# An Executable Formal Semantics of C with Applications

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There is no formal semantics for C.

There ~~is~~ no formal semantics for C.
*was*

## 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]
- *Leroy* (2010) [Small-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

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

●: Fully Described
◐: Partially Described
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**GH** denotes *Gurevich and Huggins* (1993),
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**Le** is *Leroy* (unpublished, 2010).

# 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
- ...

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- Lint/Purify/Coverity/Valgrind
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- ...

These tools are based on approximative models of C.

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

# Our Contribution

1. A complete formal semantics for C;

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

# Outline

1. Introduction
   - Introduction
   - Motivation
2. Semantics of C
3. Semantics-Based Analysis Tools
   - Interpreter
   - State-space Search
   - Model Checker

# C Specifications

- The C Programming Language (K&R) (1978)
- 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 9899:2011 “C11”
  - 683 pp.
  - 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.

# What are "Bad" Programs?

undefined behavior Behavior, upon use of a non-portable or erroneous program construct or of erroneous data, [with] no requirements. [C11, §3.4.3:1]

- 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

# Undefined Behaviors are Fundamental to C

C has over 200 explicitly undefined kinds of behaviors.

- Division by zero
- Referring to an object outside its lifetime
- Signed overflow
- ...

# 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 (Jessie plugin) and Havoc “prove” it returns 4

# 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 (Jessie plugin) "proves" it returns 'x'

# Valid Nondeterminism

```
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 (Jessie plugin) and Havoc "prove" it can only return 2

# Semantics-Based Analysis Tools

**We are *not* saying that these analysis tools are bad!**

However, it is hard to argue for soundness without a semantics.

Instead of embedding different models of C in every tool, we need:

- An explicit and testable definition of C
- To build tools that conform to this semantics

# Outline

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We have the first arguably complete formal definition of a conforming freestanding implementation of C.

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**Freestanding** All language features except complex (i.e., imaginary) numbers, and only a subset of the standard library.

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# A Complete Definition of C

We have the first arguably complete formal definition of a conforming freestanding implementation of C.

**Conforming** Must accept all portable programs, but can also accept non-portable programs.

**Freestanding** All language features except complex (i.e., imaginary) numbers, and only a subset of the standard library. It includes only `<float.h>` `<iso646.h>`, `<limits.h>`, `<stdalign.h>`, `<stdarg.h>`, `<stdbool.h>`, `<stddef.h>`, and `<stdint.h>`.

[C11, §4:6]

# Extensively Tested Definition

- Tested against the GCC torture tests:
  - Of 1093 test programs, 776 appear to be standards compliant. Of those, we pass 770 (>99%).
  - Better results than Clang or GCC itself; one fewer than ICC.
- Tested against test suites of other compilers (Clang, LCC, etc.)
- Tested against thousands of programs generated by Csmith

# Our Work is More Complete

| | | | | Definition | | | | |
|---|---|---|---|---|---|---|---|---|
| Feature | GH | CCR | CR | No | Pa | BL | Le | ER |
| Bitfields | ● | ◐ | ○ | ○ | ◐ | ○ | ○ | ● |
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| Concurrency | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ◐ |
| Break/Continue | ◐ | ● | ◐ | ● | ● | ● | ● | ● |
| Goto | ◐ | ○ | ○ | ○ | ● | ○ | ● | ● |
| Switch | ◐ | ● | ○ | ○ | ● | ◐ | ◐ | ● |
| Longjmp | ○ | ○ | ○ | ○ | ○ | ○ | ○ | ● |
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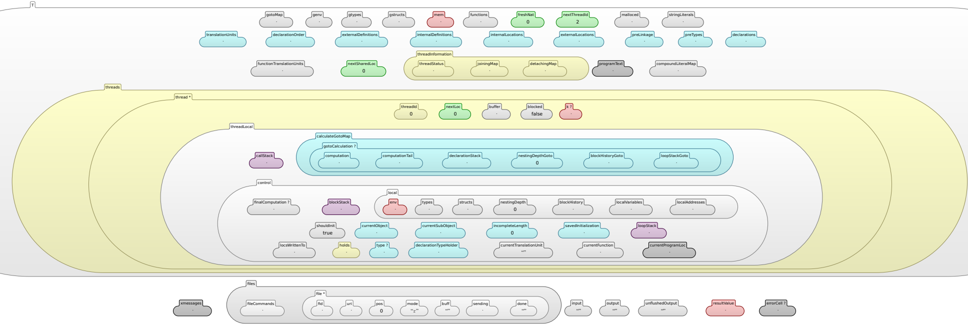
**ER** is *Ellison and Roșu* (our work).

# Some Information about Our Semantics

Mechanized in the $\mathbb{K}$ Framework (`http://k-framework.org/`)

- Rewriting-style semantics
- Syntax, configuration, rewrite rules

# C's 𝕂 Configuration



# Example Rules

$V : T$ is a value $V$ with type $T$.
$[V] : T$ is an l-value $V$ with type $T$.

`lookup` $\quad \langle \frac{X}{[L] : T} \cdots \rangle_{\mathsf{k}} \quad \langle \cdots X \mapsto L \cdots \rangle_{\mathsf{env}} \quad \langle \cdots X \mapsto T \cdots \rangle_{\mathsf{types}}$

`ref` $\quad \langle \frac{\&([L] : T)}{L : \mathsf{pointerType}(T)} \cdots \rangle_{\mathsf{k}}$

`deref` $\quad \langle \frac{*(L : \mathsf{pointerType}(T))}{[L] : T} \cdots \rangle_{\mathsf{k}}$

(This rule is unsafe; see paper for details.)

# Some Information about Our Semantics

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

# Outline

# Semantics-Based Analysis Tools

These tools are provided “for free” by rewriting logic and $\mathbb{K}$:

- Interpreter
- State-space explorer
- LTL Model-checker
- Debugger
- Program verifier (via Matching Logic)

# Outline

# Normal Interpretation

```
$ cat hello_world.c

#include <stdio.h>
int main(void) {
   printf("Hello world!\n");
}
```

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$ cat hello_world.c

#include <stdio.h>
int main(void) {
   printf("Hello world!\n");
}

$ kcc hello_world.c
$ ./a.out

Hello world!
```

# Interpretation to Find Bugs

```
$ cat buggy_strcpy.c
```

```c
#include <string.h>
int main(void) {
   char dest[5], src[5] = "hello";
   strcpy(dest, src);
}
```

# Interpretation to Find Bugs

```
$ cat buggy_strcpy.c

#include <string.h>
int main(void) {
   char dest[5], src[5] = "hello";
   strcpy(dest, src);
}

$ kcc buggy_strcpy.c
$ ./a.out

ERROR! KCC encountered an error while executing this program.
Description: Reading outside the bounds of an object.
File: buggy_strcpy.c
Function: strcpy
Line: 4
```

# Real World Application

This generated interpreter has been used in automated testcase reduction (Regehr, et al.)

- It's fast enough to be useful
- Catches bugs that other tools (e.g., Valgrind) do not
- No spurious errors

# Outline

# Search to Find Bugs

```
$ cat eval_order.c

int denominator = 5;

int setDenominator(int d) {
   return denominator = d;
}
int main(void) {
   return setDenominator(0) + (7 / denominator);
}
```

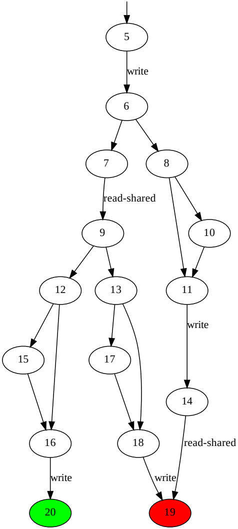
# Search to Find Bugs

```
$ cat eval_order.c

int denominator = 5;

int setDenominator(int d) {
   return denominator = d;
}
int main(void) {
   return setDenominator(0) + (7 / denominator);
}

$ kcc eval_order.c
$ SEARCH=1 ./a.out
```

# Search to Find Bugs (Cont.)

```
2 solutions found
--------------------------------------------------------------
Solution 1
Program got stuck
File: eval_order.c
Line: 8
Description: Division by 0.
--------------------------------------------------------------
Solution 2
Program completed successfully
Return value: 1
```

# Search to Find Bugs (Cont.)



# Search to Find Bugs (Cont.)

```
$ clang -O0 eval_order.c && ./a.out
Floating point exception
$ clang -O2 eval_order.c && ./a.out
$
```

# Search to Explore Nondeterminism

```
$ cat nondet.c

int r;

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

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

# Search to Explore Nondeterminism

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$ cat nondet.c

int r;

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

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

$ kcc nondet.c
$ SEARCH=1 ./a.out
```

# Search to Explore Nondeterminism (Cont.)

```
2 solutions found
------------------------------------------------------------
Solution 1
Program completed successfully
Return value: 1
------------------------------------------------------------
Solution 2
Program completed successfully
Return value: 2
```

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# LTL-Based Model Checking

```
$ cat lights.c
```

```
typedef enum {green, yellow, red} state;
state lightNS = green; state lightEW = red;
int changeNS() {
  switch (lightNS) {
    case(green): lightNS = yellow; return 0;
    case(yellow): lightNS = red; return 0;
    case(red):
      if (lightEW == red) { lightNS = green; } return 0;
}}
...
int main(void) { while(1) { changeNS() + changeEW(); } }
```

# LTL-Based Model Checking

```
$ cat lights.c

typedef enum {green, yellow, red} state;
state lightNS = green; state lightEW = red;
int changeNS() {
  switch (lightNS) {
    case(green): lightNS = yellow; return 0;
    case(yellow): lightNS = red; return 0;
    case(red):
      if (lightEW == red) { lightNS = green; } return 0;
}}
...
int main(void) { while(1) { changeNS() + changeEW(); } }

#pragma __ltl safety: [] (lightNS == red \/ lightEW == red)
#pragma __ltl progressNS: [] <> (lightNS == green)
```

# LTL-Based Model Checking (Cont.)

```
$ kcc lights.c
$ MODELCHECK=safety ./a.out
```

# LTL-Based Model Checking (Cont.)

```
$ kcc lights.c
$ MODELCHECK=safety ./a.out

False! The `safety' property does not hold.
```

# LTL-Based Model Checking (Cont.)

```
$ kcc lights.c
$ MODELCHECK=safety ./a.out

False! The `safety' property does not hold.

# change "changeNS() + changeEW()" to "changeNS(); changeEW()"
```

# LTL-Based Model Checking (Cont.)

```
$ kcc lights.c
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# change "changeNS() + changeEW()" to "changeNS(); changeEW()"

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# LTL-Based Model Checking (Cont.)

```
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# change "changeNS() + changeEW()" to "changeNS(); changeEW()"

$ kcc lights.c
$ MODELCHECK=safety ./a.out

True! The `safety' property holds.
```

# LTL-Based Model Checking (Cont.)

```
$ kcc lights.c
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False! The `safety' property does not hold.

# change "changeNS() + changeEW()" to "changeNS(); changeEW()"

$ kcc lights.c
$ MODELCHECK=safety ./a.out

True! The `safety' property holds.

$ MODELCHECK=progressNS ./a.out
```

# LTL-Based Model Checking (Cont.)

```
$ kcc lights.c
$ MODELCHECK=safety ./a.out

False! The `safety' property does not hold.

# change "changeNS() + changeEW()" to "changeNS(); changeEW()"

$ kcc lights.c
$ MODELCHECK=safety ./a.out

True! The `safety' property holds.

$ MODELCHECK=progressNS ./a.out

True! The `progressNS' property holds.
```

# Summary

We have the first arguably complete formal semantics of C

- Is executable, and has been thoroughly tested against the GCC torture test suite
- Can be used to generate analysis tools
- Demonstrates that rewriting-based semantics can handle large languages and all their gritty details
- Available at `http://c-semantics.googlecode.com/`