Memory Safety in Systems Languages

Major Area Exam

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What is a System?

Infrastructure software upon which applications are built

Operating Systems

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

Embedded Systems, Compilers, Garbage Collectors, Device Drivers, File Systems

Systems Languages

- Past systems languages: ALGOL, PL/I, Fortran, BCPL/B, C, Mesa/Cedar, Pascal/Modula-2/Oberon, C++, ...
- C: the de-facto standard
  - Data structure representation control
  - Memory management control
  - Complete mutability via pointers
  - Performant
  - Legacy
- C: the unsafe standard
  - Unchecked array operations
  - Pointers $\equiv$ arrays
  - Unsafe casts
  - Aliasing
  - **Undefined behavior**

Memory Safety

- Memory safety error: reads or writes outside the referent's storage
  - Spatial: outside referent's **address bounds**
  - Temporal: outside referent's **lifetime**
- Ideal technique is
  - Efficient and expressive
  - Purely static
  - Precise
  - Automatic
- Memory errors become **type errors**, management happens at **compile-time**

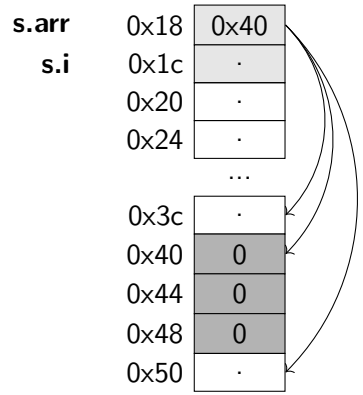
Spatial Safety

Always access within object's **bounds**

Some approaches:

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

```
struct { int *arr; int i; } s;
s.arr = calloc(3, sizeof(int));
```



Spatial Safety Example

```
1  int find_token(int *data,
2                 int *end,
3                 int token)
4  {
5      int *p = data;
6      while (p < end) {
7          if (*p == token) break;
8          p++;
9      }
10     return (*p == token);
11 }
```

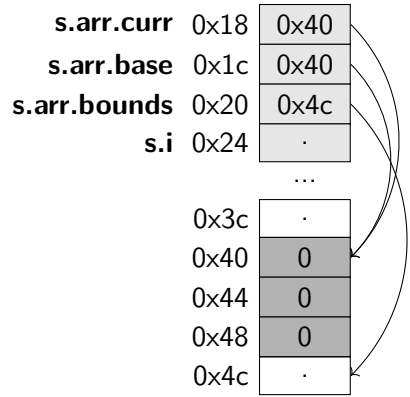
Potential pointer dereference problems:

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

Fat Pointers

- Added base and bound addresses
- Instrument all pointers and functions
- Insert runtime checks **before dereferences**
- Advantages:
  - Quickly find and retrieve metadata
  - Complete spatial safety
  - No sub-object overflows
- Disadvantages:
  - Breaks binary compatibility
  - Metadata propagation
  - Code bloat, memory usage, runtime overhead
  - Unsafe casts overwriting metadata

```
struct fptr { int *curr;
     int *base; int *bound; };
struct { struct fptr arr; int i; } s;
s.arr.curr = calloc(3, sizeof(int));
```



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

Cyclone[2]:

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

[1] Austin, Breach, and Sohi, "Efficient Detection of All Pointer and Array Access Errors", 1994.

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

Fat Pointer Approaches

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

Fail-Safe C[6]:

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

[3] Necula, McPeak, and Weimer, "CCured", 2002.

[4] Necula, Condit, et al., "CCured", 2005.

[5] Siff et al., "Coping with Type Casts in C", 1999.

[6] Oiwa, "Implementation of the Memory-safe Full ANSI-C Compiler", 2009.

Fat Pointers Preventing Spatial Errors

```
1  int find_token(int *data,
2                 int *end,
3                 int token)
4  {
5      int *p = data;
6      while (p < end) {
7
8
9
10         if (*p == token) break;
11
12
13         p++;
14     }
15
16     return (*p == token);
17 }
```

```
1  int find_token(int *SEQ data,
2                 int *SAFE end,
3                 int token)
4  {
5      int *SEQ p = data;
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]

- *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

```
1
2
3
4
5  int find_token(
6    int *data,
7    int *end,
8    int token)
9  {
10     int *p = data;
11
12     while (p < end) {
13
14         if (*p == token) break;
15         p++;
16     }
17
18     return (*p == token);
19 }
```

```
1  struct ptr_info {
2      void *base;
3      unsigned long bound;
4  };
5  int find_token(
6    int *data, ptr_info *data_info,
7    int *end,  ptr_info *end_info,
8    int token)
9  {
10     int *p = data;
11     ptr_info  p_info = *data_info;
12     while (p < end) {
13         CHECK_SPATIAL(p, sizeof(*p), p_info);
14         if (*p == token) break;
15         p++;
16     }
17     CHECK_SPATIAL(p, sizeof(*p), p_info);
18     return (*p == token);
19 }
```

Referent Objects

Objects[8, 9]

- Metadata about **objects**, not pointers
- Global database relates every allocated address to corresponding object metadata
- Every pointer to same object shares same metadata
- Bounds check on **pointer arithmetic**
- 2-12x overhead

Advantages:

- Compatible with uninstrumented code

Disadvantages:

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

[8] Jones and Kelly, "Backwards-compatible bounds checking for arrays and pointers in C programs", 1997.

[9] Ruwase and Lam, "A Practical Dynamic Buffer Overflow Detector", 2004.

The Sub-Object Problem

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

- `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

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

[10] Dhurjati and Adve, "Backwards-compatible Array Bounds Checking for C with Very Low Overhead", 2006.

[11] Lattner and Adve, "Automatic Pool Allocation", 2005.

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

Referent Objects Example

```
1  int find_token(int *data,
2                 int *end,
3                 int token)
4  {
5      int *p = data;
6      while (p < end) {
7          if (*p == token) break;
8
9
10
11
12         p++;
13     }
14     return (*p == token);
15 }
```

```
1  int find_token(int *data,
2                 int *end,
3                 int token)
4  {
5      int *p = data;
6      while (p < end) {
7          if (*p == token) break;
8          int *q = p + 1;
9          int size = 1 << TABLE[p>>4];
10         int base = p & ~(size - 1);
11         assert(q >= base && q - base < size);
12         p++;
13     }
14     return (*p == token);
15 }
```

Softbound

Softbound[13]

- Base and bound metadata for each pointer, stored in disjoint metadata table
- Total spatial safety of **pointer-based** approaches
- Source compatibility, separate compilation of **object-based** approaches
- Runtime bounds checks on each dereference
- Propagate metadata as extra arguments
- Arbitrary casts allowed
- 67% overhead

[13] Nagarakatte, Zhao, Milo MK Martin, et al., "SoftBound", 2009.

Dependent Types

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

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

$$\texttt{nil} : \texttt{Vector 0 a}$$

$$\texttt{cons} : \Pi \texttt{n:Nat.a} \rightarrow \texttt{Vector n a} \rightarrow \texttt{Vector (n+1) a}$$

$$\texttt{(cons 'a' (cons 'b' nil))} : \texttt{Vector 2 Char}$$

$$\texttt{head} : \Pi \texttt{n:Nat.Vector (n+1) a -> a}$$

$$\texttt{head nil} \Rightarrow \text{Rejected!}$$

- 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

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

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

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
  - `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

```
1  int find_token(int *data,
2                 int *end,
3                 int token)
4  {
5
6
7      int *p = data;
8      while (p < end) {
9
10
11         if (*p == token) break;
12
13         p++;
14     }
15
16
17     return (*p == token);
18 }
```

```
1  int find_token(int * bound(data, end) data,
2                 int * sentinel end,
3                 int token)
4  {
5      assert(data != NULL);
6      assert(end != NULL);
7      int *p bound(p, end) = data;
8      while (p < end) {
9          assert(p != NULL);
10         assert(p < end);
11         if (*p == token) break;
12         assert(p <= p + 1 <= end);
13         p++;
14     }
15     assert(p != NULL);
16     assert(p < end);
17     return (*p == token);
18 }
```

Abstract Syntax, For Your Consideration

$x, y \in$ Variables op $\in$ Binary ops $n \in$ Integers comp $\in$ Comparison Ops

Ctors $C ::= \text{int} \mid \text{ref} \mid \text{array}$

Types $\tau ::= C \mid \tau_1\ \tau_2 \mid \tau\ e$

L-exprs $l ::= x \mid *\, e$

Exprs $e ::= n \mid l \mid e_1\ \text{op}\ e_2$

Cmds $c ::= l := e \mid \text{assert}(\gamma) \mid c_1; c_2 \mid \ldots$

Preds $\gamma ::= e_1\ \text{comp}\ e_2 \mid \text{true} \mid \gamma_1 \wedge \gamma_2$

Typing Rules, For Your Consideration

Local Expressions: $\Gamma \vdash_L e : \tau$

$$\frac{\Gamma(x) = \tau}{\Gamma \vdash_L x : \tau}\ (\textsc{local name}) \qquad \frac{}{\Gamma \vdash_L n : \mathit{int}}\ (\textsc{local num})$$

Non-local Expressions: $\Gamma \vdash e : \tau \Rightarrow \gamma$

$$\frac{\Gamma \vdash e : \mathsf{ref}\ \tau \Rightarrow \gamma}{\Gamma \vdash *e : \tau \Rightarrow \gamma}\ (\textsc{deref})$$

Commands: $\Gamma \vdash c \Rightarrow c'$

$$\frac{x \in \mathsf{Dom}(\Gamma) \qquad \forall (y : \tau_y) \in \Gamma,\ \Gamma \vdash y[e/x] : \tau_y[e/x] \Rightarrow \gamma_y}{\Gamma \vdash x := e \Rightarrow \mathsf{assert}(\bigwedge_{y \in \mathsf{Dom}(\Gamma)} \gamma_y);\ x := e}\ (\textsc{var write})$$

The Interesting Rules

Dereferencing

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

Arithmetic

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

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

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*

Low*[25]

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

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

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

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

Quick Spatial Recap

Spatial Safety

- Arrays and pointers
- Fat pointers
- Referent objects
- Dependent types

Temporal Safety

Prevent accessing object that has been **previously deallocated**

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

Temporal Safety Example

```
1  int attach(struct sock *sk) {
2      if (sk->bad) {
3          free(sk); return 1;
4      }
5      return 0;
6  }
7  void mq_notify(sigevent *n) {
8      struct sock_t *sock;
9      while (n->try) {
10         sock = malloc_sock(n->info);
11         if (attach(sock)){
12                 //sock = NULL;
13             break;
14         }
15     }
16     if (sock) free(sock);
17 }
```

Potential pointer dereference problems:

- Double frees
- Dangling pointers

A Real Bug

- Linux Kernel in `ipc/mqueue.c`
- July 2017
- `https://bugzilla.redhat.com/show_bug.cgi?id=1470659`

Goals:

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

A Comment on Garbage Collection

Garbage collection

- Relinquish control of object location and layout to runtime
- Complete temporal safety, but...
  - Non-zero overhead
  - Drag
  - 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.

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
- 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
- Memsafe[29]
  - Set bounds of deallocated pointer to invalid value

[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.

Lock Example

```
1  int attach(struct sock *sk,
2        key_t sk_key,
3        lock_t *sk_lock_addr) {
4      if (sk_key != *sk_lock_addr)
5        abort();
6      if (sk->bad) {
7          if (Freeable_ptrs_map.lookup(sk_key) != sk)
8            abort();
9          free(sk);
10         *sk_lock_addr = INVALID_KEY;
11         deallocate_lock(sk_lock_addr);
12         return 1;
13     }
14     return 0;
15 }
```

```
1  void mq_notify(sigevent *n) {
2      struct sock_t *sock;
3      key_t sock_key;
4      lock_t *sock_lock_addr;
5      while (n->try) {
6          sock = malloc_sock(n->info);
7          sock_key = Next_key++;
8          sock_lock_addr = allocate_lock();
9          *(sock_lock_addr) = sock_key;
10         Freeable_ptrs_map.insert(sock_key, sock);
11         if (attach(sock)){
12             break;
13         }
14     }
15     if (sock) {
16         if (Freeable_ptrs_map.lookup(sock_key) != sock)
17           abort();
18         free(sock);
19         *(sock_lock_addr) = INVALID_KEY;
20         deallocate_lock(sock_lock_addr);
21     }
22 }
```

Effects

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

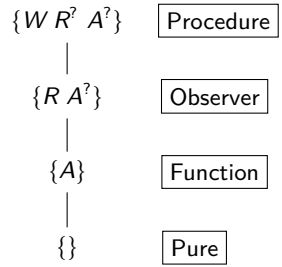
- Opening a file
- Modifying an object

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

Effects

Fluent Languages,[31] MFX[32]

- Mix functional and imperative languages
- Every expression has a **effect class**, restricting which subroutines or sublanguage features it may use
- Identify **referentially transparent** expressions via a side effect lattice
- Effect masking: inference to delimit regions of memory and their lifetimes



E.g.

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

[31] David K. Gifford and John M. Lucassen, "Integrating functional and imperative programming", 1986.

[32] J. M. Lucassen and D. K. Gifford, "Polymorphic Effect Systems", 1988.

Effects

Type and Effect Systems[33]

- Extend the simply-typed lambda calculus with annotations
- Various forms of analyses, incl. Side Effect Analysis and **Region** Inference

$$
\begin{array}{rl}
\text{Exprs} & e ::= c \mid x \mid \mathtt{fn}_{\pi}\ x\ \Rightarrow e \mid e_1\ e_2 \mid \mathtt{new}_{\pi}\ x\ :=\ e_1\ \mathtt{in}\ e_2 \mid\ !x \mid x := e \\
\text{Types} & \tau ::= \mathtt{int} \mid \mathtt{bool} \mid \tau_1 \to \tau_2 \mid \tau_1 \xrightarrow{\phi} \tau_2 \mid \tau\ \mathtt{ref} \mid \tau\ \mathtt{ref}\ \varrho \\
\text{Effect Region} & \phi ::= \{!\pi\} \mid \{\pi :=\} \mid \{\mathtt{new}\ \pi\} \mid \phi_1 \cup \phi_2 \mid \varnothing \\
\text{PrgPts} & \varrho ::= \{\pi\} \mid \varrho_1 \cup \varrho_2 \mid \varnothing
\end{array}
$$

$$\Gamma \vdash e\ :\ \tau\ \&\ \phi$$

[33] F. Nielson and H. R. Nielson, "Type and Effect Systems", 1999.

Region-Based Memory Managememt

Regions[34]

- Divide heap into stack of sub-heaps (i.e. regions)
- Regions grow on individual allocation; **entire** region deallocated
- Explicit region polymorphism
- Sound type system **guarantees safety** of deallocations
- Region inference identifies:
  - Points where entire regions are allocated and deallocated
  - Into which region values should go
- Unreasonable object lifetimes due to LIFO ordering of region lifetimes

[34] Tofte and Talpin, "Region-Based Memory Management", 1997.

Early Use of Regions

Capability Calculus[35]

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

Also see:

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

[35] Crary, Walker, and Morrisett, "Typed Memory Management in a Calculus of Capabilities", 1999.

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

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

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

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

Regions in Cyclone

Cyclone,[40] again!

- Three region types:
  - single **heap** region
  - **stack** regions
  - **dynamic** regions
- Lifetime subtyping: region A $<:$ region B $\Leftrightarrow$ region A **outlives** region B
- Sane defaults by inferring region annotations on pointer types

[40] Grossman et al., "Region-based Memory Management in Cyclone", 2002.

Regions in Cyclone

- Pointer can escape scope of their regions
- Type system tracks **capability** (live regions set)
- Check needed **liveness** on pointer dereference
- Function **effect**: set of regions it might access
- Calculate function's effect from prototype alone

```
1  struct Set<α, ρ, ϵ>
2  {
3    list_t<α, ρ> elts;
4    int (*cmp)(α,α; ϵ);
5  }
```

```
1  struct Set<α, ρ>
2  {
3    list_t<α, ρ> elts;
4    int (*cmp)(α,α; regions_of(α));
5  }
```

Some Cyclone Abstract Syntax

kinds	κ	$::= T \mid R$
type and region vars	α, ρ	
region sets	ϵ	$::= \varnothing \mid \alpha \mid \epsilon_1 \cup \epsilon_2$
region constraints	γ	$::= \varnothing \mid \gamma, \epsilon <: \rho$
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	$::= e \mid s_1; s_2 \mid \mathbf{if}\ (e)\ s_1\ \mathbf{else}\ s_2 \mid \rho : \{\tau\ x_\rho = e;\ s\} \mid \mathbf{region} \langle \rho \rangle\ x_\rho\ s \mid \ldots$
	...	

Example Cyclone Judgments

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

- Δ : in-scope type/region vars
- Γ : mapping of in-scope vars to types
- γ : constraints relating lifetimes
- ϵ : capability, i.e. live regions

$$\frac{\gamma \vdash \epsilon \Rightarrow \rho}{\Delta; \Gamma; \gamma; \epsilon \vdash x_\rho : \Gamma(x_\rho)} \ (\text{VAR}) \qquad \frac{\Delta; \Gamma; \gamma; \epsilon \vdash e : \tau * \rho \qquad \gamma \vdash \epsilon \Rightarrow \rho}{\Delta; \Gamma; \gamma; \epsilon \vdash *e : \tau} \ (\text{DEREF})$$

$$\frac{\Delta; \Gamma; \gamma; \epsilon \vdash e_1 : \tau_2 \xrightarrow{\epsilon_1} \tau \qquad \Delta; \Gamma; \gamma; \epsilon \vdash e_2 : \tau_2 \qquad \gamma \vdash \epsilon \Rightarrow \epsilon_1}{\Delta; \Gamma; \gamma; \epsilon \vdash e_1(e_2) : \tau} \ (\text{CALL})$$

$$\frac{\Delta; \Gamma; \gamma; \epsilon \vdash e : \forall \alpha : \kappa \rhd \gamma_1 . \tau_2 \qquad \Delta \vdash \tau : \kappa \qquad \gamma \vdash \gamma_1[\tau_1/\alpha]}{\Delta; \Gamma; \gamma; \epsilon \vdash e\langle \tau_1 \rangle : \tau_2[\tau_1/\alpha]} \ (\text{TYPE-INST})$$

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

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)

[41] Grossman et al., *Formal Type Soundness for Cyclone's Region System*, 2001.

Linear Types

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

- The **world** is a non-duplicatable resource
- Track proper modification of world
- Efficiency: safe to destructively update an array
- **Memory management: can immediately collect used values**

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

[43] Wadler, "Linear types can change the world", 1990.

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

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.

[45] Ennals, Sharp, and Mycroft, "Linear Types for Packet Processing", 2004.

COGENT

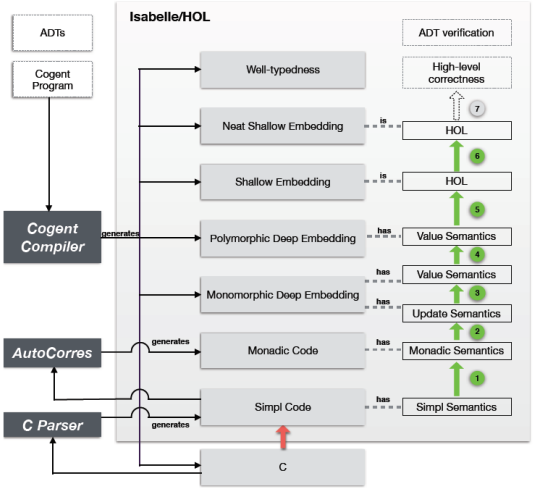
COGENT[46,47]

- Pure, polymorphic language with linear types for writing low-level systems code
- Efficient machine code with in-place updates
- Linear types:
  - Ensure safe handling of heap-allocated objects
  - Equational functional semantics via mutable state/imperative effects
- Reason with **interactive theorem prover**
- Missing functionality can be implemented in C, manually verified
- No trusted compiler, runtime, or garbage collector needed

[46] Amani et al., "Cogent", 2016.

[47] O'Connor et al., "COGENT", 2016.

COGENT



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)

Vault[49]

- 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

Ordered types for memory layout[50]

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

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

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

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

Ownership

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

LCL[51]

- `owned` annotation to denote reference with obligation to release storage
- `dependent` annotation for sharing; user ensures lifetimes contained properly

Ownership Types[52]

- Object's definition includes **unique** object context that owns it

Singularity[53]

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

[51] Evans, "Static Detection of Dynamic Memory Errors", 1996.

[52] Clarke, Potter, and Noble, "Ownership Types for Flexible Alias Protection", 1998.

[53] Fähndrich et al., "Language Support for Fast and Reliable Message-based Communication in Singularity OS", 2006.

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)

```
1  let (snd, rcv) = channel();
2  join(move || {
3        let mut v = Vec::new();
4        v.push(0);
5        snd.send(v);
6        v.push(1);
7      },
8      move || {
9        let v = rcv.recv().unwrap();
10       println!("Received: {:?}", v);
11     });
```

[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
- Effects and regions
- Linear types
- Ownership and borrowing

Conclusion

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

Thanks!