School of Computer Science & Engineering

Trustworthy Systems Group

Pancake: A Language for Verified Systems Programming

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Pancake: overview

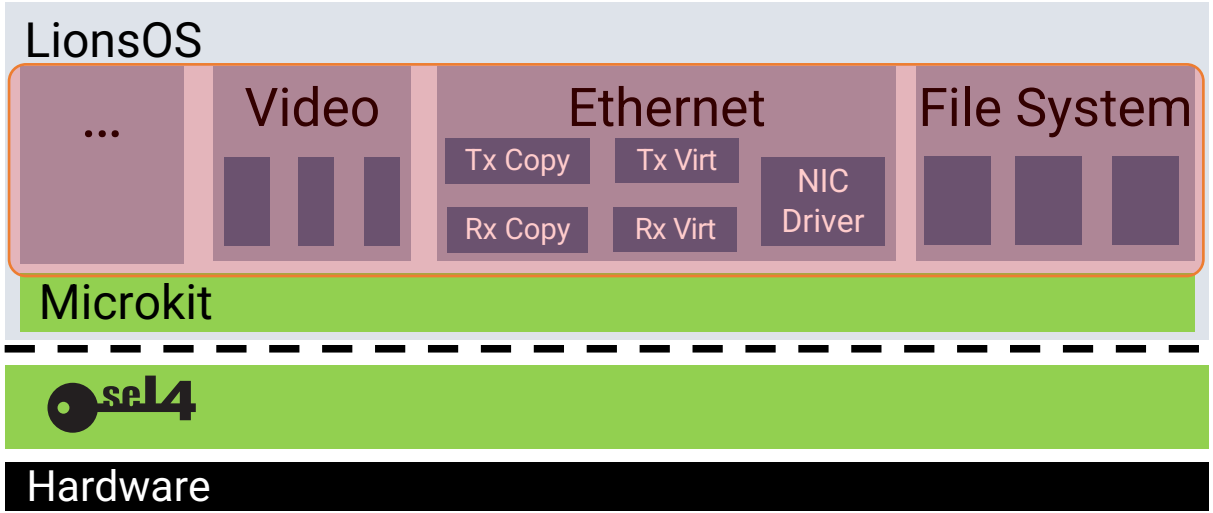
PANCAKE
A Language for
Verified Systems Programming

- **Pancake** [PLOS'23] is an in-development language for verified low-level systems programming
- With a verified compiler, developed on HOL4.
- **In particular**: it aims for verified "device drivers" and other OS components.
- **Design goals:**
  - Simple, easy to learn syntax
    -> for ease of adoption
  - Simple, easy formal semantics
    -> for ease of verification
  - Light resource footprint: no runtime, no GC
    -> for performance and verifiability

Device driver bugs are the leading cause of OS compromise, accounting for the majority of the CVEs

Pancake and seL4

Pancake aims to enhance the guarantee at this level



Pancake: contributors

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Pancake : sample code

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Looks similar to C?

Pancake aims to be instantly familiar to C programmers

```
export fun handle_irq() {
  var got_char = 0;
  got_char = getchar();

  if (got_char == -1) {
    return -1;
  } else {
    while true {
        var buffer_addr = @base + 544;
        var dequeue_ret = 0;
        // 0: dequeue_avail rx
        dequeue_ret = serial_dequeue_avail(0, buffer_addr);
        if (dequeue_ret != 0) {
          // dequeue_avail ring is empty
          return -1;
        }
        var enqueue_ret = 0;
        // 0: enqueue_used rx
        enqueue_ret = serial_enqueue_used(0, got_char, buffer_addr);
        if (enqueue_ret != 0) {
          return -1;
        }
      }
  }
}
```

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- No types!
  - Everything is a machine word

- Simpler semantics!
  - Complete formal semantics fits in a few hundred lines of HOL4
  - Almost nothing is undefined behaviour

- With a verified compiler!
  - Semantic equality from AST to ISA levels
  - Using part of CakeML

If you are verifying your code anyway, types don't seem to help much actually

Simplifying design decisions:
- No dynamic allocation
- Single-threaded only
- No pointers to stack variables
- No side effects in expressions

CakeML

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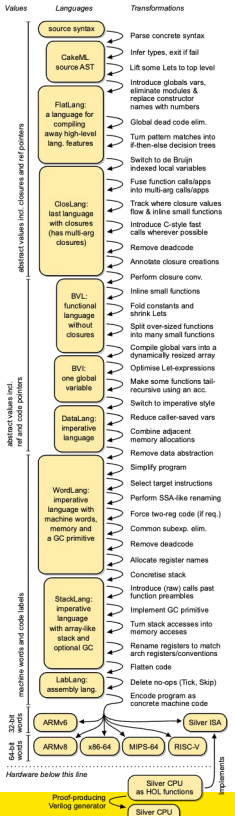
Pancake is an offspring of CakeML.

CakeML is an impure functional programming language similar to Standard ML

```
fun exists f xs =
  case xs of [] => False
| x::xs => f x orelse exists f xs
```

The machine code generated at the bottom has the same observable events as the source AST



...with

- optimising compiler & bootstrapped binary
- verified from AST down to the ISA level
- developed on theorem prover HOL4

CAKEML
A Verified Implementation of ML

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Compiling into CakeML

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This is used for bootstrapping the binary compiler

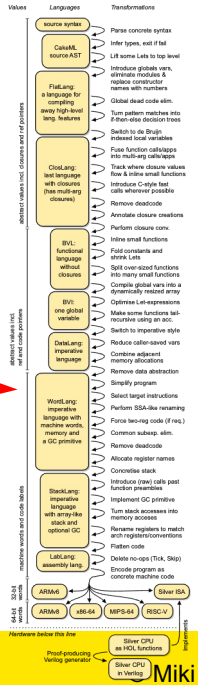
HOL (synthesis) [ICFP'12]

PureCake [PLDI'23]

Kalas [ITP'22]

Pancake [PLOS'23]

Pancake compiles into wordLang, halfway through the compiler (CakeML is too high level)



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Compiling into CakeML

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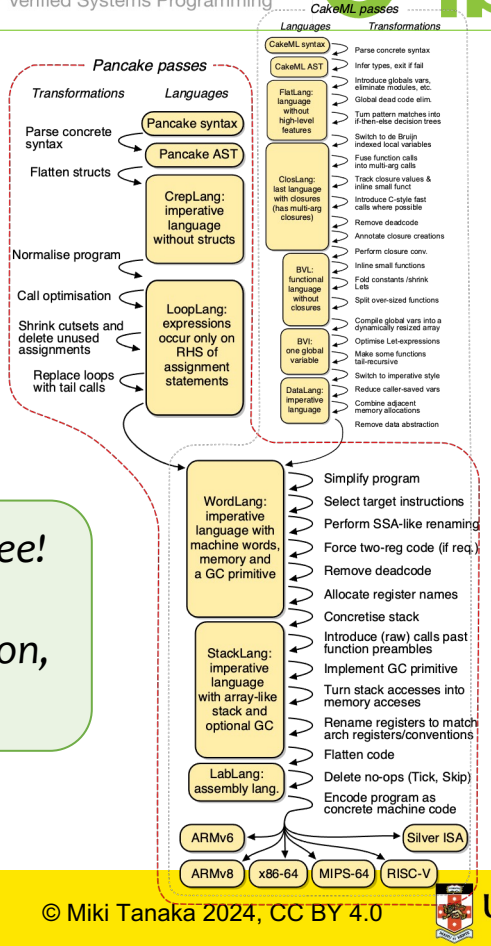
- End-to-end correctness is proved for Pancake compiler
- wordLang:
  after GC is introduced, where everything's a word,
  and almost everything is unmanaged except the stack
- No GC for Pancake
- We extended Pancake with
  shared memory feature
  (but not for CakeML)

Half a verified compiler for free!
(no need to verify register allocation, instruction selection, etc.)



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Compiling into CakeML

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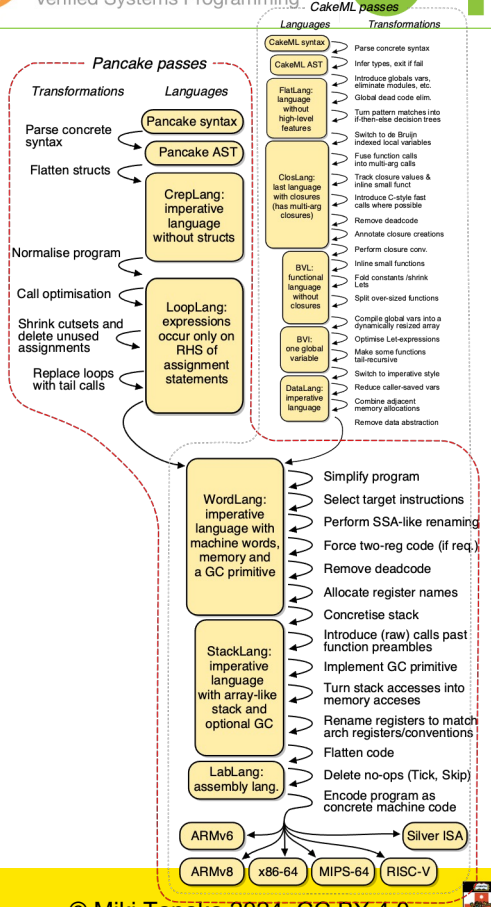
Bootstrapped binary for Pancake is available (as part of CakeML binary)

```
./cake --pancake
```

Pancake compiler is defined as a HOL function. Pancake binary is obtained via CakeML by the synthesis tool and in-logic compilation.

https://cakeml.org/



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Pancake : performance

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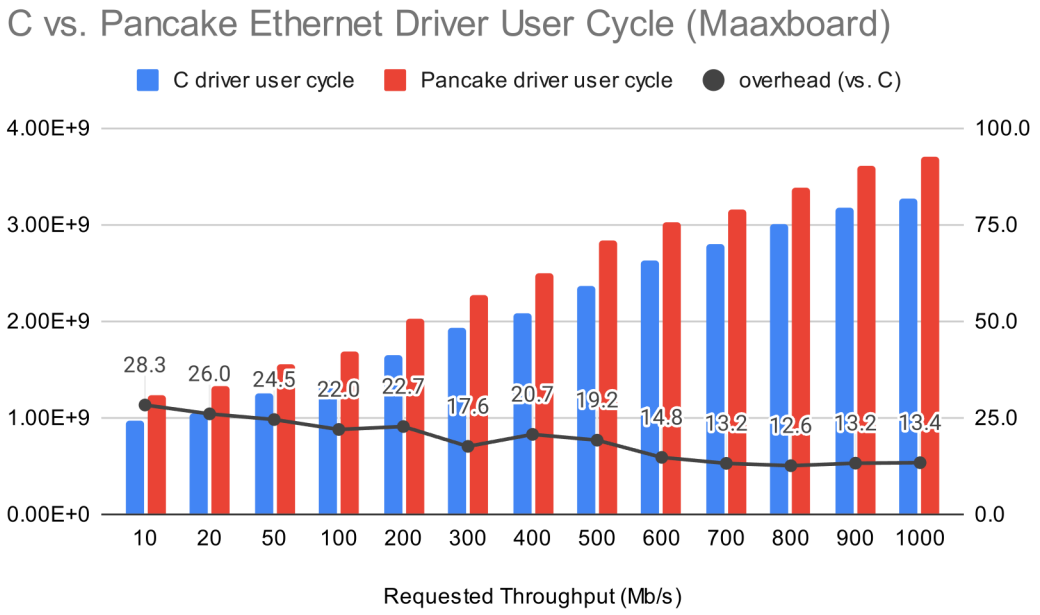
Good progress in relatively short time

But still noticeable overhead.

- Reducing ffi calls
- Better code generation

Further improvement expected



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Pancake : semantics

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Functional big-step semantics [ESOP'16]

- Used for compiler correctness proof (similar to CakeML)
- Deterministic
  - Not great for non-determinism
- Finite structure
  - Not great for divergence

The "state" carries a clock and an oracle:
- Divergence = as limit of (clock -> ∞)
- Evaluation uses the oracle to model ffi

Interaction tree semantics [Xia et al, POPL'20]

- Coinductive, captures interactions and continuations
  - Direct representation of divergence
  - No clock or oracle in the state*
- Semantic itree interacts with any oracle
- Soundness proved

Pancake: driver verification

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SMT:
Translation
from Pancake to Viper

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Target:
virtualiser
serial driver
ethernet driver
....

HOL4:
Functional big-step semantics
Interaction tree semantics

x

direct verification
Hoare logic

HOL4:
Decompilation
from Pancake to HOL

Pancake

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Thank you!

(Almost) all this stuff is open source and freely available here:
https://code.cakeml.org

Read more at:
https://cakeml.org/pancake

Hang out with us on Discord:
https://discord.gg/a8UUs6Ce6m