Formal Verification of High-Level Synthesis

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CHICAGO SPLASH2021

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Outline

Example

Verification

Results

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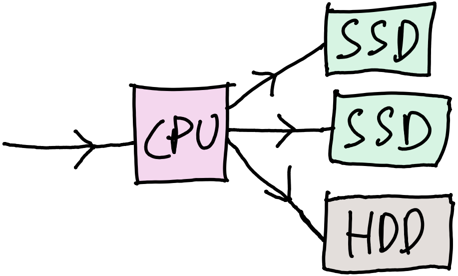
The Need to Design Hardware Accelerators

Hardware accelerators are needed more and more industries.

- Using a **CPU** everywhere not always the best choice.



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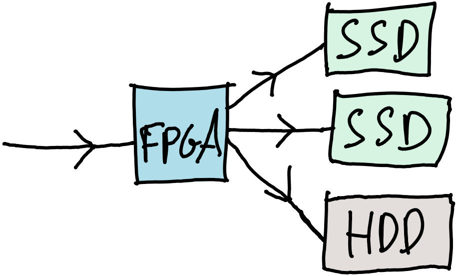
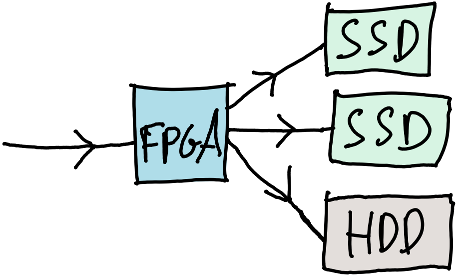


The Need to Design Hardware Accelerators

Hardware accelerators are needed more and more industries.

- Using a **CPU** everywhere not always the best choice.
- **Field-Programmable Gate Arrays (FPGA)** provide a good alternative.
- FPGAs act as **reprogrammable hardware**, therefore can be made application specific.



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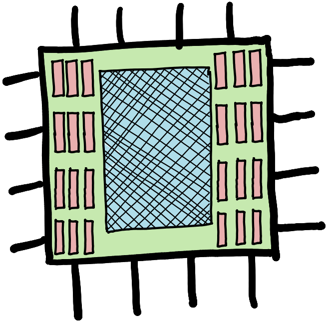
- FPGA's are programmable circuits with two main components.



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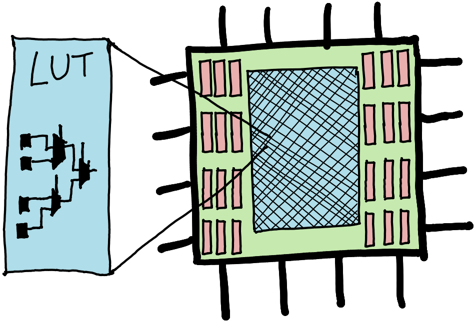

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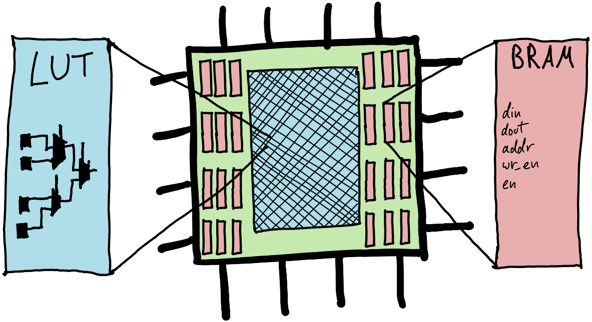
- **BRAMs** provide accessible storage.



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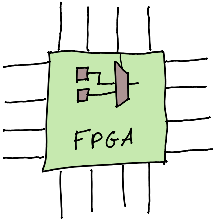
- FPGAs contain **LUTs** and programmable interconnects.



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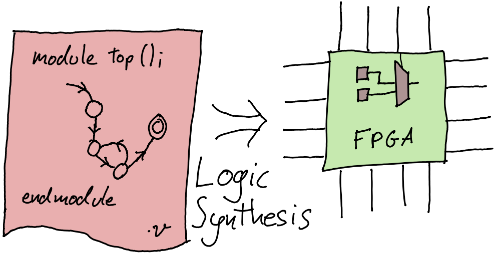

Fine control

Long to design

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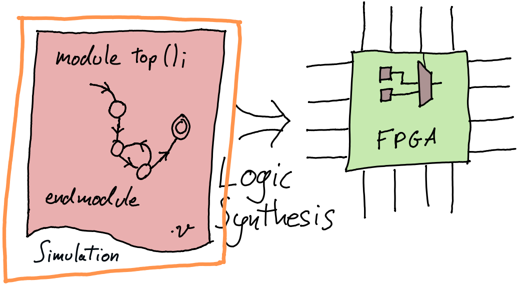

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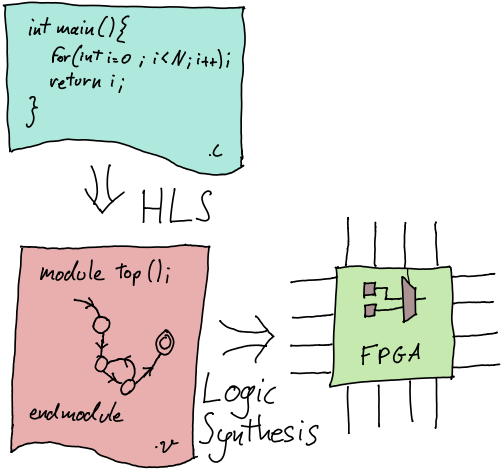

Quick to design

Less control

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So How do we Program an FPGA?

- FPGAs contain **LUTs** and programmable interconnects.
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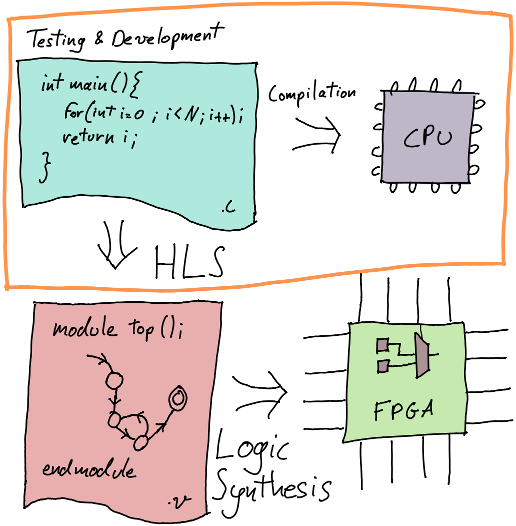
- High-Level Synthesis is an alternative.
- Faster testing through execution.



↑ Quick to design ↓ Less control

Motivation for Formal Verification

Difficult to debug HLS tools:

- Simulation can take a long time.
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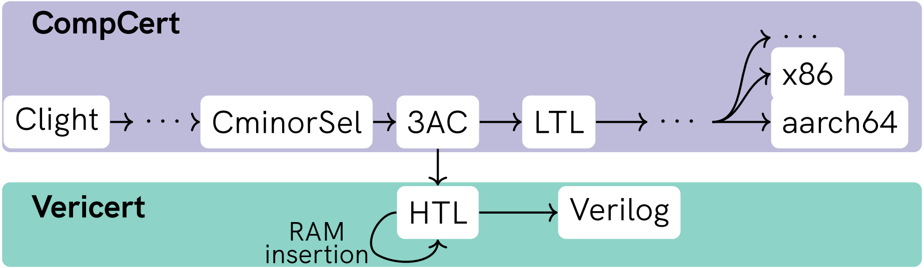
- Correctness is important in hardware, testing is done at every level.

High-level synthesis is often quite unreliable:

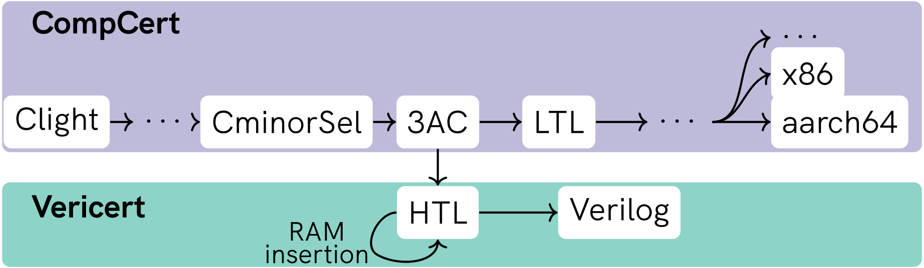
- Intel's OpenCL could not be fuzzed because of too many issues (Lidbury et al. [2015]).
- We fuzzed HLS tools (Herklotz et al. [2021]) and found they failed on **2.5%** of simple random test cases.

Solution



Use CompCert, a fully verified C compiler, and add an HLS backend.

Solution



Support for: all **control flow**, **fixedpoint**, **non-recursive functions** and **local arrays/structs/unions**.

Outline

Example

Verification

Results

Example: 3AC

```
int main() {
    int x[2] = {3, 6};
    int i = 1;
    return x[i];
}
```

Example of a very simple program performing loads and stores.

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Example: 3AC

- **three address code (3AC)** instructions are represented as a control-flow graph (CFG).
- Each instruction links to the next one.

```
main() {
    x5 = 3
    int32[stack(0)] = x5
    x4 = 6
    int32[stack(4)] = x4
    x1 = 1
    x3 = stack(0) (int)
    x2 = int32[x3 + x1 * 4 + 0]
    return x2
}
```

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Example: HTL Overview

The representation of the **finite state-machine with datapath** is abstract and called **HTL**.

```
Definition datapath := ℤ⁺ ↦ Verilog.stmnt
Definition controllogic := ℤ⁺ ↦ Verilog.stmnt
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Definition datapath := ℤ⁺ ↦ Verilog.stmnt
Definition controllogic := ℤ⁺ ↦ Verilog.stmnt

Record module: Type := mkmodule {
    mod_datapath: datapath;
    mod_controllogic: controllogic;
    mod_reset: reg;
    mod_ram: ram_spec;
    ...
  }.
```

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Example: Translation (3AC $\rightarrow$ HTL)

Translation from **control-flow graph** into a **finite state-machine with datapath**.

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- Each **3AC instructions** translated into equivalent **Verilog statements**.
- Function **stack** implemented as **Verilog array**.
- Pointers for loads and stores translated to array addresses.
  - **Byte** addressed to **word** addressed.

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Example: Memory Inference Pass

- An HTL → HTL translation removes loads and stores.
- Replaced by accesses to a proper **RAM**.

```
stack[{{{reg_5 + 32'd0} + {reg_1 * 32'd4}} / 32'd4}]
```

becomes

```
u_en <= ( ~ u_en); wr_en <= 32'd0;
addr <= {{{reg_3 + 32'd0} + {reg_1 * 32'd4}} / 32'd4};
```

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Verilog Syntax

```
module top(input clk, input [31:0] in1,
           output reg [31:0] out1);
  reg [31:0] reg_1, tmp;

  always @(posedge clk) begin
    reg1 <= in1;
  end

  always @(posedge clk) begin
    tmp = reg1;
    out1 <= tmp;
  end
endmodule
```

- Verilog example for a simple shift register.

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endmodule
```

- Verilog example for a simple shift register.
- Always block run in parallel

Example: Translation (HTL → Verilog)

```
module main(reset, clk, finish, return_val);
  input [0:0] reset, clk;
  output reg [0:0] finish = 0;
  output reg [31:0] return_val = 0;
  reg [31:0] reg_3 = 0, addr = 0, d_in = 0,
             reg_5 = 0, wr_en = 0,
             state = 0, reg_2 = 0,
             reg_4 = 0, d_out = 0, reg_1 = 0;
  reg [0:0] en = 0, u_en = 0;
  reg [31:0] stack [1:0];
  // RAM interface
  always @(negedge clk)
    if ({u_en != en}) begin
      if (wr_en) stack[addr] <= d_in;
      else d_out <= stack[addr];
      en <= u_en;
    end
```

- Finally, translate the FSMD into Verilog.

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- Finally, translate the FSMD into Verilog.
- This includes a RAM interface.

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Example: Translation (HTL → Verilog)

```
// Data-path
always @(posedge clk)
  case (state)
    32'd11: reg_2 <= d_out;
    32'd8: reg_5 <= 32'd3;
    32'd7: begin
      u_en <= ( ~ u_en); wr_en <= 32'd1;
      d_in <= reg_5; addr <= 32'd0;
    end
    32'd6: reg_4 <= 32'd6;
    32'd5: begin
      u_en <= ( ~ u_en); wr_en <= 32'd1;
      d_in <= reg_4; addr <= 32'd1;
    end
    32'd4: reg_1 <= 32'd1;
    32'd3: reg_3 <= 32'd0;
    32'd2: begin
      u_en <= ( ~ u_en); wr_en <= 32'd0;
      addr <= {{{reg_3 + 32'd0} + {reg_1 * 32'd4}} / 32'd4};
    end
    32'd1: begin finish = 32'd1; return_val = reg_2; end
    default: ;
  endcase
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- Finally, translate the FSMD into Verilog.
- This includes a RAM interface.
- Data path is translated into a case statement.

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    end
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- Finally, translate the FSMD into Verilog.
- This includes a RAM interface.
- Data path is translated into a case statement.
- Ram loads and stores automatically turn off RAM.

Example: Translation (HTL → Verilog)

```
// Control logic
always @(posedge clk)
  if ({reset == 32'd1}) state <= 32'd8;
  else case (state)
         32'd11: state <= 32'd1;
         32'd8: state <= 32'd7;
         32'd7: state <= 32'd6;
         32'd6: state <= 32'd5;
         32'd5: state <= 32'd4;
         32'd4: state <= 32'd3;
         32'd3: state <= 32'd2;
         32'd2: state <= 32'd11;
         32'd1: ;
         default: ;
       endcase
endmodule
```

- Finally, translate the FSMD into Verilog.
- This includes a RAM interface.
- Data path is translated into a case statement.
- Ram loads and stores automatically turn off RAM.
- Control logic is translated into another case statement with a reset.

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Verilog Semantics (Adapted from Lööw et al. (2019))

- Top-level semantics are **small-step operational semantics**.

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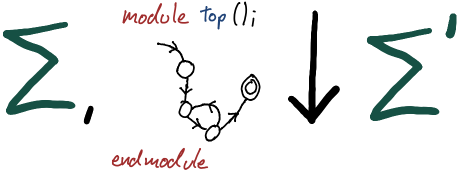
- At each clock tick, the **whole module** is executed using **big-step semantics**.



How do we prove the HLS tool correct?

- We have an **algorithm** describing the **translation**.
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Behaviour	Guarantee
Converging	Means a result is obtained, Verilog and C results must be equal.
Diverging	C is in an infinite loop, Verilog must execute indefinitely.
Wrong	Such as undefined behaviour, no guarantees need to be shown.

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Main Challenges in Proof

Translation of memory model

Abstract/infinite memory model translated into **concrete/finite RAM**.

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Integration of Verilog Semantics

- **Verilog semantics** differs from CompCert's main assumptions of intermediate language semantics.
- Abstract values like the **program counter** now correspond to **values in registers**.

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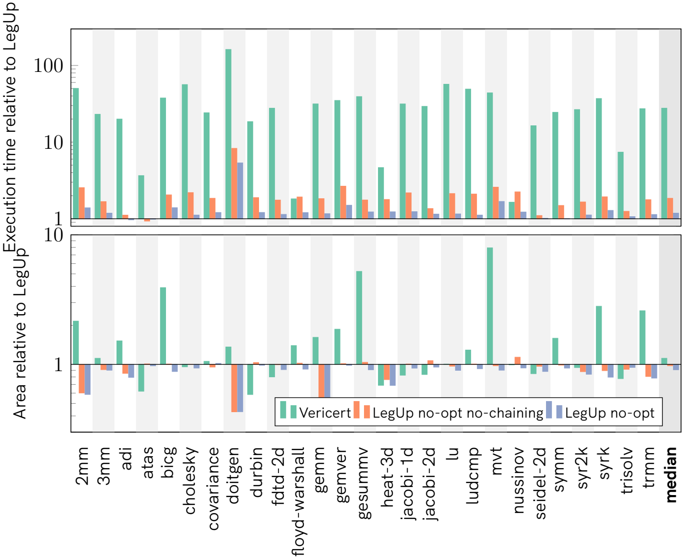
The bad news: with division approximately 27× slower



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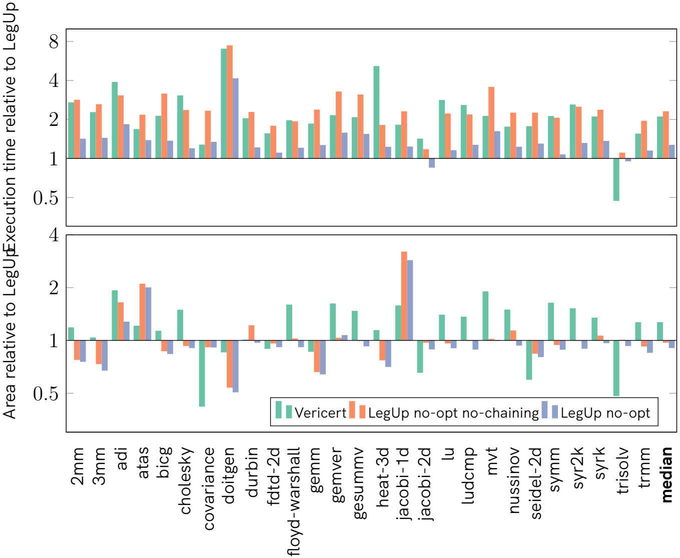
The better news: without division about 2× slower



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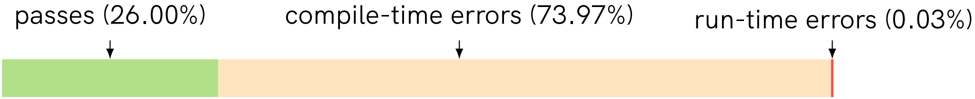
Fuzzing Vericert with Csmith

Fuzzed Vericert with Csmith to check correctness theorem.

- One bug was found in the pretty printing.
- Many compile-time errors are expected.
- Mainly rejected because of wrong size.



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Conclusion

Written a formally verified high-level synthesis tool in **Coq** based on **CompCert**.

- HLS tool **proven correct in Coq** by proving translation of CFG into FSMD.
- Small optimisations implemented such as **Ram Inference**.
- Performance without divisions comparable to LegUp without optimisations.

Thank you

Documentation

https://vericert.ymhg.org

GitHub

https://github.com/ymherklotz/vericert

OOPSLA'21 Preprint

https://ymhg.org/papers/fvhls_oopsla21.pdf

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References

Yann Herklotz, Zewei Du, Nadesh Ramanathan, and John Wickerson. An empirical study of the reliability of high-level synthesis tools. In *2021 IEEE 29th Annual International Symposium on Field-Programmable Custom Computing Machines (FCCM)*, pages 219–223, 2021. doi: 10.1109/FCCM51124.2021.00034.

Christopher Lidbury, Andrei Lascu, Nathan Chong, and Alastair F. Donaldson. Many-core compiler fuzzing. In *Proc. of the 36th ACM SIGPLAN Conf. on Programming Language Design and Implementation*, PLDI '15. ACM, 2015. doi: 10.1145/2737924.2737986.