# An Executable Formal Semantics of C with Applications

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There is no formal semantics for C.

# There are partial semantics

- *Gurevich and Huggins* (1993) [ASM]
- *Cook, Cohen, and Redmond* (1994) [Denotational]
- *Cook and Subramanian* (1994) [Denotational]
- *Norrish* (1998) [Small- and big-step SOS]
- *Black* (1998) [Axiomatic]
- *Papaspyrou* (2001) [Denotational]
- *Blazy and Leroy* (2009) [Big-step SOS]

But, they simplify or leave out large parts of the language: Nondeterminism, casts, bitfields, unions, struct values, variadic functions, memory alignment, `goto`, dynamic memory allocation (`malloc()`), . . .

# But, Previous Definitions Leave out Features

| | Definition | | | | | |
|---|---|---|---|---|---|---|
| Feature | GH | CCR | CR | No | Pa | BL |
| Bitfields | ● | ◐ | ○ | ○ | ◐ | ○ |
| Enums | ◐ | ● | ○ | ○ | ● | ○ |
| Floats | ○ | ○ | ○ | ○ | ◐ | ● |
| Struct/Union | ● | ● | ● | ◐ | ● | ● |
| Struct as Value | ○ | ○ | ○ | ● | ○ | ○ |
| Arithmetic | ◐ | ● | ● | ○ | ● | ● |
| Bitwise | ○ | ● | ○ | ○ | ● | ● |
| Casts | ◐ | ◐ | ○ | ◐ | ◐ | ● |
| Functions | ● | ● | ◐ | ● | ● | ● |
| Exp. Side Effects | ● | ● | ○ | ● | ● | ○ |
| Variadic Funcs. | ○ | ○ | ○ | ○ | ○ | ○ |
| Eval. Strategies | ○ | ◐ | ○ | ● | ● | ○ |
| Overflow | ○ | ○ | ○ | ○ | ○ | ○ |
| Volatile | ○ | ○ | ○ | ○ | ○ | ◐ |
| Concurrency | ○ | ○ | ○ | ○ | ○ | ○ |
| Break/Continue | ◐ | ● | ◐ | ● | ● | ● |
| Goto | ◐ | ○ | ○ | ○ | ● | ○ |
| Switch | ◐ | ● | ○ | ○ | ● | ◐ |
| Longjmp | ○ | ○ | ○ | ○ | ○ | ○ |
| Malloc | ○ | ○ | ○ | ○ | ○ | ○ |

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# No Semantics-Based Tools Either

There are many useful C analysis/verification tools, including:

- Lint/Purify/Coverity/Valgrind
- Blast
- Havoc
- Slam
- VCC
- Frama-C/Caduceus

These tools are based on approximative models of C.

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- Hard to argue for the soundness of the tools
- Most tools are not even based on an *incomplete* semantics.

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2. Semantics-based analysis tools for C;
3. Constructive evidence that rewriting-based semantics scale.

# Outline

# C Specifications

- ANSI C (1989)
- ISO/IEC 9899:1990 “C90”
- ISO/IEC 9899:1999 “C99”
  - 540 pp.
  - 62 person-years of work (from 1995–1999)
  - Work continued until 2007
  - About 50 new features over C90, and many fixes
- ISO/IEC 9899:201x “C1X”
  - Adds first support for concurrency

# Do We Really Need Formal Analysis Tools?

**Question.**

What happens when the approximative models of C fall short?

**Answer.**

Bad programs get proved correct, or behaviors go missing.

# Two Unsequenced Writes to 'x'

```
int main(void) {
   int x = 0;
   return (x = 1) + (x = 2);
}
```

**Undefined according to C standard**

| | |
|---|---|
| GCC4, MSVC: | returns 4 |
| GCC3, ICC, Clang: | returns 3 |

Both Frama-C and Havoc "prove" it returns 4

# What is Undefined Behavior?

undefined behavior: Behavior, upon use of a non-portable or erroneous program construct or of erroneous data, [with] no requirements.

- In essence, this refers to problematic situations that are hard to identify statically or expensive to identify dynamically
- Implementations can do *anything* for undefined behavior, including failing to compile, crashing, or appearing to work
- Examples: division by zero, referring to an object outside its lifetime, `(x = 1) + (x = 2)`

# Left Shift of Negative Number

```c
int main(void){
   return -5 << 2;
}
```

**Undefined according to C standard**

| | |
|---|---|
| GCC, ICC, Clang: | returns $-20$ |
| MSVC: | returns 127 |

Both Frama-C and Havoc “prove” it returns $-20$

# Write to String Literal

```
int main(void) {
   "foo"[0] = 'x';
   return "foo"[0];
}
```

**Undefined according to C standard**

| | |
|---|---|
| GCC: | doesn't compile |
| ICC, Clang: | segmentation fault |
| MSVC: | returns 'f' |

Frama-C "proves" it returns 'x'

# Undefined Behaviors are Fundamental to C

This was just 3 undefined programs. There are over 190 explicitly undefined categories of behaviors in C.

# Valid Nondeterminism

```c
int r;

int f(int x) {
   return (r = x);
}

int main(void) {
   return f(1) + f(2), r;
}
```

**Defined (Could return 1 or 2)**

GCC, ICC, MSVC, Clang: returns 2

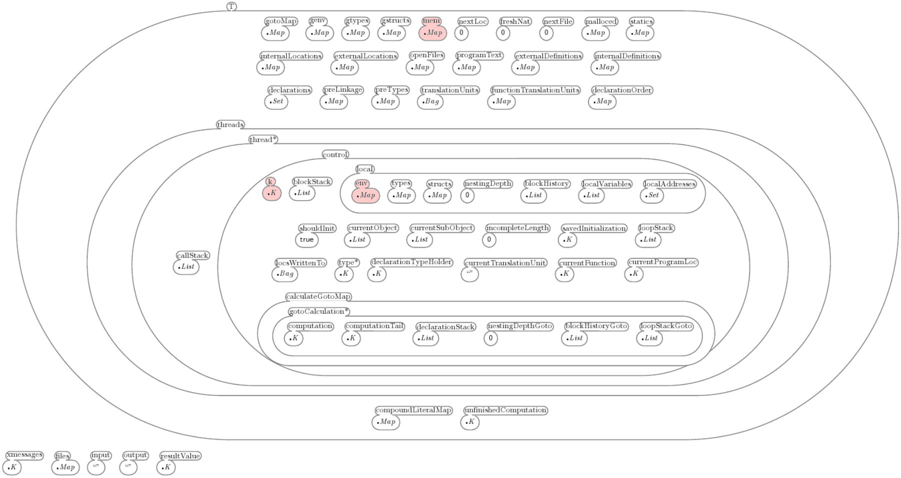
Both Frama-C and Havoc “prove” it can only return 2

# Motivation Summary

When the models of C used by analysis tools are too simplistic

- Tools can draw incorrect conclusions about programs
- Hard to argue for soundness without a semantics to compare against

# Configuration of C



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**Freestanding** A precisely defined subset of all possible C features. This is the subset of C used when writing the kernel of an operating system. It includes only `<float.h>` `<iso646.h>`, `<limits.h>`, `<stdalign.h>`, `<stdarg.h>`, `<stdbool.h>`, `<stddef.h>`, and `<stdint.h>`.

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1. Introduction
   - Introduction
   - Motivation
2. Current Work
   - Current Work on C
   - Work on Analysis Tools

# Our Current Work on C

- We currently have a preliminary semantics that is *more complete* than other semantics to date.
- Tested against the GCC torture tests:
  - Of 1093 tests, 776 tests appear to be standards compliant. Of those, we pass 770 (>99%).

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```
int f(void){
   signed char c = -1;
   return c < 0;
}
int main(void){
   if (f() != 1) { abort(); }
   return 0;
}
```

# Our Current Work is Already More Complete

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**ER** is *Ellison and Roșu* (our current work).

# Some Statistics about Our Semantics

- Mechanized in $\mathbb{K}$ Framework
- 150 syntactic operators
- 5900 source lines of code
- 1200 different $\mathbb{K}$ rules
- Only 80 rules for statements
- Only 160 for expressions
- 500 rules for declarations and types!

# Outline

# Generic Tools

These tools are provided "for free" by rewriting logic and Maude:

- Interpreter
- Debugger
- State-space search

Our tests have shown these tools work just as well with C as with tools based on definitions of smaller languages.

# Interpretation to Find Bugs

# Search to Find Bugs

# LTL-Based Model Checking

# Test Case Reduction

# Duff's Device

- Unstructured control flow (goto, switchs)

```
int n = (count+7)/8;
switch(count%8) {
   case 0: do{ *dest++ = *src++;
   case 7: *dest++ = *src++;
   case 6: *dest++ = *src++;
   case 5: *dest++ = *src++;
   case 4: *dest++ = *src++;
   case 3: *dest++ = *src++;
   case 2: *dest++ = *src++;
   case 1: *dest++ = *src++;
   } while(--n>0);
}
```