systems Languages

Major Area Exam

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June 11, 2018

Committee:

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Outline

Motivation

What is a System?

Infrastructure software upon which applications are built

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Operating Systems

- Process abstraction
- Multiplex physical hardware resources
- Partition and abstract **memory**

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- Memory errors become type errors, management happens at compile-time

Outline

- Motivation
- Spatial Safety
  - Fat Pointers and Shadow Structures
  - Referent Objects
  - Dependent Types
- Temporal Safety
  - Capabilities and Locks
  - Effects and Regions
  - Linear Types and Ownership

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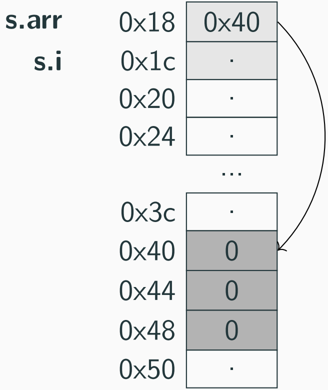

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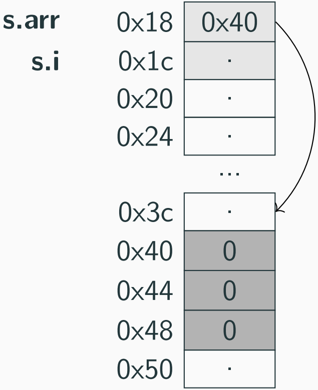

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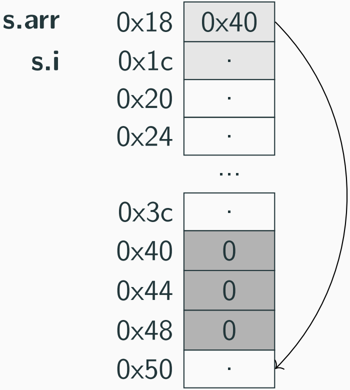

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Some approaches:

- Fat Pointers and Shadow Structures
- Referent Objects
- Dependent Types

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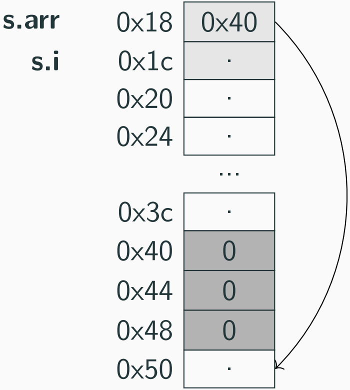

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Potential pointer dereference problems:

- Null
- Uninitialized
- Out-of-bounds
- Manufactured

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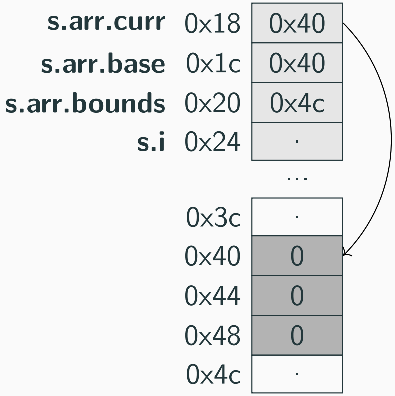

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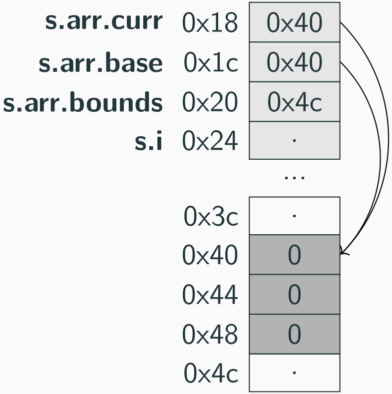

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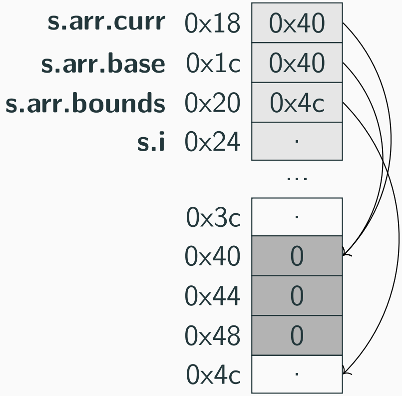

Fat Pointer Approaches

SafeC[1]:

- Safe pointers have value, base, and size
- Complete spatial safety, if transparent storage management and no safe pointer attribute manipulation
- 275% space overhead, 2-6x runtime overhead, 0.35-3x code size overhead
- Some static optimization based on still-valid previous checks

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Cyclone[2]:

- Annotations for non-array vs array pointers (can specify size)
- Tagged unions and automatic tag injection

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CCured[3]

- Separate pointers on usage (SAFE, SEQ, WILD)
- Whole-program inference to find as many SAFE then SEQ pointers as possible
- Reduce WILD pointers[4] using physical subtyping[5] for upcasts
- Special pointer RTTI carrying runtime type for downcasts

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Fail-Safe C[6]:

- Combines fat pointers w/ fat integers and virtual structure offsets

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7           assert(p.base != 0 &&
8                  0 <= p.cur &&
9                  p.cur < p.bound);
10          if (*p.cur == token) break;
11          p.cur = p.cur + (1 * sizeof(int));
12          p.base  = p.base;   // optimized out
13          p.bound = p.bound;  // "           "
14      }
15      ...(repeat lines 7-9)...
16      return (*p.cur == token);
17  }
```

Pointer-Based – Shadow Structures

MSCC[7]

[7] Xu, DuVarney, and Sekar, "An Efficient and Backwards-compatible Transformation to Ensure Memory Safety of C Programs", 2004.

Pointer-Based – Shadow Structures

MSCC[7]

- *Split* metadata from pointer, preserving layout
- Every value has linked shadow structure mirroring entire data structure
- Transform every function call to take additional metadata parameters
- Wrappers for external functions; cannot detect memory errors

[7] Xu, DuVarney, and Sekar, "An Efficient and Backwards-compatible Transformation to Ensure Memory Safety of C Programs", 2004.

Shadow Structures Example

```c




int find_token(
  int *data,
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struct ptr_info {
    void *base;
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  int *data, ptr_info *data_info,
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{
    int *p = data;
    ptr_info  p_info = *data_info;
    while (p < end) {
        CHECK_SPATIAL(p, sizeof(*p), p_info);
        if (*p == token) break;
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Referent Objects

Objects[8,9]

- Metadata about objects, not pointers

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- 2-12x overhead

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Advantages:

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Disadvantages:

- Special mechanisms to handle legal OOB pointers
- Splay-tree object lookup overhead
- Incomplete spatial safety: sub-object overflows

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The Sub-Object Problem

```
struct node {char str[3]; void (*func)(); };
struct node *n = (struct node *) malloc(sizeof(node));
char *s = n.str;
strcpy(s, "bad!");
```

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- `n` and `s` have the same address ⇒ map to same object in global database
- `strcpy` will see `s`'s size as that of `n`

Referent Objects Approaches

SafeCode[10]

- Use automatic pool allocation (APA)[11]
- Use separate, smaller data structures to store bounds metadata for each partition
- 1.2x overhead

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Baggy Bounds Checking (BBC)[12]

- Compact bounds representation and efficient way to look up object bounds
- Align base addresses to be multiple of padded size
- Replace splay tree with small lookup table
- 0.6x overhead

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{
    int *p = data;
    while (p < end) {
        if (*p == token) break;
        int *q = p + 1;
        int size = 1 << TABLE[p>>4];
        int base = p & ~(size - 1);
        assert(q >= base && q - base < size);
        p++;
    }
    return (*p == token);
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Softbound

Softbound[13]

- Base and bound metadata for each pointer, stored in disjoint metadata table

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- Arbitrary casts allowed
- 67% overhead

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Outline

Dependent Types

Dependent types are *typed-valued functions*[14]

[14]Pierce, *Advanced topics in types and programming languages*, 2005.

[15]Martin-Löf, "Constructive mathematics and computer programming", 1984.

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$$\texttt{Vector} : \texttt{Nat} \to \texttt{Type} \to \texttt{Type}$$

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\texttt{(cons 'a' (cons 'b' nil))} &: \texttt{Vector 2 Char}
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- Based on type theory work by Martin-Löf[15]
- Undecidability of type checking: arbitrary computation to check type equality
- Work on defining equality and restricting forms of index terms

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Early Uses of Dependent Types

Dependent ML[16] and Cayenne[17]

- Reduce static array bound checking to constraint satisfiability
- DML uses *indexed types*: limit indices to linear integer and boolean expressions; compile-time decidable
- Cayenne has *no restrictions* on types: undecidability of arbitrary expression equivalence and thus type checking

Xanadu[18]

- Imperative environment
- Restrict index expressions in types to integer constraint domain

[16] Xi and Pfenning, "Eliminating Array Bound Checking Through Dependent Types", 1998.

[17] Augustsson, "Cayenne—a Language with Dependent Types", 1998.

[18] Xi, "Imperative programming with dependent types", 2000.

Dependent Types in Imperative Languages

SafeDrive[19] and Deputy[20,21]

- User-added annotations relating pointers to bounds

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SafeDrive[19] and Deputy[20,21]

- User-added annotations relating pointers to bounds
  - `safe`, `sentinel`, `count(n)`, `bound(lo,hi)`
  - Use constants/variables/field names in immediately enclosing scope
- Three-phase pass over annotated C programs, emits C code
  1. Automatic addition of bounds annotations for pointer types
  2. Flow-insensitive type checking (insert run-time checks; helps decidability)
  3. Flow-sensitive check optimization
- More C Support with dependent union tags , Safe TinyOS[22]

---

[19] Zhou et al., "SafeDrive", 2006.

[20] Condit et al., "Dependent Types for Low-Level Programming", 2007.

[21] Anderson, "Static Analysis of C for Hybrid Type Checking", 2007.

[22] Cooprider et al., "Efficient Memory Safety for TinyOS", 2007.

Deputy Example for Spatial Safety

```c
int find_token(int *data,
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Abstract Syntax, For Your Consideration

$x, y \in \text{Variables} \quad \text{op} \in \text{Binary ops} \quad n \in \text{Integers} \quad \text{comp} \in \text{Comparison Ops}$

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\begin{array}{rrcl}
\textit{Ctors} & C & ::= & \text{int} \mid \text{ref} \mid \text{array} \\
\textit{Types} & \tau & ::= & C \mid \tau_1\ \tau_2 \mid \tau\ e \\
\textit{L-exprs} & l & ::= & x \mid *\,e
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\begin{array}{rrcl}
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\textit{Cmds} & c & ::= & l := e \mid \text{assert}(\gamma) \mid c_1 ; c_2 \mid \ldots \\
\text{Preds} & \gamma & ::= & e_1\ \text{comp}\ e_2 \mid \text{true} \mid \gamma_1 \wedge \gamma_2
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The Interesting Rules

Dereferencing

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Arithmetic

$$\frac{\Gamma \vdash e : \mathsf{array}\ \tau\ e_{len} \Rightarrow \gamma_e \qquad \Gamma \vdash e' : \mathsf{int} \Rightarrow \gamma_{e'}}{\Gamma \vdash e + e' : \mathsf{array}\ \tau\ (e_{len} - e') \Rightarrow \gamma_e \wedge \gamma'_e \wedge (0 \leqslant e' \leqslant e_{len})}\ (\textsc{array arith})$$

Dependent Types in Imperative Languages

Týr[23]

- Augments LLVM IR with dependent pointer types
- Uses programmer annotations insert run-time bounds checks
- LLVM optimizations remove always-true checks; error if always-false

[23] De Araújo, Moreira, and Machado, "Týr", 2016.

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[25] Protzenko et al., "Verified Low-level Programming Embedded in F*", 2017.

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Checked C[24]

- Extend C with two *checked pointer types*: `_Ptr<T>` and `_Array_ptr<T>`
- Associated bounds expressions indicating where bounds are stored
- Isolate (un)safe code with *checked code regions*

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Low*[25]

- DSL for verified, efficient low-level programming in F*
- Write F* syntax against library modelling lower-level view of C memory

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Quick Spatial Recap

Spatial Safety

- Arrays and pointers

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Quick Spatial Recap

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- Arrays and pointers
- Fat pointers
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- Dependent types

Outline

Temporal Safety

Prevent accessing object that has been previously deallocated

Temporal Safety

Prevent accessing object that has been previously deallocated

- Capabilities and locks
- Effects and regions
- Linear types and ownership

Temporal Safety Example

```
int attach(struct sock *sk) {
    if (sk->bad) {
        free(sk); return 1;
    }
    return 0;
}
void mq_notify(sigevent *n) {
    struct sock_t *sock;
    while (n->try) {
        sock = malloc_sock(n->info);
        if (attach(sock)){
            //sock = NULL;
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- Double frees
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Goals:

- Good: Detecting use-after-free
- Better: Eliminating free entirely

A Comment on Garbage Collection

Garbage collection

[26] Boehm and Weiser, "Garbage Collection in an Uncooperative Environment", 1988.

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- Relinquish control of object location and layout to runtime

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  - Reduced reference locality, increased page fault/cache miss rates
- Some spatial approaches (e.g. Fail-Safe C, CCured) use Boehm-Demers-Weister[26]

[26] Boehm and Weiser, "Garbage Collection in an Uncooperative Environment", 1988.

Outline

Capabilities and Locks

[27] Nagarakatte, Zhao, Milo M.K. Martin, et al., “CETS”, 2010.

[28] Nagarakatte, M. M. K. Martin, and Zdancewic, “Everything You Want to Know About Pointer-Based Checking”, 2015.

[29] Simpson and Barua, “MemSafe”, 2013.

Capabilities and Locks

- SafeC, MSCC
  - Unique capability associated with each memory block
  - Stored in capability store, marked invalid on free
  - Check if pointer's capability copy is still valid on dereference

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- SafeC, MSCC
  - Unique capability associated with each memory block
  - Stored in capability store, marked invalid on free
  - Check if pointer's capability copy is still valid on dereference
- CETS[27,28]
  - Each allocation has unique (never reused) key and lock address
  - Freeing allocated object changes value at lock location, so key and lock value don't match

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- Memsafe[29]
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int attach(struct sock *sk,
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    if (sk_key != *sk_lock_addr)
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        if (Freeable_ptrs_map.lookup(sk_key) != sk)
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Outline

Effects

Effect types describe the *effects* of the computation leading to a value[30]

- Opening a file
- Modifying an object

[30]Pierce, *Advanced topics in types and programming languages*, 2005.

Effects

Fluent Languages,[31] MFX[32]

- Mix functional and imperative languages

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$\{W\ R^?\ A^?\}$ Procedure

$\{R\ A^?\}$ Observer

$\{A\}$ Function

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E.g.

- `update` is Procedure
- `nth` is Observer
- `arrayCreate` is Function
- `length` is Pure

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Type and Effect Systems[33]

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Region-Based Memory Managememt

Regions[34]

- Divide heap into stack of sub-heaps (i.e. regions)

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- Unreasonable object lifetimes due to LIFO ordering of region lifetimes

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Early Use of Regions

Capability Calculus[35]

- Arbitrarily-ordered region allocation/deallocation, via capability tracking
- Capability: set of regions presently valid to access

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Also see:

- RC[36]
- Reaps[37]
- Control-C[38] and Type Homogeneity[39]

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Cyclone,[40] again!

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- Sane defaults by inferring region annotations on pointer types

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- Function effect: set of regions it might access
- Calculate function's effect from prototype alone

Regions in Cyclone

- Pointer can escape scope of their regions
- Type system tracks capability (live regions set)
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```
struct Set<α, ρ, ϵ>
{
  list_t<α, ρ> elts;
  int (*cmp)(α,α; ϵ);
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```

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struct Set<α, ρ, ε>
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```
struct Set<α, ρ>
{
  list_t<α, ρ> elts;
  int (*cmp)(α,α; regions_of(α));
}
```

Some Cyclone Abstract Syntax

kinds	κ	$::= T \mid R$
type and region vars	α, ρ	
region sets	ϵ	$::= \emptyset \mid \alpha \mid \epsilon_1 \cup \epsilon_2$
region constraints	γ	$::= \emptyset \mid \gamma, \epsilon <: \rho$
constructors	τ	$::= \alpha \mid \mathsf{int} \mid \tau_1 \xrightarrow{\epsilon} \tau_2 \mid \tau @ \rho \mid \mathsf{handle}(\rho) \mid \forall \alpha : \kappa \rhd \gamma.\tau \mid \ldots$
expressions	e	$::= x_\rho \mid v \mid e \langle \tau \rangle \mid * e \mid \mathbf{new}(e_1) e_2 \mid e_1(e_2) \mid \& e \mid \ldots$
functions	f	$::= \rho : (\tau_1\ x_\rho) \xrightarrow{\epsilon} \tau_2 = \{s\} \mid \Lambda \alpha : \kappa \rhd \gamma.f$
statements	s	$::= e \mid s_1 ; s_2 \mid \mathbf{if}\ (e)\ s_1\ \mathbf{else}\ s_2 \mid \rho : \{\tau\ x_\rho = e;\ s\} \mid \mathbf{region}\langle\rho\rangle\ x_\rho\ s \mid \ldots$
	$\ldots$	

Example Cyclone Judgments

$\Delta; \Gamma; \gamma; \epsilon; \tau \vdash_{stmt} s$

$\Delta; \Gamma; \gamma; \epsilon \vdash e : \tau$

$\Gamma \vdash \epsilon \Rightarrow \rho$

Example Cyclone Judgments

$\Delta; \Gamma; \gamma; \epsilon; \tau \vdash_{stmt} s$ $\quad\quad$ $\Delta; \Gamma; \gamma; \epsilon \vdash e : \tau$ $\quad\quad$ $\Gamma \vdash \epsilon \Rightarrow \rho$

Δ : in-scope type/region vars

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$$\frac{\gamma \vdash \epsilon \Rightarrow \rho}{\Delta; \Gamma; \gamma; \epsilon \vdash x_\rho : \Gamma(x_\rho)} \ (\textsc{var}) \qquad \frac{\Delta; \Gamma; \gamma; \epsilon \vdash e : \tau * \rho \qquad \gamma \vdash \epsilon \Rightarrow \rho}{\Delta; \Gamma; \gamma; \epsilon \vdash *e : \tau} \ (\textsc{deref})$$

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Cyclone Results

Soundness Theorem[41]:

- The program cannot get stuck from type errors or dangling-pointer dereferences.
- The terminating program deallocates all regions it allocates

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Benchmarks

- 86 lines of region annotation-related changes across 18,000 lines (6%)
- Eliminate heap allocation entirely for web-server
- Near-zero overhead (from garbage collection and bounds checking)

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Outline

Linear Types

Linear types[42,43] ensure that every variable is used exactly *once*.

- The world is a non-duplicatable resource

[42] Girard, "Linear logic", 1987.

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- **Memory management: can immediately collect used values**

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Applied Linear Types

Clay[44]

- Type-theoretic basis for giving type-safe code more control over memory
- Singleton types to type check loads, coercion functions to modify values' type safely

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Clay[44]

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PACLANG[45]

- Program network processors for handling packets
- Unique ownership property: each packet in heap is referenced by exactly one thread
- Allow mutable aliasing within the same thread
- Operations for a functions to 1) take ownership or 2) create local aliases

[44] Hawblitzel et al., "Low-Level Linear Memory Management", 2004.

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COGENT

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- Missing functionality can be implemented in C, manually verified
- No trusted compiler, runtime, or garbage collector needed

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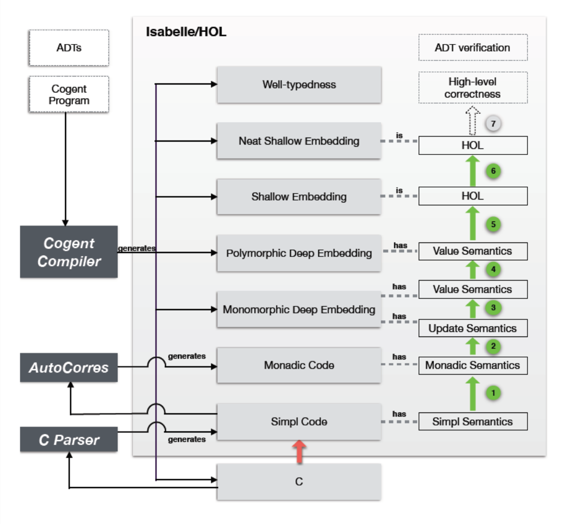

ADTs
Cogent Program
Cogent Compiler
generates
AutoCorres
C Parser
Isabelle/HOL
Well-typedness
Neat Shallow Embedding
Shallow Embedding
Polymorphic Deep Embedding
Monomorphic Deep Embedding
generates
Monadic Code
Simpl Code
generates
C
ADT verification
High-level correctness
7
is
HOL
6
is
HOL
5
has
Value Semantics
4
has
Value Semantics
3
has
Update Semantics
2
has
Monadic Semantics
1
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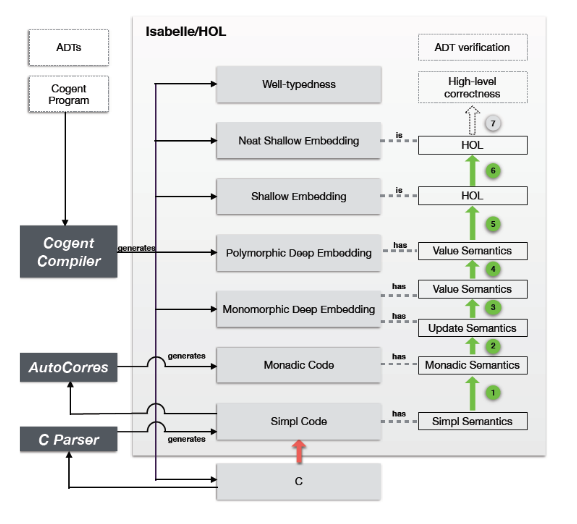

Person-Months of Work

- Proof Framework: 33.5
- Compiler: 10
- Proofs: 18

Lines (kLOC)

- Isabelle theorems: 17
- Compiler: 9.5
- ext2 Filesystem: 6.5 (Isabelle/HOL: 76.7)

Other Linear Types

Quasi-linear types[48]

- Distinguish consumed values from those that may be returned
- Use κ to control how often a variable of type τ^κ is used (many times locally)

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- Keys associate static capabilities with run-time resources
- Annotate functions with effect clause (pre- and post-conditions on held-key set)
- Windows 2000 locking errors, IRP ownership model

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Ordered types for memory layout[50]

- Variables must be used in order $\Rightarrow$ memory locations
- *Orderly lambda calculus* for size-preserving memory operations

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Ownership

Types can represent ownership and prevent *aliasing* and *mutation* on the same location.

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Singularity[53]

- Type system tracks resources, passes ownership of arguments to callee

---

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Rust[54,55,56]

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let (snd, rcv) = channel();
join(move || {
      let mut v = Vec::new();
      v.push(0);
      snd.send(v);
      v.push(1);
    },
    move || {
      let v = rcv.recv().unwrap();
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Quick Temporal Recap

- Capabilities and pointer-based metadata

Quick Temporal Recap

- Capabilities and pointer-based metadata
- Effects and regions

Quick Temporal Recap

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Thanks

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