Template-based Circuit Understanding

Adrià Gascón[1] Pramod Subramanyan[2] Bruno Dutertre[1]
Ashish Tiwari[1] Dejan Jovanović[1] Sharad Malik[2]

[1]SRI International

[2]Princeton University

Motivation

Verify/reverse-engineer a digital circuit

$\Rightarrow$

EXTRACT and UNDERSTAND subcomponents

Verify/reverse-engineer a digital circuit

$\Rightarrow$

EXTRACT and UNDERSTAND subcomponents

- FSM extraction [Shi et. al.]
- Functional aggregation and matching [Subramanyan et. al.]
- Word identification and propagation [Li et. al.]
- Identification of repeated structures [Hansen et. al.]

Verify/reverse-engineer a digital circuit

$\Rightarrow$

EXTRACT and UNDERSTAND subcomponents

- FSM extraction [Shi et. al.]
- Functional aggregation and matching [Subramanyan et. al.]
- Word identification and propagation [Li et. al.]
- Identification of repeated structures [Hansen et. al.]

Most of these techniques do not the find the right permutations in word components

Verify/reverse-engineer a digital circuit

$\Rightarrow$

EXTRACT and UNDERSTAND subcomponents

What does it mean to *understand* a *combinational* circuit $\mathcal{C}$?

- Find an equivalent higher-level definition
  - Flatten verilog netlist $\rightarrow$ High-level Verilog
  - Basic Boolean logic $\rightarrow$
    Boolean Logic $+$ Words and operations on Words

What does it mean to *understand* a *combinational* circuit $\mathcal{C}$?

- Find an equivalent higher-level definition
  - Flatten verilog netlist $\rightarrow$ High-level Verilog
  - Basic Boolean logic $\rightarrow$
    Boolean Logic + Words and operations on Words

Goal

Given purely Boolean Formula $\mathcal{C}$, produce "equivalent" Formula $\mathcal{F}$ over the theory of bitvectors.

A Combinational Boolean circuit $\mathcal{C}(I, O)$ is

(a) a list of input Boolean variables $I = \langle x_1, ..., x_n \rangle$ and

(b) a list $O = \langle f_1, \ldots, f_m \rangle$ of single-output Boolean formulas with inputs I.

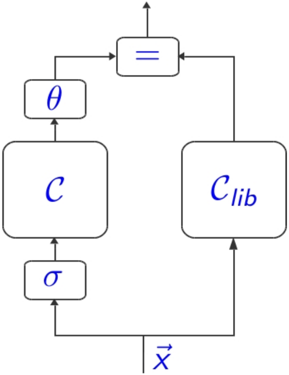
For $\vec{x} \in \{0, 1\}^n, \vec{y} \in \{0, 1\}^m$, by $\mathcal{C}(\vec{x}, \vec{y})$ we denote that $\mathcal{C}$ produces output $\vec{y}$ on input $\vec{x}$

The library aproach

Check functional equivalence against a library of known components.

- $\mathcal{C}(\langle x_1, \ldots, x_n \rangle, \langle f_1, \ldots, f_m \rangle)$
- $\mathcal{C}_{lib}(\langle x_1, \ldots, x_n \rangle, \langle g_1, \ldots, g_m \rangle)$
- Fixed permutations σ, θ

$$\forall\ i \in \{1, ..., m\}, \vec{x} \in \{0, 1\}^m :$$
$$f_{\theta(i)}(\sigma(\vec{x})) = g_i(\vec{x})$$

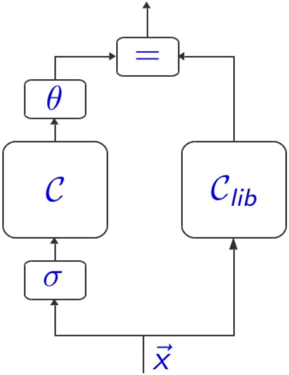


The library aproach

Check functional equivalence against a library of known components.

- $\mathcal{C}(\langle x_1, \ldots, x_n \rangle, \langle f_1, \ldots, f_m \rangle)$
- $\mathcal{C}_{lib}(\langle x_1, \ldots, x_n \rangle, \langle g_1, \ldots, g_m \rangle)$
- Fixed permutations σ, θ

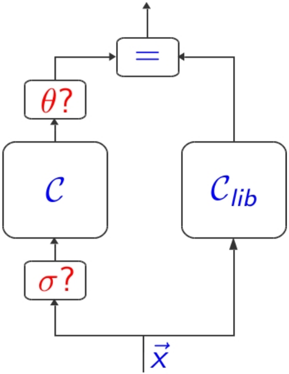
$$\forall\ i \in \{1, ..., m\}, \vec{x} \in \{0,1\}^m : \\ f_{\theta(i)}(\sigma(\vec{x})) = g_i(\vec{x})$$



Limitation: Permutations σ, θ must be known.

Permutation-independent equivalence checking

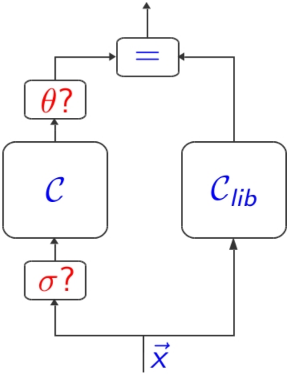
- $\mathcal{C}(\langle x_1, \ldots, x_n \rangle, \langle f_1, \ldots, f_m \rangle)$
- $\mathcal{C}_{lib}(\langle x_1, \ldots, x_n \rangle, \langle g_1, \ldots, g_m \rangle)$
- To be determined permutations σ, θ



$$\exists \sigma, \theta : \\ \quad \forall i \in \{1, \ldots, m\}, \vec{x} \in \{0,1\}^m : \\ \quad\quad f_{\theta(i)}(\sigma(\vec{x})) = g_i(\vec{x})$$

Permutation-independent equivalence checking

- $\mathcal{C}(\langle x_1, \ldots, x_n \rangle, \langle f_1, \ldots, f_m \rangle)$
- $\mathcal{C}_{lib}(\langle x_1, \ldots, x_n \rangle, \langle g_1, \ldots, g_m \rangle)$
- <u>To be determined</u> permutations σ, θ



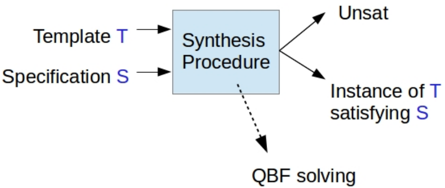
$$\exists \sigma, \theta : \\ \quad \forall i \in \{1, ..., m\}, \vec{x} \in \{0,1\}^m : \\ \qquad f_{\theta(i)}(\sigma(\vec{x})) = g_i(\vec{x})$$

Limitation: Still too restrictive.

1. $\mathcal{C}$ usually does not have a "standard" functionality.
2. $\mathcal{C}$'s functionality must be fully matched.

Template-based synthesis

Instead of a reference circuit, our approach requires a template of a specific form.



How do our templates look like?

A template T of a combinational circuit $\mathcal{C}(I, O)$ is:

- A subset $O_T \subseteq O$,
- a partition $I = (I_C \cup \bigcup_{i=1}^{n}(W_i))$, and
- a conjuntion of *guarded assignments* of the form

$$a_i \;:\; \psi_i(I_C) \Rightarrow \big(\theta(O_T) := \phi_i(\sigma(W_{i_1}), \tau(W_{i_2}))\big)$$

where

- ψ_i is a to be determined assignment on I_C,
- θ, σ, τ are to be determined permutations, and
- ϕ_i is a binary function over words.
- $i_1, i_2 \in \{1, \ldots, n\}$.

1. Circuit $\mathcal{C}(I, O)$
2. Subset outputs := O
3. Partition I := control ∪ inputsA ∪ inputsB
4. Template with
   (a) To be determined assignments v1, v2
   (b) To be determined permutations p, q

```
(and
    (=>
        (value v1 control)
        (=
            outputs
                (bv-add
                    (permute p inputsA)
                    (permute q inputsB)
    )   )           )

    (=>
        (value v2 control)
        (= outputs
            (ite
                (bv-slt
                    (permute p inputsA)
                    (permute q inputsB)
                )
                (mk-bv 32 1)
                (mk-bv 32 0)
)   )   )   )
```

1. Circuit $\mathcal{C}(I, O)$
2. Subset outputs := O
3. Partition I := control ∪ inputsA ∪ inputsB
4. Template with
   (a) To be determined assignments v1, v2
   (b) To be determined permutations p, q

$$\exists p, q, v1, v2 : \\ \forall \vec{x} \in \{0,1\}^n, \vec{y} \in \{0,1\}^m : \\ \mathcal{C}(\vec{x}, \vec{y}) \Rightarrow T(p, q, v1, v2, \vec{x}, \vec{y})$$

```
(and
    (=>
        (value v1 control)
        (=
            outputs
                (bv-add
                    (permute p inputsA)
                    (permute q inputsB)
    )    )          )

    (=>
        (value v2 control)
        (= outputs
            (ite
                (bv-slt
                    (permute p inputsA)
                    (permute q inputsB)
                )
                (mk-bv 32 1)
                (mk-bv 32 0)
)   )   )   )
```

Check validity of Boolean formulas over the theory of bit-vectors with two levels of quantification (∃∀ QF_BV):

$$\exists \vec{x} : C(\vec{x}) \wedge \forall \vec{y} : A(\vec{x}, \vec{y})$$

1. High-level preprocessing and simplifications [Wintersteiger et. al.]
2. Counterexample-refinement loop, similar to the approach used in 2QBF solvers [Ranjan et. al., Janota et. al.]
3. Functional signatures [Mohnke et. al.]

(1) Miniscoping:

$$\exists \vec{x} : A \vee B \ \rightarrow \ \exists \vec{x} : A \ \vee \ \exists \vec{x} : B$$

$$\forall \vec{x} : A \wedge B \ \rightarrow \ \forall \vec{x} : A \ \wedge \ \forall \vec{x} : B$$

(2) Equality resolution:

$$\exists \vec{x} : C(\vec{x}) \wedge \forall \vec{y} : (\bigwedge_i (y_i = x_i) \Rightarrow B(\vec{y}))$$

$$\rightarrow$$

$$\exists \vec{x} : E(\vec{x}) \wedge \forall \vec{y} : \bigcup_i (\{y_i \rightarrow x_i\})(B(\vec{y}))$$

(3) Distinguishing signatures.

Distinguishing Signatures

An output signature s_{out} is a function $s_{out} : \mathcal{B}_n \to \mathcal{D}$ such that, for every function f and permutation τ:

$$s_{out}(f(x_1, \ldots, x_n)) = s_{out}(f(\tau(x_1), \ldots, \tau(x_n)))$$

Distinguishing Signatures

An output signature s_{out} is a function $s_{out} : \mathcal{B}_n \to \mathcal{D}$ such that, for every function f and permutation τ:

$$s_{out}(f(x_1, \ldots, x_n)) = s_{out}(f(\tau(x_1), \ldots, \tau(x_n))))$$

$$\begin{aligned}
&\exists \sigma, \theta : \\
&\quad \forall i \in \{1, ..., m\}, \vec{x} \in \{0,1\}^m : \\
&\qquad f_{\theta(i)}(\sigma(\vec{x})) = g_i(\vec{x})
\end{aligned}$$

Distinguishing Signatures

An output signature s_{out} is a function $s_{out} : \mathcal{B}_n \rightarrow \mathcal{D}$ such that, for every function f and permutation τ:

$$s_{out}(f(x_1, \ldots, x_n)) = s_{out}(f(\tau(x_1), \ldots, \tau(x_n))))$$

$$\begin{aligned} &\exists \sigma, \theta : \\ &\quad \forall i \in \{1, ..., m\}, \vec{x} \in \{0,1\}^m : \\ &\qquad f_{\theta(i)}(\sigma(\vec{x})) = g_i(\vec{x}) \end{aligned}$$

$$\exists x, y : s_{out}(f_x) \neq s_{out}(g_y) \Rightarrow \theta(y) \neq x$$

Distinguishing Signatures

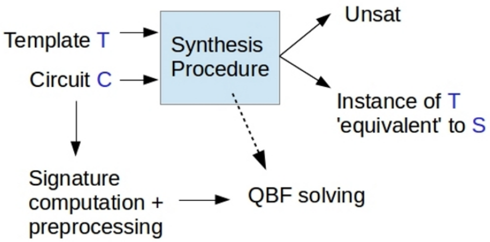
An output signature s_{out} is a function $s_{out} : \mathcal{B}_n \to \mathcal{D}$ such that, for every function f and permutation τ:

$$s_{out}(f(x_1, \ldots, x_n)) = s_{out}(f(\tau(x_1), \ldots, \tau(x_n))))$$

$$\begin{aligned}
&\exists \sigma, \theta : \\
&\quad \forall i \in \{1, ..., m\}, \vec{x} \in \{0,1\}^m : \\
&\qquad f_{\theta(i)}(\sigma(\vec{x})) = g_i(\vec{x}) \wedge \theta(y) \neq x
\end{aligned}$$

$$\exists x, y : s_{out}(f_x) \neq s_{out}(g_y) \Rightarrow \theta(y) \neq x$$

- We consider one input signature and one output signature.
  - Input dependency
  - Output dependency
- Signatures can be computed *independently* in the circuit and the template.



Benchmarks (40 Sat/40 Unsat):

- Reverse engineering benchmarks generated from high-level (behavioral) Verilog using the Synopsys Compiler.
- From ISCAS, an academic processor implementation, and synthetic examples.
- ALUs, multipliers, shifters, counters...

Tools:

- Yices (Yices format)
- Z3 (SMT2 format)
- Bloqqer + DepQBF (QDimacs)
- Bloqqer + RareQs (QDimacs)
- Bloqqer + sKizzo (QDimacs)
- Cir-CEGAR (Mini-SAT) (QDimacs + top titeral)

Variants:

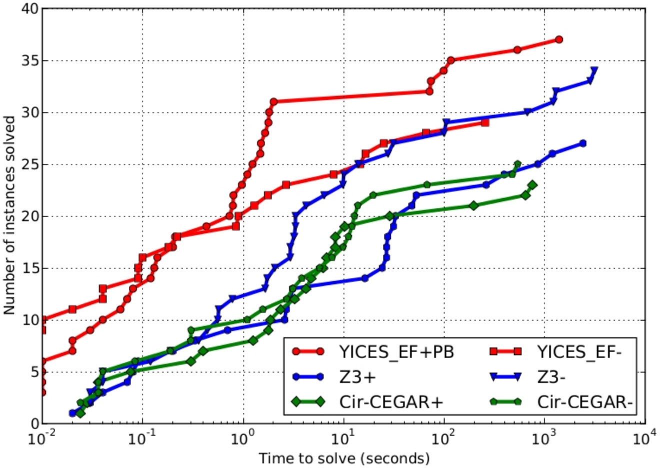
- Considered two simple encodings for permutations
- Studied effect of preprocessing, encodings, and signatures

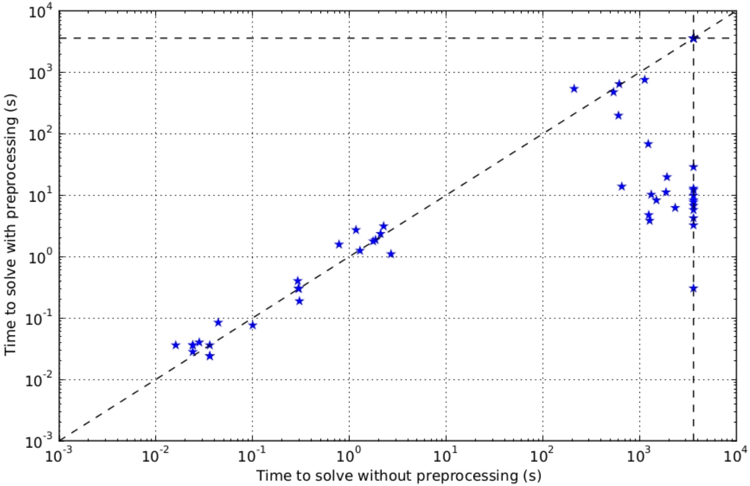
Conclusion and further work

- Yices and Z3 are sensitive to the encoding of permutations
- Preprocessing and signatures are harmless and crucial in many cases
- Benchmarks are available in SMT2, YICES, QBF and (soon) QCIR
- Just putting together two SAT/SMT solvers is not enough
- QDIMACS encoding is not suitable for this kind of synthesis

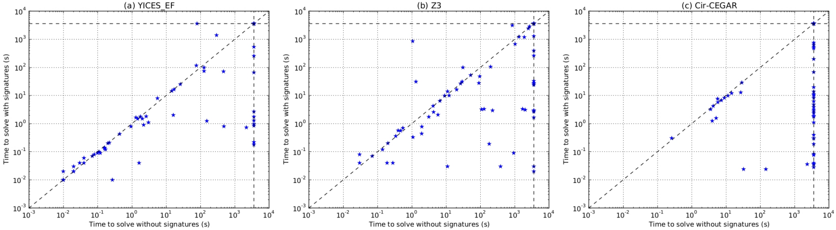
- Integrate signature computation in the Exist-Forall loop
- Compare to other synthesis algorithms

Questions? Comments? Suggestions?


Number of instances solved
Time to solve (seconds)
YICES_EF+PB
YICES_EF-
Z3+
Z3-
Cir-CEGAR+
Cir-CEGAR-



Time to solve with preprocessing (s)
Time to solve without preprocessing (s)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



(a) YICES_EF
(b) Z3
(c) Cir-CEGAR
Time to solve with signatures (s)
Time to solve without signatures (s)