# Memory Safety in Systems Languages

## Major Area Exam

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**Committee:**

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# Outline

# Motivation

# What is a System?

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

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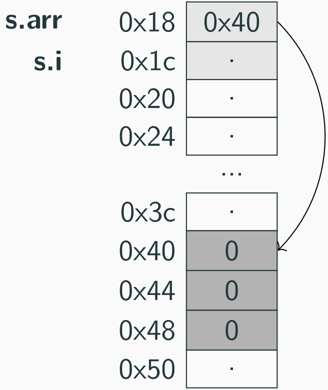

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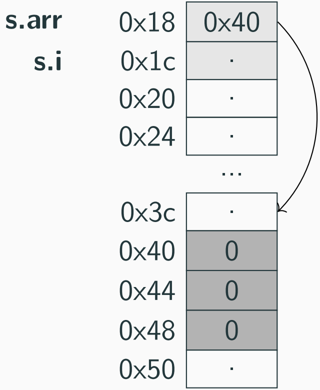

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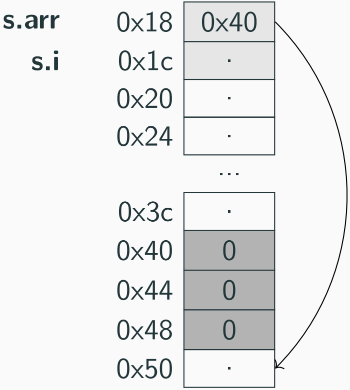

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Some approaches:

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

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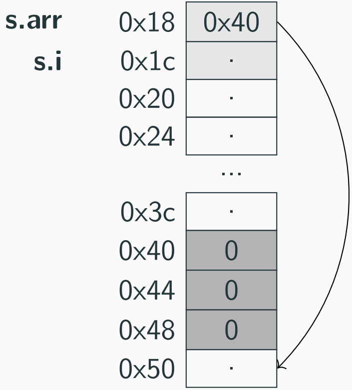

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Potential pointer dereference problems:

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

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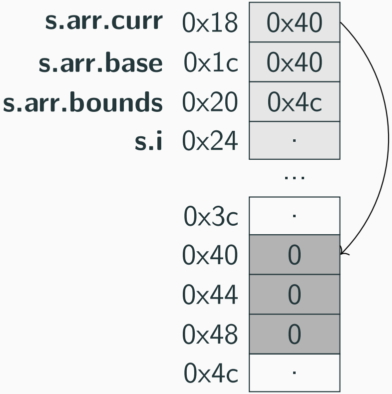

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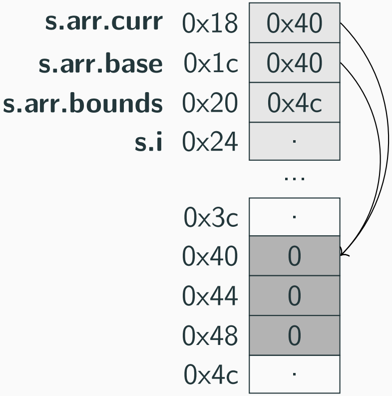

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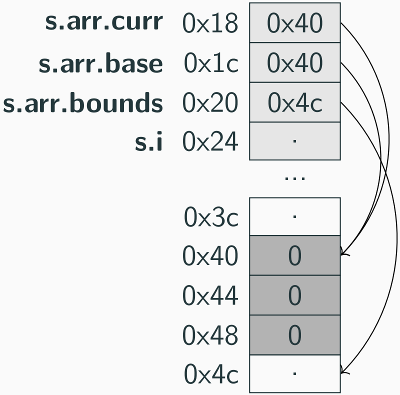

# Fat Pointer Approaches

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
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6       while (p.cur < end) {
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

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int find_token(
  int *data,
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struct ptr_info {
    void *base;
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{
    int *p = data;
    ptr_info  p_info = *data_info;
    while (p < end) {
        CHECK_SPATIAL(p, sizeof(*p), p_info);
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## Objects[8,9]

- Metadata about objects, not pointers

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Advantages:

- Compatible with uninstrumented code

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 *q = p + 1;
        int size = 1 << TABLE[p>>4];
        int base = p & ~(size - 1);
        assert(q >= base && q - base < size);
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# Softbound

Softbound[13]

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

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- 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.

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

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

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

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

# Dependent Types in Imperative Languages

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.

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## Deputy Example for Spatial Safety

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int find_token(int *data,
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    int *p = data;
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        if (*p == token) break;

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# Abstract Syntax, For Your Consideration

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

$$\begin{array}{rl} \textit{Ctors} & C ::= \text{int} \mid \text{ref} \mid \text{array} \\ \textit{Types} & \tau ::= C \mid \tau_1\ \tau_2 \mid \tau\ e \\ \textit{L-exprs} & l ::= x \mid *\ e \end{array}$$

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$$\frac{\Gamma \vdash e : \text{array } \tau \;\; e_{len} \Rightarrow \gamma_e}{\Gamma \vdash *e ; \tau \Rightarrow \gamma_e \wedge (0 < e_{len})} \text{ (ARRAY DEREF)}$$

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Arithmetic

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

## 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.

[24] Ruef et al., "Checked C for Safety, Gradually", 2017.

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Checked C[24]

- Extend C with two *checked pointer types*: `_Ptr<T>` and `_Array_ptr<T>`
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Low*[25]

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# Quick Spatial Recap

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# Outline

# Temporal Safety

Prevent accessing object that has been previously deallocated

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

# Temporal Safety Example

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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)){
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    if (sock) free(sock);
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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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  - Loss of real-time guarantees/predictability
  - 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
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- Memsafe[29]
  - Set bounds of deallocated pointer to invalid value

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

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

$\{A\}$ $\boxed{\text{Function}}$

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

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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]

- Extend the simply-typed lambda calculus with annotations

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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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## Regions in Cyclone

- Pointer can escape scope of their regions

# Regions in Cyclone

- Pointer can escape scope of their regions
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struct Set<α, ρ, ε>
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struct Set<α, ρ>
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# Some Cyclone Abstract Syntax

| | | | |
|---|---|---|---|
| kinds | $\kappa$ | $::=$ | $T \mid R$ |
| type and region vars | $\alpha, \rho$ | | |
| region sets | $\epsilon$ | $::=$ | $\emptyset \mid \alpha \mid \epsilon_1 \cup \epsilon_2$ |
| region constraints | $\gamma$ | $::=$ | $\emptyset \mid \gamma, \epsilon <: \rho$ |
| constructors | $\tau$ | $::=$ | $\alpha \mid \mathsf{int} \mid \tau_1 \xrightarrow{\epsilon} \tau_2 \mid \tau @ \rho \mid \mathsf{handle}(\rho) \mid \forall \alpha : \kappa \rhd \gamma . \tau \mid \ldots$ |
| 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 | $s$ | $::=$ | $e \mid s_1 ; s_2 \mid \mathbf{if}\ (e)\ s_1\ \mathbf{else}\ s_2 \mid \rho : \{\tau\ x_\rho = e;\ s\} \mid \mathbf{region}\langle \rho \rangle\ x_\rho\ s \mid \ldots$ |

…

# Example Cyclone Judgments

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

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## Cyclone Results

Soundness Theorem[41]:

- The program cannot get stuck from type errors or dangling-pointer dereferences.
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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

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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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- 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

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

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## COGENT

COGENT[46,47]

- Pure, polymorphic language with linear types for writing low-level systems code

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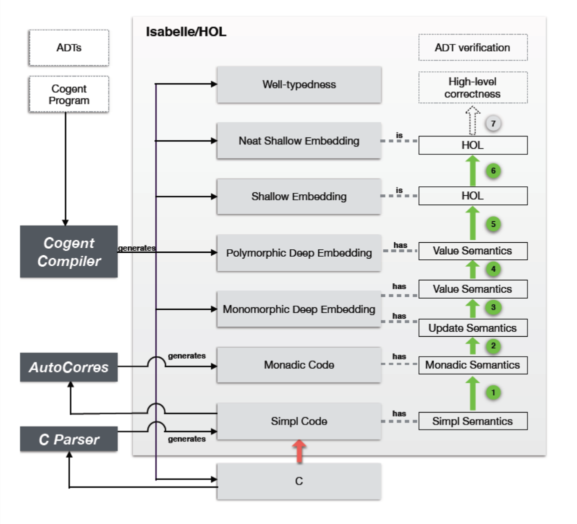

ADTs
Cogent Program
Isabelle/HOL
ADT verification
High-level correctness
Well-typedness
Neat Shallow Embedding
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Monomorphic Deep Embedding
Monadic Code
Simpl Code
C
Cogent Compiler
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generates
is
has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

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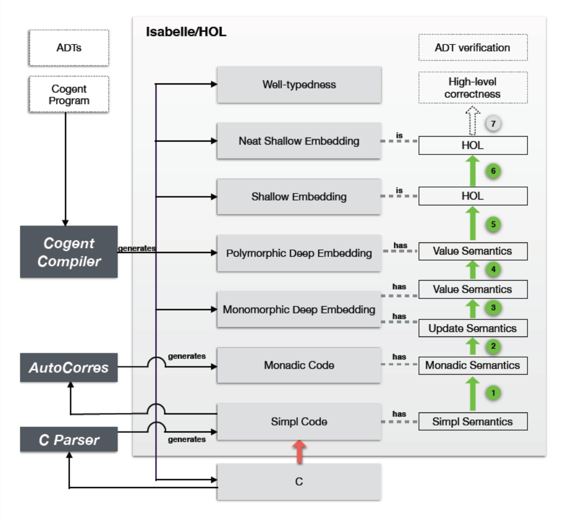


Person-Months of Work

- 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 $\kappa$ to control how often a variable of type $\tau^\kappa$ is used (many times locally)

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- Annotate functions with effect clause (pre- and post-conditions on held-key set)
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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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Singularity[53]

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

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let (snd, rcv) = channel();
join(move || {
        let mut v = Vec::new();
        v.push(0);
        snd.send(v);
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    move || {
        let v = rcv.recv().unwrap();
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[55] Levy et al., "Ownership is Theft", 2015.

[56] Jung et al., "RustBelt", 2017.

# Rust[54,55,56]

- Ownership and lifetimes
- Type system enforces that objects have unique owners
- Objects may be borrowed for no longer than owner
- Object automatically deallocated when owner leaves scope
- Unsafe sections for mutating raw pointers and aliased state
- Regions ≈ lifetimes (region capabilities ≈ lifetime tokens)

```
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();
      println!("Received: {:?}", v);
    });
```

[54] Matsakis and Klock, "The Rust Language", 2014.

[55] Levy et al., "Ownership is Theft", 2015.

[56] Jung et al., "RustBelt", 2017.

# Quick Temporal Recap

- Capabilities and pointer-based metadata

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- Effects and regions

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- Capabilities and pointer-based metadata
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# Conclusion

- Memory errors $\equiv$ *type errors*

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# Conclusion

- Memory errors $\equiv$ *type errors*
- *Static* memory management
- Isolate unsafe world
- Be reasonable and optimistic

# Thanks

Thanks!

# Referent Objects Approaches

J&K[57]

- Maintain table of all known valid storage objects
- Map a ptr to a desciptor of the object into which it points
- Pad objects w/ extra byte
- check ptr arith and use, b/c result cannot refer to diff object from one from which it is originally derived
- object for which the ptr is valid is only determined by checking ptr itself, looking it up in object table
- Incomplete because cannot pad parameters, would change layout
- 11-12x overhead

CRED[58]

- More generic solution
- 2x overhead

[57] Jones and Kelly, “Backwards-compatible bounds checking for arrays and pointers in C programs”, 1997.

# BBC

Baggy Bounds Checking (BBC)[59]

- Trades memory for performance, fastest object bounds checker
- 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 on SPECINT 2000 benchmark
- Partition memory into slots with slot_size bytes (table has entry per slot rather than per byte)
- Pad every object s.t. size is power of two, align base addresses to be multiple of their padded size
- Mark if OOB to prevent later dereference
- Handle OOB withint slot_size/2 bytes from original object

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[59]Akritidis et al., "Baggy Bounds Checking", 2009.

# Other Spatial Approaches

- Purify[60] (reveal during testing, object based, has temporal safety)
- Valgrind[61] (reveal during testing)

[60] Hastings and Joyce, "Purify", 1991.

[61] Nethercote and Seward, "How to shadow every byte of memory used by a program", 2007.

# Intel MPX

Intel MPX

- ”new instructions that a compiler can insert to accelerate disjoint per-pointer metadata access and bounds checking”
- 4 new 128-bit bound registers
- BNDCL, BNDCU
- BNDSTC, BNDLDX
- BNDMK – create bounds metadata for a pointer
- Extends func call conventions to include these bound registers
- Disjoint metadata for ptrs in memory
- Does not address temporal errors
- ’Incremental deployment’ by checking if loaded pointer is same as redundantly-stored ptr in disjoint metadata structure => loss of comprehensiveness
- Metadata isn’t updated on *integer stores* (b/c don’t know to treat it as a ptr)

# Alias Types

Alias types[62]

- Problem: registers must be reused for data of different types constantly
- Aliasing constraints: describe shape of store; functions use to specify what they expect part of the store to look like
- Location and store polymorphism: dependence between pointer types and constraints, abstract away size/shape of store
- More expressive than linear: although aliasing constraints are linear, ptr values that flow through computation are not
- Constraint is mapping from locations to types; Pointer to location l has singleton type ptr(l)

[62] Smith, Walker, and J. G. Morrisett, "Alias Types", 2000.

# More Object-Based Temporal Safety

- Mark locations which were de-allocated in shadow memory space (i.e. track a few bits of state for each byte in memory, indicating if location is currently valid)
- Detect access of de-allocated locations
- Fails if pointer points again to re-allocated space
- Memcheck (10x slowdown)
- Address Sanitizer[63]
  - Tripwire approach
  - 73% slowdown
  - Can detect small-stride buffer overflows

[63] Serebryany et al., "AddressSanitizer: A Fast Address Sanity Checker", 2012.

# Extended Static Checking

Extended Static Checking (ESC)[64]

- Use automatic theorem prover to detect index bounds in Modula-3
- Use info in annotations to assist
- Easier than C b/c no ptr arithmetic

Also see: ESC/Java[65]

[64] Detlefs, "An Overview of the Extended Static Checking System", 1995.

[65] Flanagan et al., "Extended Static Checking for Java", 2002.

# LCLint

LCLint[66]

- Leverage LCLint, an annotation-assisted buffer detection tool
- Annotations that constrain possible values a reference contains before/after funcall
- Function pre/post-condition with:

  `requires`, `ensures`, `unique`, `returned`, `modifies`, `out` clauses
- Assumptions are `minSet`, `maxSet`, `minRead`, `maxRead`
- Generates constraints at expression level, resolved w/ checking at statement level
- Heuristics to deal with loops nicely enough; neither sound nor complete

Also see: ESC/Modula-3 ,[67] ESC/Java[68]

[66] Larochelle and Evans, "Statically Detecting Likely Buffer Overflow Vulnerabilities", 2001.

[67] Detlefs, "An Overview of the Extended Static Checking System", 1995.

[68] Flanagan et al., "Extended Static Checking for Java", 2002.

# CSSV

CSSV[69]

- Source-to-source translation
- Instruments program w/ additional variables describing string attrs
- Adds assert statements checking for unsafe string ops
- Statically analyze instr. version with *integer analysis* to determine possible assertion failures
- Handles overlapping ptrs, etc.
- Disadv: # vars in instr. quadratic in # in orig.

[69] Dor, Rodeh, and Sagiv, "CSSV: Towards a Realistic Tool for Statically Detecting All Buffer Overflows in C", 2003.

# Early Use of Regions

RC[70]

- Region-support for C, focus on preventing dangling pointers
- No restrictions on region lifetimes, pointers can point anywhere
- Maintain a reference count of external pointers pointing to objects in region
- Type system + annotations (`sameregion`, `traditional`, `parentptr`) to help compiler remove annotation operations
- Annotations (`sameregion`, `traditional`, `parentptr`) to prevent updating associated region
- Restrict C by disallowing arbitrary integer-to-pointer casts
- Break cyclic data structures before deleting regions
- No memory safety guarantee
- 27%-11% overhead

[70] Gay and Aiken, "Language Support for Regions", 2001.

# More Early Use of Regions

Reaps[71]

- Combine regions and heaps into "reaps"; regions until `reapFree` deallocates individual object
- Place freed object on a heap; subsequent allocations use heap until exhausted
- Use Lea allocator generally, unless you need fast regions (i.e. reaps)

Control-C[72]

- Single region active at any given time
- Pointer value containing region address must be provably dead before `rfree`
- Automatic Pool Allocation and Type Homogeneity[73] for safe dangling pointers

[71] Berger, Zorn, and McKinley, "OOPSLA 2002", 2002.

[72] Kowshik, Dhurjati, and Adve, "Ensuring Code Safety Without Runtime Checks for Real-time Control Systems", 2002.

[73] Dhurjati, Kowshik, et al., "Memory safety without runtime checks or garbage collection", 2003.

# CETS

CETS

- Extends SoftBound
- Validity bit stored in global dictionary
- Each objects gets unique id as key to dictionary, pointers associated with id
- enforces full safety
- 48% for temporal, 116% overhead for full (Softbound-CETS) on SPEC
- incompatiblity issues of SoftBound too

# Softbound-CETS

- In absence of wrappers, code will not experience vilations as long as external libaries d no return ptrs or update ptrs in memory
- Benefits from LLVM maintaing ptr info from src in IR: large # of checks can be eliminated statically using check elim opt
- 76% overhead on avg on SPEC benchmarks

# Memsafe

Memsafe[74]

- Use spatial data for temporal safety by setting bounds of deallocated ptr and all its aliased ptrs in metadata space to an invalid value;
- Subsequent deference of such a deallocated ptr will raise an exception as bounds metadata is invalid
- Also stores some object-based metadata in global database, looking up only when ptr-based meatadata is insufficient for proving temporal safety
- Free(p) => p=invalid (i.e. addr_p->base=1 addr_p->bound=0)
- Spatial safety checks involving the base/bound of invalid ptr are guaranteed to always report a safety violation
- Inserts assignments of invalid ptr at end of a procedure for each local variable whose address is taken (so ptr to stack object can't escape)
- Models in-memory ptr assignments as epxlicit assignments using alias analysis and $\phi$-like ssa extension call $\rho$2-function

[74] Simpson and Barua, "MemSafe", 2013.

# Regions Example

```
// Example prototypes
char?ρ1 strcpy<ρ1,ρ2>(char?ρ1 d,
  const char ?ρ2 s);
char?ρH strdup<ρ>(const char?ρ s);
char?ρ strlen<ρ>(const char?ρ s);

// Dangling pointer prevention
int *ρL p;
L:{ int x = 0;
    p = &x;
  }
*p = 42;
```

```
// Polymorphic Recursion
void fact<ρ>(int*ρ result, int n) {
 L: { int x = 1;
      if (n > 1) fact<ρL>(\&x,n-1);
      *result = x*n; }
}
int g = 0;
int main() { fact<ρH>(\&g, 6); return g
 ; }
```

# Quasi-Linear Types

Quasi-linear types[75]

- Relax linear type strong condition
- Distinguish between consumed values vs those that may be returned
- Use $\kappa$ to control how often a variable of type $\tau^{\kappa}$ is used
- $\kappa = \delta$: accessed many times *locally*, cannot be returned
    - 0: not used at all
    - 1: value accessed at most once
    - $\omega$: accessed arbitrary number of times
    - $\delta$: accessed many times *locally*, cannot be returned with result
- Quasi-linear value (1) accessed as $\delta$ and then strictly as linear
- Inspired PACLANG

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[75] Kobayashi, "Quasi-linear Types", 1999.

# Other Linear Types

Vault[76]

- Keys associate static capabilities with run-time resources
- Functions annotated with effect clause (pre- and post-conditions on held-key set contents)
- Freed regions before leaving scope
- Types enforce code must free a region
- static enforcement of various protocols
- Restrict aliasing, tracks fine-grained effects (requires more annotations)
- Windows 2000 locking errors, IRP ownership model

[76] DeLine and Fähndrich, "Enforcing High-level Protocols in Low-level Software", 2001.

# Ordered Types

Ordered types for memory layout[77]

- Restrict linear types (remove exchange property)
- Variables cannot change position $\Rightarrow$ locations in memory
- "Orderly lambda calculus" for size-preserving memory operations
- Coercions to manipulate ordered variables in frontier (combine/split to treat as different types)

[77] Petersen et al., "A Type Theory for Memory Allocation and Data Layout", 2003.

# Typestate

Typestate[78]

- Avoid nonsensical execution sequences statically (using uninitialized value)
- Typestate is static invariant of each variable name at program point
- Define a lattice of states and typestate transition system between them
- Linear types help because of restricting pointer assignment (1-1 mapping between variable names and run-time objects)

[78] Strom and Yemini, "Typestate", 1986.

# Some Practical Affine Types

Alms[79]

- Practical and general purpose
- Affine types: a *weakening* of linear types: can drop but not duplicate
- Affine capabilities: separate a read-only reference to array from an affine writeable reference
- Define ${}^{a}\lambda_{ms}$ (based on System $F^{\omega}_{<:}$) and proof of soundness
- Implemented a capability-based interface to Berkeley sockets
- Basis of Rust's type system

[79] Tov and Pucella, "Practical Affine Types", 2011.

# Low-Level Liquid Types

Low-Level Liquid Types (LTLL)[80]

- Refinement types where predicates are conjunctions over qualifiers
- Functions qualified over locations they operate on
- Deal with collections using *location folding* for checking out a copy to do strong updates on
- Tries to deal with lack of types, mutation, unbounded collections that make type-based mechanisms difficult

[80] Rondon, Kawaguchi, and Jhala, "Low-level Liquid Types", 2010.

# Cyclone

Cyclone[81]:

- Annotations for non-array vs array pointers (can specify size)
- Tagged unions and automatic tag injection
- Need user annotations more than other approaches
- 40 percent runtime overhead
- Uses regions + automatic memory management for temporal safety (free is a no-op) (see nice example)
- Never null don't need checks, use @; push back null checks from uses to their sources
- Restrict arithmetic on regular pointers

[81] Jim et al., "Cyclone: A Safe Dialect of C.", 2002.

# All Cyclone's Abstract Syntax

| | | |
|---|---|---|
| kinds | $\kappa$ | $::= T \mid R$ |
| type and region vars | $\alpha, \rho$ | |
| region sets | $\epsilon$ | $::= \emptyset \mid \alpha_n \epsilon_1 \cup \epsilon_2$ |
| region constraints | $\gamma$ | $::= \emptyset \mid \gamma, \epsilon <: \rho$ |
| constructors | $\tau$ | $::= \alpha \mid \mathsf{int} \mid \tau_1 \xrightarrow{\epsilon} \tau_2 \mid \tau_1 \times \tau_2 \mid \tau * \rho \mid$ |
| | | $\mathsf{handle}(\rho) \mid \forall \alpha : \kappa \rhd \gamma . \tau \mid \exists \alpha : \kappa \rhd \gamma . \tau$ |
| expressions | $e$ | $::= x_\rho \mid v \mid e \langle \tau \rangle \mid (e_1, e_2) \mid e.i \mid\ * e \mid \mathbf{rnew}(e_1) e_2 \mid$ |
| | | $e_1(e_2) \mid \&e \mid e_1 = e_2 \mid \mathbf{pack}[\tau_1, e]\ \mathbf{as}\ \tau_1$ |
| values | $v$ | $::= i \mid f \mid \&p \mid \mathbf{region}(\rho) \mid (v_1, v_2) \mid \mathbf{pack}[\tau_1, v]\ \mathbf{as}\ \tau_2$ |
| paths | $p$ | $::= x_\rho \mid p.i$ |
| functions | $f$ | $::= \rho : (\tau_1\ x_\rho) \xrightarrow{\epsilon} \tau_2 = \{s\} \mid \Lambda \alpha : \kappa \rhd \gamma . f$ |
| statements | $s$ | $::= e \mid \mathbf{return}\ e \mid s_1 ; s_2 \mid \mathbf{if}\ (e)\ s_1\ \mathbf{else}\ s_2 \mid \mathbf{while}\ (e)\ s \mid$ |
| | | $\rho : \{\tau\ x_\rho = e;\ s\} \mid \mathbf{region}\langle \rho \rangle\ x_\rho\ s \mid \rho : \{\mathbf{open}[\alpha, x_\rho] = e;\ s\} \mid s\ \mathbf{pop}[\rho]$ |

# Fail-Safe C

- Safe implementation of ANSI-C, handles casts very well
- Extend fat pointers to also contain
  - 'Cast' flag embedded in two-word representation: enables optimization by not needing to do a long memory access via reading header information elsewhere
  - 'Virtual Offsets' instead of real memory address offsets
- Fat Integer: integer large enough to hold any pointer value
- Virtual offset: corresponds to program-visible size
- Virtual size: real size of equivalent data type in native C impl.

# Fat Pointers

Cuckoo[82]

- Store array size in memory before array dimensions' first element
- Name of an array is pointer to an *array*, not first object
- Type system for preventing assignment of automatic objects into longer-lifetime pointers
- Wrap dynamic memory allocation (type homogeneous pool-based)
- Forbid addition and subtraction expressions including pointer operands
- Compile-time checks if array bounds are constants, otherwise run-time checks

---

[82] West and Wong, "Cuckoo", 2005.

# Hardware and Other Support for Spatial Safety

- Hardbound[83]
- Stackguard[84] (inserts canaries)
- Light-weight Bounds Checking[85] (guard zones with good performance)
- Manual MM to high-level languages[86]
- PCC[87]
- BitC[88] (a retrospective on BitC, what they were looking for (not too interesting))
- Intel MPX
- Watchdog: Nagarakatte 2012
- (Hybrid): WatchdogLite

[83] Devietti et al., "Hardbound", 2008.

[84] Cowan et al., "StackGuard: Automatic Adaptive Detection and Prevention of Buffer-Overflow Attacks", 1998.

[85] Hasabnis, Misra, and Sekar, "Light-weight Bounds Checking", 2012.

[86] Kedia et al., "Simple, fast, and safe manual memory management", 2017.

[87] Necula, "Proof-carrying Code", 1997.

[88] Shapiro, Sridhar, and Doerrie, *Warning*, 2008.

# Rust OS

Rust OS[89]

- Ownership *hinders* resource sharing
- AMM not optimized for HW resources/device drivers
- Closures' req for dynamic memory is bad for embedded systems
- Many resources not dynamically allocated
- Mutably borrow static resources
- Embedded systems typically have one primary execution thread, so aliasing in same thread is okay
- Rust doesn't allow mutable aliasing, so extend type system with execution contexts
- Type records thread of value's owner: allow multiple borrows of value within same thread, not across threads

[89] Levy et al., "Ownership is Theft", 2015.

## No Time

- Mudflap: Eigler 2003
- Criswell: Secure Virt Arch 2007
- PariCheck: Younan: 2010