On the Potential of Coq as the Platform of Choice for Hardware Design

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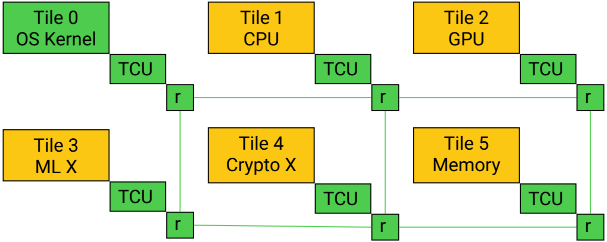
The TCB reduction argument for operating system design

- **Monolithic OS:** all hardware and a large OS kernel (with drivers, file system, network stack etc.)
- **Micro-kernel OS:** all hardware and a tiny OS kernel (w/o drivers, file system, network stack etc.)
- **M^3:** tiny hardware (called TCU) and a tiny kernel.[1]



- **Our goal:** a tiny hardware, i.e., NoC and TCU, *formally-verified* in Coq and a tiny kernel

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[1] Nils Asmussen et al. “M3: A Hardware/Operating-System Co-Design to Tame Heterogeneous Manycores”. In: ASPLOS ’16

Programming in Kôika

Registers: Definition

```
Inductive reg_t :=
  | r0
  | r1
  .
```

Types

```
Definition R idx := match idx with
  | r0 => bits_t 4
  | r1 => bits_t 10
end.
```

Initialization

```
Definition r idx : R idx := match idx with
  | r0 => Bits.of_nat sz 18
  | r1 => Bits.of_nat sz 18
end.
```

Functions/Actions

```
Definition _divide :
  uaction reg_t empty_ext_fn_t :=
{{ let v := read0(r0) in
   let odd := v[0b~0~0~0~0] in
   if !odd then
     write0(r1, v >> 0b~1)
   else
     write0(r1,v) }}.
```

Rules

```
Inductive rule_name_t :=
  | divide
  | multiply
  .
```

Rules $\mapsto$ Actions

```
Definition rules r := match r with
  | divide   => _divide
  | multiply => _multiply
  end.
```

Schedule

```
Definition collatz : scheduler := divide |> multiply |> done.
```

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[1] Thomas Bourgeat et al. "The essence of Bluespec: a core language for rule-based hardware design". In: PLDI 2020

[2] This example code is due to the Kôika authors.

From Tests to Lemmas

A test with fixed inputs and register initializations:

```
Example cannot_write_feature_without_kernel_bit:

  let inputs := init_inputs in
  let r := init_registers in (* kernel bit is [0] *)

  run_function r ext_ifaces inputs handle_requests
    (fun ctxt out =>
       get_kernel_bit(ctxt.[FEATURES]) = Ob~0).
  check.
Defined.
```

A lemma reasoning generalizing over inputs and register initializations:

```
Lemma cannot_write_feature_without_kernel_bit:
  ∀ (reg:reg_t)
    (inputs:input)
    (r : R reg), get_kernel_bit(r FEATURES) = Ob~0 ->

  run_function r ext_ifaces inputs handle_requests
    (fun ctxt out =>
       get_kernel_bit(ctxt.[FEATURES]) = Ob~0).
  check.
Defined.
```

Some First Performance Numbers

- Area and timing comparison: Original Verilog design vs Kôika design (up to implementation status)
- Running on an FPGA at 100 MHz

	Timing (ps)		Area			
	WNS	WHS	LUT	FF	DSP	Nets
Verilog	4112	12	3361	1566	1	7541
Kôika	5067	5	3224	1950	0	6603

WNS – worst negative slack, WHS – worst hold slack

LUT – look up table, FF – flip flop, DSP – dig. sig. proc.

- **Promising**: Our design is on-par with the original Verilog implementation.[1]

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[1] Oguzhan Türk. "A formally verified Hardware Design of a Communication Unit in a Micro-Kernel Operating System". MA thesis. University of Technology, Dresden, Germany, 2022. URL: `https://github.com/Barkhausen-Institut/tcu-koika/blob/main/documentation/Report/Thesis/Turk_Oguzhan_Master_Thesis.pdf`

Lessons learned

Kôika is a great abstraction for designing HW

and junior hardware engineers can get into it (easily with a little tutorial) but

- long-time HW engineers love their Verilog
- transactional execution is problematic

Notations work well for designing an EDSL but

- error messages still look rough and
- it is easier to fix broken definitions, lemmas than Notations.

Interpretation is great for writing tests

especially for HW engineers because HW tooling is not as easy but

- is tough when Kôika type checking/evaluation gets stuck.

Performance was mostly depending on `vm_compute`

- Having `vm_compute` in the types did not work well.
- Often `vm_compute` resulted in long evaluation times or failed.

Fun with `vm_compute`

- Actions and functions in Kôika are untyped and need to be type-checked.
- Type checking a Kôika term heavy relies on `vm_compute`.
- Example:

```
Definition min (size : nat) {reg_t : Type} : UInternalFunction reg_t empty_ext_fn_t :=
{{ fun min (a: bits_t size) (b: bits_t size) : bits_t size =>
     if a < b then a else b }}.
```

- Fails to type check and reports a massive (3000 lines <) term.
- **Diagnosis:** `vm_compute` does not solve but unfold decidable equality, e.g., `eq_dec size size`.

Fun with `vm_compute`

- Approaches:
  1. Evolution of the tactic for type-checking to be able to solve decidable equalities.
     - Some performance numbers:

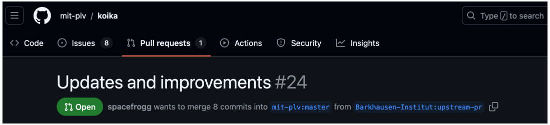
size	**tc w/** `vm_compute`	**tc with evolved tactic**
10	0.008 s	0.75 s
100	0.015 s	1.67 s
1000	0.061 s	10.2 s

     - Our evolved tactic (based on `cbn`) is 100 – 150 times slower.
  2. Direct construction of well-typed terms.
     - Drop-in replacement plus minor type changes:

```
Definition min {reg_t} {R : reg_t -> type} (size : nat) : function R empty_Sigma :=
{{ fun min (a: bits_t size) (b: bits_t size) : bits_t size =>
     if a < b then a else b }}.
```

     - **And** type checking performance is on-par with `vm_compute`.
     - PR coming soon!

Kôika Updates / Improvements



Updates and improvements #24

Open spacefrogg wants to merge 8 commits into `mit-plv:master` from `Barkhausen-Institut:upstream-pr`

- Coq 8.18 / OCaml 4.14
  - Add necessary scope hints
  - Update proofs and OCaml code
- Tool chain → dune 3
  - Generate tests/examples rules w/ OCaml (retires `etc/configure`)
  - Future: decouple `cuttlec` and experiment `Makefile`
- Stable development env. + CI
  - Nix flake + Makes CI runner
  - Provides software provenance
  - Future: integrate with `Coq nix toolbox`

Outlook and Research Directions

- Introduce tactics into Kôika for more complex proofs.
- Try MetaCoq for implementating the dynamics of a NoC.
- Introduce compiler transformations to
  - reduce the transactional overheads and
  - optimize Kôika programs.
- Towards composition of Kôika designs and
- Hardware modules.